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Service Life Assessment of Concrete with ASR and Possible Mitigation

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LIST OF TABLES

LIST OF FIGURES

TABLE OF CONTENTS

CHAPTER

ABSTRACT

Alkali Silica Reaction (ASR) is a particular type of chemical reaction involving hydroxyl ions present in the pore water of concrete and a certain form of silica present in some aggregates. ASR can cause deterioration of concrete highways, runways, bridges and other structures. As there are many interacting and interdependent parameters that influence its occurrence, the ASR phenomenon is complex. ASR is difficult to recognize, identify, and monitor. There are conflicting views on the effect of ASR on concrete properties. It is recognized that of all the possible methods of controlling the deleterious expansion caused by ASR in concrete, the use of admixtures can impart the most realistic advantages to the properties of concrete. In spite of much research carried out on the role of admixtures in controlling ASR expansion, there are still some aspects of the mechanism of the reaction of admixtures and their effects that are not clearly understood. This report includes an extensive literature review of all these issues related to ASR. The guidelines of using admixtures in different states of the United States and organizations are also presented in this paper. ASR expansion and Na_2O equivalent relationship equation is derived by using evolutionary algorithm. ASR reaction rating is also discussed in this paper.

CHAPTER 1
INTRODUCTION

1.1 Alkali Silica Reaction

Alkali-Silica reaction is a particular type of chemical reaction involving hydroxyl ion present in the pore water of concrete and certain forms of silica which are present in some aggregates. The chemical reaction also requires water for the alkali-silica gel reaction product which swells with the absorption of moisture to be produced.

The process can be expressed as a two-step process:

1. Alkali + Silica = Gel Reaction Product
2. Gel reaction Products + Moisture = Expansion

The amount of gel and the swelling pressure exerted are often sufficient to induce microcracking and then expansion of the surrounding concrete. According to Jones and Clark [1998], the surface of the concrete does not expand to the same extent as the interior of the concrete. The reason for this is that the surface is subject to leaching of the alkalis required for the reaction. This causes tensile stresses to be created in the surface, which can in turn induce surface macro cracking.

Some of the deleterious features of alkali-silica reaction in concrete structures include cracking, expansion and misalignment of structural elements as well as spalling of fragments of surface concrete as ‘pop-outs’. The presence of gel in fractures is also associated with aggregate particles within the concrete [Swamy 1992]. If ASR is not treated, it can continue to cause further deterioration such as expansion and cracking, corrosion of reinforcing steel, freezing and thawing damage as well as sulfate attack [Adams and Stokes 2002].

The ASR phenomenon is complex, as there are many interacting and interdependent parameters that influence its occurrence. ASR is difficult to recognize, identify, and monitor. There is no single test that can predict the accuracy of determining ASR. There are a lot of papers on the test procedures, many of which have conflicting views. There are also conflicting views on some aspects regarding the effect of ASR on concrete properties. There is also a lot of confusion among researchers with regard to the mitigation of ASR using admixtures, as well as determining the exact amount of different admixtures required and their corresponding effects on the ASR process.

1.2 Objective

The main objective of this research is to review and evaluate the literature and practice regarding the alkali silica problem in concrete pavements. The evaluation will include the effect of ASR on concrete, factors affecting ASR, and mitigation methods for ASR adopted by different agencies and states. It is also the objective of this research to develop ASR performance equations as well as prediction of ASR expansion and rating.

1.3 Organization of the report – shouldn't this section be on the previous page to explain how the chapters are laid out? This seems out of place here.

Chapter one describes the alkali silica reaction and states the objective of this research. The second chapter describes the background studies based on different papers published in different journals. Chapter three describes the data analysis and the evolutionary algorithm used to develop the equations for ASR and variable relationship. Chapter four gives the concluding remarks.

CHAPTER 2
BACKGROUND STUDIES

2.1 The Effects of ASR on the Properties of Concrete and Reinforced Concrete Members

Numerous research efforts have been devoted to characterizing effects of ASR on the properties of concrete and reinforced concrete members. From available literature, it appears that ASR has considerable effect on concrete properties as described below.

Effects on Concrete Compressive Strength

There are differences in opinion on the effect of ASR on concrete compressive strength. Jones and Clark [1998] state that ASR reduces the compressive strength of concrete, with reduction increasing with increase in expansion. The restraining effect of the less reactive surface layer of a specimen affects the apparent strength. The cube test is relatively insensitive to ASR expansion, while the sensitivity of a cylinder is dependent on its height to diameter ratio. Jones and Clark [1998] also state that for most cases, the strength of ASR concrete can be calculated from the reduction factors given by Doran [1992]. These factors should, however, be applied to the strength of an equivalent non-reactive concrete of the same age rather than the concrete’s 28 day strength.

Fan and Hanson [1998] conducted studies on the structural behavior of reinforced concrete beams and the mechanical behavior of concrete and gave the following observations. Change in mechanical properties of concrete cylinders was insignificant before visible ASR cracks occurred. After cracking however, substantial reduction was observed. At an age of 6 months in ASR accelerated conditioning, the compressive strength reduced by 24 percent compared with the corresponding 28 day values. Monnette et al. [2002] studies showed however that ASR reduced compressive stiffness, resonant frequency, and flexural strength of concrete, but not the compressive strength. It must be noted in that report, test specimens were conditioned submerged in one normal sodium hydroxide solution and were not subjected to cycles of wetting and drying as would occur in practice. It cannot be conclusively stated that ASR reduces compressive strength. There are differences in opinion on this matter.

Effects on Modulus

Jones and Clark [1998] noted that Young's modulus of concrete can be significantly reduced by ASR. The reduction is due to microcracks rather than the expansion. The authors also suggested that in the Young's modulus case, the results from cores should be compared with the estimated expansion at the position where the core was removed.

Fan and Hanson [1998] showed that at an age of 6 months, dynamic modulus was reduced by 31 percent compared with the corresponding 28 days value. A study conducted by Monette et al. [2002] demonstrated that the static modulus of elasticity is very sensitive to the damage in concrete by ASR, whereas the dynamic modulus of elasticity was less sensitive. It can be concluded that ASR reduces concrete modulus.

Effect on Tensile Strength

Jones and Clark [1998] concluded in their research that the direct tensile strength of concrete is significantly reduced by ASR. The cylinder splitting test is less sensitive to the effects of ASR than the other tensile strength tests because it causes failure along predetermined line.

Effect on Flexural Strength

Monette et al. [2002] found that flexural strength of concrete was reduced by ASR expansions and suggested that flexural tensile strength is more sensitive to the effects of ASR expansion than compressive strength. However, because reinforcing steel is used in the tension zones of reinforced concrete members, this reduction is not significant in practice.

Effect on the structural Behavior of Reinforced Concrete Beams

Fan and Hanson [1998] came to the conclusion that ASR has more detrimental effect on the mechanical properties of concrete cylinders than on the structural behavior of reinforced concrete beams. Their study shows that after conditioning for one year, the flexural strength of the reactive beams which experienced ASR cracking was nearly the same as that of the non-reactive concrete beams. Effects of ASR on flexural strength of the preloaded and cracked beams were insignificant. Similar observations were noted by Monette et al. [2002]. Their study showed that ASR did not reduce the flexural capacity of simply supported and under reinforced concrete beams conditioned under sustained or cyclic service loads. It thus appears that ASR does not affect the flexural capacity of reinforced beams.

Effect on the Shear Strength of Concrete Beams

It is generally agreed that ASR increases shear strength of concrete beams. Jones and Clark [1998] suggested that prestress developed by ASR expansion enhances the shear strength and stiffness of beams; however, they also mentioned that the amount of prestress generated may be less than that calculated from surface expansion. Ahmed et al. [1999] investigated the shear capacity of reinforced concrete beams affected by alkali silica reaction and gave the following observation: the provision of longitudinal compression reinforcement and shear links reduced the width of cracks and managed to change the orientation of cracks such that they are more closely parallel to the reinforcement. Ahmed et al. [1999] stated that alkali-silica reaction increases the shear capacity of reinforced beams both with and without shear reinforcement.

Effect on the Tensile Bond Strength of Reinforcement in Concrete

Ahmed et al. [1999] conducted an experiment on the effect of ASR on the bond strength of concrete beams. They reported that the reduction in the bond strength due to ASR is consistent with the lap length of the tensile reinforcement. They also suggested the use of minimum equivalent lap length of 54∅ for ASR cases.

2.2 Factors Affecting ASR

There are not many researches on the factors affecting ASR. From the few studies found in the literature, it appears that ASR may be affected by several factors to a varying degree of importance as described below.

The Alkali Limit

An article by Hill [1996] discusses alkali limit development over the years. Based on Hill's [1996] review, the following information is gathered regarding the limit. The Na_2O equivalent of Portland cement, 0.60% maximum, originated in the early 1940s following recognition of concrete distress caused by alkali-silica reaction by the California Division of Highways and US Bureau of Reclamation. The Na_2O equivalent is calculated as the sum of $Na_2O + 0.658\ K_2O$. Over the years, it has been effective in preventing distress from alkali-silica reaction in many but not all cases. It had been recognized by early investigators that there were cases in which cements with Na_2O equivalents less than 0.60% and under some circumstances, less than 0.40% Na_2O equivalent might cause deleterious expansion. Aggregates have since been identified that require additional mitigating process such as inclusion of admixtures. Countries in Western Europe as well as Canadian states focused on the total alkali in the concrete. In the United Kingdom, a limit of 3 kg of Na_2O equivalent per cubic meter of concrete has been recommended for concrete containing reactive aggregates. Although the principal source of alkali in concrete is the cement used, the addition of alkali from other sources can also play a part. For example, by the use of sea water, the alkali contributed by the sodium chloride should be incorporated into calculations for total alkali content [Swamy 1992].

In addition to the alkalis derived from the constituents of concrete, it was suggested by Swamy [1992] to give consideration to the absorption of alkalis by hardened concrete in contact with sea water, some groundwater, and other materials such as de-icing salts. A number of studies suggest that the exposure to deicing salt or seawater can initiate ASR. Studies also show that exposure to deicing salt or seawater can initiate or accelerate alkali-silica reactivity by supplying additional alkalis to concrete. The principal mechanism proposed is pH increase in the concrete pore solution. However, there are studies showing significant decrease of the OH^- ion concentration in the pore solution of mortar bars stored in NaCl solution compared to control bars immersed in distilled water or stored at 100% RH despite the fact that the latter expanded less. It is suggested that the Cl^- ions would accelerate ASR as long as the OH^- ion concentration remains over a certain limit [Be´rube´et al. 2002]. The authors showed that the Cl^- and Na^+ ion concentrations increased in the pore solution of the near surface layers of field and laboratory concrete investigated and exposed to NaCl solution while the K^+ and OH^- ion concentration and then the pH decreased. The authors concluded that making concrete with a low alkali content is an effective way to prevent expansion due to alkali-silica reaction even for concretes exposed to seawater or deicing salts.

The Reactive Silica Component in the Aggregate

A form of reactive silica is essential for the ASR to take place. As little a quantity as 2 percent of reactive component has been reported in some cases where severe distress in concrete has occured [Swamy 1992]. Although most rocks are capable of containing reactive forms of silica, the requirements for a silicious material to be reactive are that it should be a form of silica that is poorly crystalline or contain many lattice defects, or be amorphous or glassy in character [Swamy 1992].

The Effect of Relative Humidity and Temperature

The influence of temperature variation and cycling on reaction and expansion is a matter of debate. It is narrated that at high temperature, reaction and expansion are initiated early, but as the reaction continues, both the reaction rate and expansion rate slow down. By contrast, reactive concretes and mortars stored at lower temperature react more slowly, but eventually the expansion exceeds that of concrete and mortar at higher temperature [Swamy 1992]. Another study by Olafsson [1986] showed that expansion is a function of temperature. The experiment showed that the maximum rate of expansion at

23º C was only 1/3 -1/5 of the maximum rate at 38º C. It therefore appears that there are conflicting views on this factor.

It is generally however accepted that the expansion of alkali-silica reaction vary directly with the percentage of relative humidity. Investigation by Olafsson [1986] also reveals that by reducing the relative humidity from 100% to below 90%, the total expansion caused by alkali aggregate expansion can be reduced. The lower the RH, the greater is the reduction in expansion. The decreased rate of expansion delays deterioration.

The Effect of Restraint

SHRP-C-342 reports that in most concrete and pavement structures, restraint to the reactive aggregate is developed both internally and externally of the concrete. The weight of concrete in a large structure can produce compression, and steel reinforcement would restrain expansion parallel to the direction of the reinforcement. Studies [Ahmed et al. 1998] support the conclusion that reinforcement restrains expansion parallel to the direction of the reinforcement.

Fan and Hanson's [1998] investigation gave the following results: ASR cracking exhibited a random or map pattern on the plain concrete specimens; dominant cracks on the reinforced concrete specimens were oriented in the direction parallel to the longitudinal direction. The authors also reported that ASR expansion in the direction of the reinforcement was reduced from about 4000 micro-strain in plain prisms to about 2000 micro-strain in prisms with 0.54 % reinforcement due to restraint. Highway pavements offer an interesting example of one-dimensional restraint, which minimizes transverse cracking so that longitudinal cracking is predominant [SHRP C 342]. The SHRP-C-342 report also mentions that the effect of expansion can be complicated by the effects of drying and growth of shrinkage cracks in exposed surfaces, as well as the differences in reaction sites caused by differences in moisture content.

The Effect of Gel Reaction Product

The interaction between the alkali in cement and reactive silica in aggregates in the presence of moisture produces an alkali-silica gel which swells on the absorption of water. This gel varies in composition and is complex. The relationship between the composition of the gel, its viscosity and ability to swell with absorption of water are complex and not clearly understood at the present time. The analysis of the EPMA what’s this? data shows that ASR gels containing calcium appear to be simple two component mixtures in which the swelling component is an alkali silicate gel of low and nearly constant alkali-silica ratio. The analysis gave the important result that on an anhydrous basis, for ASR gels to be free of the swelling component, the CaO content must be more than about 53% and the SiO_2 content must be less than 40% [SHRP C 342]. The behavior of gel in concrete however, is still not understood well and needs further research.

2.3 Mitigation of ASR

Different guidelines for preventing ASR in new and old concrete structures have been adopted by various national or state agencies around the world. Those guidelines are often based on local past experience with the problem or an arbitrary decision.
Malvar et al. [2002] cited different organizations which provided recommendations for the mitigation of ASR. The comparison is presented in Table 2.1. (Add DelDOT spec requirements to Table?)

Table 2.1 Comparison of recommendations by different organizations

Organizations	Recommendations	Comments
CALTRANS	1.15% fly ash replacement level if the fly ash has less than 2% CaO 2. 30% fly ash replacement level if CaO content is than 10%	CALTRANS emphasize on the use of fly ash.
AASHTO Lead States	Methods to prevent ASR in new concrete structures include: 1. Low-alkali and or blended cements. 2. Minimum 15% Class F fly ash or 25% GGBFS cement replacement. 3. Lithium admixtures.	Does not provide options for use of admixtures such as silica fume and natural pozzolans.
New Mexico State Highway and Transportation Department	1. Test aggregates according to AASHTO T 303 or ASTM C 1293 with expansion limits of 0.1 and 0.4%respectively. 2. If aggregate is potentially reactive than the following minimum admixtures are to be incorporated a) 20% of Class F fly ash by weight of cement b) 25 to 50% GGBFS c) Lithium nitrate-4.6L/m^3 of solution per kg of cement sodium equivalent.	Emphasizes on the use of AASHTO T 303 test. Minimum Class F fly ash 20% is greater than recommended by AASHTO Lead States

Portland Cement Association	Potentially reactive aggregates can be used in concrete in one of the three ways: 1)with a combination of pozzolan or slag with Portland or blended cement shown to be effective 2) with a blended cement shown to be effective or 3) with the alkali content in the cement and other concrete ingredients limited to levels proven to limit reactivity in field conditions.	Does not provide quantity of admixtures.

Table 2.1 Comparison of recommendations by different organizations (Continued)

Organizations	Recommendations	Comments
American Concrete Institute	1) Although a maximum of 0.6% Na_2O equivalent alkali is often used for cement, a limit of 0.4% is preferable. 2) A low-calcium oxide content is desirable for fly ash 3) GGBFS Grades 100 and 120 are recommended. 4) An expansion limit of 0.08% is suggested for ASTM C 1260. 5) Aggregates with lower particle size produce less expansion.	0.4% Na_2O equivalent use is suggested
International Center for Aggregate Research	The report recommends using at least either:1)17% calcined clay 2) 55% slag 3) 25% Class F fly ash 4) 35% Class C fly ash 5)10% silica fume 6)4.6L $LiNO_3$ per kg of Na_2O. Based on cost comparisons, it appears that use of Class F fly ash is the best alternative.	Provides various admixture options and reports that use of Class F fly ash is most cost effective.
	1) The expansion limit in CSA A23.2-25A is 0.15% (similar method as ASTM	Requires higher replacement level of Fly

Canadian Standards Association	C 1260 but with expansion limit 0.1%). 2) For the fly ash used, CSA A23.2-27A indicates that low lime contents, below 8% are preferred. 3) For highly reactive aggregates, recommended value for low lime fly ash is 25 to 30% or at least 50% GGBFS cement replacement.	ash.

2.4. The Effect of Admixtures in Controlling ASR

The use of admixtures can impart the most realistic advantages to the properties of the concrete to enhance its durability and resistance to the effects of ASR. However, though there is much research carried out on the role of admixtures in controlling ASR expansion, there are still some aspects of the mechanism of reaction of admixtures and their effects that are not clearly understood. The published literature shows differences in opinion and conflicting results about the role and effectiveness of chemicals, pozzolans, and mineral admixtures. The findings of an extensive literature survey on the effectiveness of different admixtures in controlling ASR and the different views on the impact of different admixtures are discussed in this section. The guidelines and practice of using admixtures followed in different states of the United States and in Canada are also discussed.

Fly Ash

It is generally accepted that appropriate use of fly ash can prevent ASR in concrete. Shehata et al. [2000] conducted expansion tests on concrete prisms and mortar bars containing reactive aggregate with eighteen fly ashes representing those commercially available in North America. The types of fly ash are categorized as Type F (≤ 8 ± 1% CaO), Type CI(> 8% and ≤ 20 ± 2% CaO) and Type CH(> 20% CaO). The paper indicates that the efficiency of fly ash in controlling expansion due to ASR varies within a wide range. Concrete containing 25% fly ash shows 2-year expansion values ranging from 0.14% to 0.176%. The results revealed that generally, for a given fly ash replacement level, the expansion increases as the calcium or the alkali content of the ash increases or its silica content decreases [Shehata et al. 2000].

Adams and Stokes [2002] state that low volumes of Class F fly ash can actually worsen the ASR problem, especially when the CaO percentage is greater than 5. According to a 1996 California Department of Transportation Study, replacement level of 25 to 30 % of Class F fly ash has been suggested for ASR mitigation.

Problem with high levels of Fly Ash is as follows:

High replacement levels (excess of 50%) may be required for highly reactive aggregates and high alkali cement but these can negatively impact early strengths. According to the study conducted by Lane and Ozyildrim [1999], the adverse effect of fly ash resulted in lower compressive strength. This adverse effect carried through 56 days as a consequence of low hydrating process. By 1 year however, the depression in strength level resulting from high amount of ash dissipated. The high replacement levels of fly ash produce concrete with very high electrical resistance, implying excellent overall durability. It however also causes low early strength and potential construction problems. To maintain the initial strength gain, it is suggested that water/cement ratio be lowered. Alternatively, some Departments of Transportation use replacement ratios such as replacing each bag of cement with 1.5 bags of class F fly ash [Malvar et al. 2002].

Silica Fume

The effects of silica fume on ASR have generally been considered to be favorable. Silica fume acts to reduce the alkali hydroxide content of the pore solution. Silica fume is also known to function as an extremely efficient pozzolan, reducing or even eliminating the calcium hydroxide normally formed by cement hydration. Studies have shown that calcium hydroxide needs to be present to stabilize the ASR gel. The role of calcium ions in the formation and expansion of gel produced as a result of ASR is a matter of debate. Some support the idea that the presence of calcium ions renders non-expansive gel products, while the other idea is that even though calcium-alkali-silica gels might not be expansive in nature, calcium ions are vital for deleterious ASR expansion to occur. Aquino et al. [2001] have shown that as the ASR reaction proceeds, the calcium to silica ratio of the reaction products increases following a linear trend. They suggested that calcium content in gel products may be linked to expansion.

Negative Effects of Silica Fume

Silica fume (SF) is a highly reactive pozzolan due to three notable characteristics: an average particle size of 0.1 μm., a high amorphous silica composition, and a very high surface area. Produced SF also has a very low bulk density ranging from 130 to 430 kg/m^3. This creates economic difficulties in transporting the SF from furnace sites to cement or concrete plants. Commercial suppliers have responded by processing SF using different methods of densification and compaction in order to improve the handling and transporting properties of the material. This will not cause any problem as long as the SF can be re-dispersed during concrete mixing. However, if it is not re-dispersed, two of its characteristics, small particle size and high surface area, will be greatly reduced. There also exists the possibility that the presence of undispersed agglomerates could cause additional problems.

A paradox suggested by Diamond [1997] that silica fume can induce ASR rather than mitigate it also exists. Silica fume in concrete does not always prevent ASR distress. Sometimes it can induce ASR distress. Oversized, undispersed grains can respond in concrete much as any alkali reactive aggregate would and react to generate expansive ASR gel if the alkali hydroxide concentration is high enough [Diamond 1997].

Boddy et al. [2000] investigated the effect of a product form of silica fume on its ability to control ASR. They came out with the conclusions that with all forms of SF tested, 4% replacement was not sufficient to control ASR of Spratt aggregate. At this level of replacement, the undensified and slurry forms of SF consistently performed the best, while the pelletized form of SF performed poorly relative to other mixtures. Concrete prisms containing 8% and 12% SF expanded similarly up to 1 year regardless of the product form of SF. The authors concluded that the undensified and slurry forms of SF were best at mitigating the expansion due to ASR.

Hasparyk et al. [2000] also showed that replacement level of 12 percent reduced the expansion at a threshold of 0.10% at 16 days (ASTM C 1260) with basalt and quartzite aggregates. Malvar et al. [2002] reported that the following steps should be taken when using silica fume:

1) It should be used in slurry form; 2) shreddable bags should be avoided; 3) extra mixing is recommended; and 4) proper curing must be followed.

Malvar et al. [2002] reported that 10% silica fume cement seemed to be effective for moderately reactive aggregates.

Calcined Natural Pozzolans

The use of fly ashes and ground granulated blast furnance slags in concrete is gaining acceptance, but the mineralogical composition of such by product materials are difficult to control. Pozzolans are manufactured to overcome the availability and uniformity problem associated with such by- product materials.

Barger et al. [2001] narrated the production and use of calcined natural product. They stated in their paper that Ash Grove Cement Company has tested various clay and shale materials for potential use as pozzolans in concrete and have manufactured blended cements and pozzolans from calcined clays. Test results they obtained show that mineral admixtures containing different amounts of calcined clay pozzolans performed well and showed very low expansions. The increase in calcium-silica hydrate content and changes to the calcium/silica ratio of the C-S-H gel, as well as reduction in the porosity, are suggested to be the reasons for the ASR mitigation.

Malvar et al. [2002] summarized that calcined clay can mitigate ASR at replacement levels of 10 to 20% for moderately reactive aggregates or 25% for highly reactive aggregates.

Ground-Granulated Blast –Furnace Slag (GGBFS)

Adams [2002] in his paper mentions that ACI developed a guide on the use of GGBFS in concrete in 1995 (ACI 233R). The guide indicates that a minimum of 40% cement replacement with GGBFS is needed to control ASR. Malvar et al. [2002] described the advantage of GGBFS use in pavement as the lighter color exhibited by

GGBFS which can reduce energy absorption, thus increasing pavement life by reducing temperature levels and lighting requirements. The cost of slag is also approximately ¾ of the cost of cement(I'd verify this price; I've heard it's closer to 1:1 to the price of Portland cement). However, the use of slag can lower initial concrete strength especially in cold weather.

Negative aspects of GGBFS

Lane and Ozyildrim [1999] showed in their experiment that with higher alkali cements, the minimum amount of slag is 50 percent to mitigate ASR. This level presents construction difficulties with respect to low early strength. They showed that the use of C441 results in a particular criterion (0.56% expansion at 56 days) and can require high replacement levels of slag that can result in low early strengths.

Ternary Blends (Ordinary Portland cement + Silica Fume + Fly Ash/Slag)

The problems faced by the high replacement level of fly ash and slag can be overcome by the use of ternary blends. Lane and Ozyildrim [1999] showed that incorporating small amounts of silica fume in ternary systems can be used to reduce transporting problems as well as increase ASR resistance of concrete using low replacement levels of fly ash or slag and thus avoid low early strength. Results from their experiments show that electrical resistance equivalent to that obtained in binary systems with 35% fly ash or 60% slag can be obtained in ternary systems in which 5% silica fume is combined with 15% fly ash or 25% slag.

Shehata and Thomas [2002] showed that adding 5% SF to concrete containing FA significantly reduces the 2-year expansion due to ASR. They also showed that SF significantly reduced the pore solution alkalinity at early ages (up to 28 days), but much of the alkalis initially removed from solution released back into solution at later ages. It was suggested that this could be due to the initial ASR product exchanging alkalis for calcium when FA is present in addition to SF. These alkalis are not returned to the pore solution. The reason may be because there is less calcium available, or it may be that the alkalis released from the initial SF product are sequestered by the FA or its hydration product.

Metakaolin

High- reactivity metakaolin (HRM) is a mineral admixture which is relatively new to the concrete industry. It differs from the more commonly used mineral admixtures such as fly ash and silica fume in that it is not a by-product. Ramlochan et al.'s [2000] study shows that the amount of HRM required to control the expansion to less than 0.04% at 2 years was from 15 to 20% depending on the aggregate. It was suggested that the mechanism by which this reduction occurred may due to the entrapment of alkalis by the supplementary hydrates and a consequent decrease in the pH of pore solutions (Ramlochan et al. 2000).

Rice Husk Ash

Much less is known about the efficacy of rice husk ash (RHA) in reducing ASR expansion. Rice husk ash is obtained from controlled burning of rice husk. This is also ecologically sound as rice husk residue is difficult to recycle (Hasparyk et al.2000). It has been proposed that the physicochemical properties of RHA are similar to that of SF, although the former may be even more strongly pozzolonic than the latter. Hasparyk et al. (2000) investigated the different levels of rice husk ash on expansion of mortar bars containing reactive aggregates such as basalt and quartzite. Replacement levels of 15% RHA produced the least expansion while 12% reduced the expansion to below the threshold value.

Lithium Based Admixtures

Lithium based admixtures are promising alternatives to conventional methods of preventing ASR. Adams and Stokes [2002] gave the following benefit list for using lithium based admixtures:

- Lithium based admixtures permit the use of local cost effective aggregates.
- They increases the life span of concrete structures.
- They are easy to handle and environmentally safe.

- They have no significant effect on other concrete properties.

Some of the lithium based admixtures are discussed below.

LiOH – This is a strong alkali hydroxide that completely dissolves in water and is fully ionized in solution. LiOH eventually produces enhanced concentration of OH- ions in concrete pore solution. The admixture substantially increases the challenge presented to the stability of any potentially reactive component present in the concrete [Diamond 1999] and Lumley [1997] showed that concrete containing flint cristobalite as the reactive aggregate and eq.Li_2O:eq. Na_2O ratio of 0.33 to 1 by mass was found to be effective in almost completely inhibiting ASR expansion.

Mo et al. [2002] conducted tests on the long-term effectiveness of LiOH in mitigating ASR. Their result is that ASR expansion of Beijing aggregate mortars could be inhibited long term by adding LiOH at an n(Li)/n(Na) molar ratio of 0.3 or above when the cement's effective alkali content was no more than 2.5 %. The key factors that enable lithium to inhibit ASR expansion in the long term are the lithium ion Li^+ having both a smaller ionic radius and a higher surface charge density than Na^+ or K^+. This enables it to enter the ASR product more readily than Na^+ or K^+ [Mo et al. 2000].

Effect of inadequate dosage of LiOH - Not only do inadequate dosages not provide the expected mitigation of ASR, but they may be worse than adding no admixture at all [Diamond 1999]. It is required that a dose level should be sufficiently high to enable the pH augmentation produced to be at least counterbalanced by the ameliorating effect of the lithium on the ASR gel. Lumley [1997] gave the explanation that with a particular cement, the lithium is taken up more quickly by the hydrates than the Na and K so that when the hydrates become saturated with alkali ions, more Na^+ and K^+ ions remain in solution, balancing OH^- ions.

$LiNO_3$ - The generation of LiOH and its unfavorable consequences at low dosage could be eliminated if the lithium was supplied as a neutral salt. $LiNO_3$ is a suitable form of lithium for incorporation in concrete. The introduction of $LiNO_3$ into the cement paste does not result in significant increase in the OH^- ion concentration developed in the paste.

But as with the LiOH case, only half of the lithium remains in solution and will be available to ameliorate the effects of ASR [Diamond 1999].

LiF and $LiCO_3$ – Lumley [1997] studied long term expansion tests on seven sets of concrete prisms. The compounds tested were the carbonate, hydroxide and fluoride of lithium. Lumley [1997] suggested that none of the three anions involved had a significant effect on ASR suppression. As $CO_3{}^{2-}$, OH^- and F^- would not necessarily have the same effect as each other on OH^- concentration, it is suggested that the Li: Na: K ratios are the dominant factors with respect to ASR. Diamond [1999] pointed out that incorporating almost insoluble lithium salts is essentially equivalent to incorporating LiOH directly. The same concern about the potentially harmful effects of using inadequate dosage applies for these salts also.

Lithium bearing admixtures - Thomas and Stokes [1999] studied the effects of lithium based admixture on alkali-silica reaction. A processed lithium bearing alumino-silicate, decrepitated spodumene(DS), was tested to observe its effect on ASR. Spodumene, a lithium aluminium silicate, is an important mineral source of raw material for the lithium industry. The results showed that significant quantities of lithium are released by the DS into the pore solution of pastes and mortars over time. The use of DS at levels in excess of 5 percent was effective in reducing the expansion of concrete prisms containing reactive aggregate.

2.5 Test Methods for Determining ASR

This section will encompass the review of the various laboratory tests that are available to identify alkali-reactive aggregates. Laboratory testing are often difficult, complex and time consuming. However as these tests are the surest way to evaluate the potential reactivity of aggregates, they are widely used. Petrographic studies, traditional tests and rapid accelerated test methods related to ASR are discussed, and their advantages and limitations evaluated in view of the published literatures.

Evaluation of Alkali-Reactive Aggregates

Evaluating the suitability of aggregates for concrete can be done through petrographic examination along with other instrument techniques such as X-ray diffraction and infra-red spectroscopy.

Petrographic analysis (ASTM C 295*)*: Petrographic analysis by optical microscopy has been used to investigate concrete failures. The advantages of this process are visualization of large areas at low magnification and the capability of obtaining mineralogical information of the constituting components by using different illumination. A limitation to this method is that small features may be difficult to identify based on their optical properties.

Scanning electron microscopy: Compositional data are determined by scanning electron microscopy (SEM) - energy-dispersive X -ray spectrometry (EDS). Sahu et al. [2001] stated that analysis of concrete specimens by SEM using back scattered electron (BSE) has the advantages of the BSE imaging providing information on the constituting components in phases from their backscattered intensity. SEM in addition to BSE imaging and EDS can help to obtain information about the constituent phases along their elemental composition. The limitations of SEM as noted by Sahu et al. [2001] are the visualization of a small area at a time and lack of ability to generate mineralogical information about the crystal structure.

In view of the limitations of each methods, Sahu et al. [2001] suggested that a combination of optical microscope and SEM with EDS using polished thin sections can be considered as a powerful combination of methods for the identification and characterization of features related to ASR and sulfate attack. Feature relocation software will enable the petrographer to identify an object of interest with one technique and confirm its identity with another, thereby using the strength of both techniques.

There are conflicting views about the accuracy of petrographic analysis. Touma et al. [2001] showed that petrographic examination did not correlate well with the results of the concrete prism test and the field performance data gathered on the aggregates. It appears that petrograhic analysis and the scanning process should be used in the process of evaluating alkali-silica reactivity in combination with other tests. It should not be the only test used.

Laboratory Test Methods

Choice of Salt

To accelerate the ASR process, different conditions are followed and salts are added. One of the popular practices is to study the effects of varying the cement alkali content on specific manifestation of ASR in the laboratory to select base cement of relatively low alkali content and enhance its alkali content by progressively increasing amounts of sodium or potassium hydroxide. The practice is based on the fact that cement alkalis eventually appear in the pore solution as a hydroxide. Diamond [1997] states the paradox that adding Sodium Hydroxide to raise the alkali level of cements raises the sulfate level of the pore solution instead of the hydroxide level. It has been shown that these responses are due to an almost immediate reaction between the dissolved sodium hydroxide and the gypsum of the cement. The reaction results in dissolution of the gypsum and precipitation of calcium hydroxide according to the following equation:

$2Na^+ + 2OH^- + CaSO_4.2H_2O \rightarrow Ca(OH)_2 + 2Na^+ + SO_4^{2-}$

Sacanni et al. [2001] conducted studies to establish how reliable accelerated ASR tests can be when using alkali-enriched cements. When the alkali concentration is increased by adding salts, the addition of an alkaline compound can alter the hydration reaction of the cement. In their research, sodium salts (NaCl, Na_2SO_4 and $NaHCO_3$) and sodium hydroxide was used in mortars. The tests gave the following conclusions. At 80°C the reaction of alkali-enriched cement pastes with the artificial reacting aggregate is fast enough to provide information after a few days, and the degree of expansion is dependent on the type of sodium compound used to artificially increase the amount of alkali. Sodium chloride and sodium sulfate particularly induces the highest levels of expansion. It appears therefore that the choice of salt to enhance alkali-silica reactivity and the temperature play an important role in the test methods.

Influence of dimension

For evaluating alkali reactivity of aggregates, the method of measuring the length is used most frequently. Some studies show that the dimension of the test specimen markedly affects the expansion of the mortar bars. Zhan et al. [1999] investigated the influence of the dimensions of test specimen on ASR. Their results show that the dimensions of the specimen will affect the expansion of the mortar bar not only under the condition of 95 to 100 percent RH at 20 or 40°C, but also under the autoclaved condition of 150°C in an alkaline solution. The larger the specimen, the larger the expansion will be. The effect of the dimensions of the specimen on the expansion of the mortar bar is relative to the size of the aggregate. The effect of dimensions become small when the aggregate is small, but is more pronounced when the aggregate is large.

Conventional Test methods

ASTM C227 - Standard Test method for Alkali reactivity of Cement -Aggregate Combinations (Mortar-Bar Method): This method is similar to ASTM C 1293 in terms of specimen exposure (100% relative humidity and 38ºC). According to Adams and Stokes [2002] this method can fail to show a material is reactive although the material may be reactive in the field.

ASTM C 1260 - Standard test method for potential reactivity of aggregates (Mortar bar Method): This method is widely used. Touma et al. [2001] showed with experiments that ASTM C 1260 can be used to evaluate ASR of aggregates; however, if the interpretive criteria now given in the non-mandatory appendix to ASTM C 1260 are used, the test is very severe and will result in an overestimation of the reactivity of some aggregates. They suggested that ASTM C 1260 should be used in combination with ASTM C 1293. Adams and Stokes [2002] stated that this test method has indicated potential reactivity for some aggregates in the laboratory although those aggregates do not show any deleterious effect in the field.

ASTM C 1293 - Standard test method to determine length change of concrete due to Alkali-Silica Reaction: It is considered to be the most reliable test for reactivity, but it requires a long test period i.e. one year. According to Touma et al. [2001], this test can be used by itself to determine the ASR of aggregates. They proposed a modification to this method to effectively accelerate the method so results can be generated within 13 weeks.

This they did by increasing the temperature of the environmental chamber to 60ºC. Malvar et al. [2002] report that it is difficult to assess which test ASTM C 1260 or ASTM C 1293 is more accurate.

ASTM C 441 - Standard test method for effectiveness of mineral admixtures or Ground-Granulated Blast-Furnace Slag in preventing expansion of concrete due to the Alkali-Silica Reaction: This test evaluates the effect of mineral mixtures on expansion of mortars made with Pyrex glass as admixture. There are several reasons for not adopting C441 for testing Portland cement. These are leaching of alkalis from the mortar bars during the test, poor reproducibility of the test procedure and the unsuitability of the standard reactive aggregate and Pyrex glass. Adam and Stokes [2002] stated that the behavior with actual aggregates could be considerably different.

AASHTO T 303 - Standard Test Method for Accelerated detection of Potentially Deleterious Expansion of Mortar Bars due to Alkali-Silica Reaction (T303**)**

This test method is similar to ASTM C 1260. NMSHTD recommended that any proposed aggregate be tested in accordance with AASHTO Test Method T 303 for the probability expansion due to ASR then be subjected to a modified bar test series in order to determine proper admixtures.

CHAPTER 3
DATA ANALYSIS

3.1 Introduction

This chapter presents the variables found for different structures from the study.

Pavement

ASR (% of expansion) = **f (**Na_2Oeqv of cement (%), SiO_2 of cement (%), Cl^- (mol/L), CaO/Si_2O(ASR gel), % of reinforcement, w/c ratio, temperature, relative humidity**)**

Bridge Structure

ASR (% expansion) = f (Na_2Oeqv of cement (%), SiO_2 of cement (%), Cl^- (mol/L),CaO/Si_2O(ASR gel), % of reinforcement, w/c ratio, temperature, relative humidity, weight of concrete**)**

Beams Elements of Structures

ASR (% expansion) = f (Na_2Oeqv of cement (%), SiO_2 of cement (%), CaO/SiO_2(ASR gel), % of longitudinal compression reinforcement, % of shear links)

Na_2O eqv= Na_2O + 0.658 K_2O

Regression Analysis Example for ASR

A study by Roy et al. [2003] evaluated 21 Portland cements and identified K_2O and Na_2O equivalent as significantly contributing to ASR expansion. ASTM C 441 Tests were done for the study. The data from the tests were subjected to the full multi-variate non-linear modeling. Results showed that only the equivalent alkali and the silica content of the clinker exhibit any correlation. A response surface model was fitted to the data which yielded the following relationship:

% Expansion = 1.05934 + 0.47883 Na_2O eqv - 0.05634 Si_2O

The regression and correlation analysis was performed using Mini Tab software

3.2 Source of Data

The source of data for ASR was obtained from the paper “Influence of Portland Cement Characteristics on Alkali Silica Reactivity” by Roy et al. [2003]. The materials used for the study include Portland cement, fine aggregate, and crushed pyrex cullet. The fine reactive and non-reactive aggregates were from two materials in Pennsylvania. The reactive aggregate is metamorphosed argillaceous sandstone containing framboids. Twenty one cements were selected for the study from the 114 types I and II. Table 3.1 shows the properties of the test clinker.

Two test methods were performed to monitor the development of ASR, namely ASTM C 441 and C 227. ASTM C 441 testing was done to evaluate alkali-silica reactivity of each of the 21 cements. After taking initial length measurement at 24 hours, subsequent length measurements were taken at 2,4,6,8 and 12 weeks. Table 3.2 shows the trend of ASR expansion for all 21 cements. The Evolutionary Training method was performed with the value of Na_2O equivalent, SiO_2 at the expansion values of two and eight week. These variables were chosen because they showed correlation with ASR expansion [Roy 2003]. The authors decided to use evolutionary algorithm because of its capability to analyze very limited data.

3.3 Evolutionary Computation

3.3.1. General

The three main concepts of evolutionary computation research are genetic algorithms, evolution strategies and evolutionary programming. All these computation techniques initialize the population of individuals and evolve them towards better and optimum requirements of the search space by means of a stochastic process of selection, mutation and recombination where appropriate. These techniques differ in the specific representation, mutation operators, and selection procedures. In genetic algorithms, emphasis is on chromosomal operators based on an observed genetic mechanism, for example crossover and bit mutation, evolution strategies and evolutionary programming emphasize the behavioral link between parents and offspring rather than the genetic link.

Table 3.1 Analysis of major oxides and discriminating properties of test clinker (Roy et al. 2003)

Cement	**SO_3**	**Alkalis**	**C_3A**	**Blaine**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**Na_2O**	**K_2O**
1	2.83	0.39	5.5	4084	20.91	3.97	2.99	62.97	3.27	2.83	0.095	0.45
2	2.38	0.52	3.8	3622	21.45	4.01	4.02	64.65	1.39	2.38	0.199	0.49
3	4.13	0.46	6.4	4048	20.26	4.45	3.2	63.81	1.55	4.13	0.156	0.46
4	3.77	0.76	11.7	3282	19.79	5.46	1.61	64.49	1.16	3.77	0.15	0.92
5	2.73	0.46	10	3871	20.56	5.02	1.94	63.77	3.77	2.73	0.09	0.56
6	3	0.26	10	3831	20.45	5.61	2.9	63.94	1.88	3.00	0.179	0.117
7	3.04	0.5	11.7	3705	19.81	6.03	2.54	64.46	0.88	3.04	0.24	0.39
8	3.13	0.64	9.6	4009	20.08	5.47	2.9	63.77	1.15	3.13	0.121	0.79
9	3.84	0.84	9.3	3871	20.49	5.14	2.54	63.1	1.74	3.84	0.180	1.00
10	2.81	0.91	7.5	4345	21.12	4.42	2.48	63.89	1.99	2.81	0.470	0.67
11	4.35	0.92	9.5	4029	19.61	5.25	2.6	62.43	2.11	4.35	0.20	1.09
12	3.48	0.79	6.7	3950	20.54	4.56	3018	61.01	5.01	3.48	0.25	0.82
13	2.68	0.37	5.8	3768	21.33	4.04	2088	63.85	1.25	2.68	0.133	0.36
14	2.68	0.5	7.2	3600	21.08	4.7	3.12	63.96	1.22	2.68	0.096	0.61
15	3.26	0.81	7.8	4179	20.2	4.58	2.59	62.65	2.09	3.26	0.20	0.93
16	3.05	0.07	9.5	3850	20.77	4.55	1.52	63.71	2.48	3.05	0.056	0.017
17	3.19	0.86	7.2	3384	21.25	4.29	2.44	63.37	2.04	3.19	0.39	0.71
18	3.43	1.00	10.6	3663	19.72	5.27	1.97	63.14	3.27	3.43	0.32	1.15
19	2.73	0.66	9.8	3803	20.29	5.54	2.9	64.97	1.04	2.73	0.112	0.83
20	2.9	0.39	7.4	3930	20.68	4.84	3.23	64.65	1.85	2.9	0.038	0.54
21	3.18	0.7	7.3	4104	20.4	4.63	2.91	61.76	3.96	3.18	0.32	0.57

Table 3.2 ASR mortar bar expansion at various exposures by ASTM C441 Test (Roy et al 2003)

Cement Properties			ASR expansion (%)			
Cement #	Na_2Oeqv	Si_2O	2 week	4 week	6 week	8 week
1	0.39	20.91	0.01	0.01	0.01	0.01
2	0.52	21.45	0.1	0.12	0.12	0.13
3	0.46	20.26	0.16	0.19	0.18	0.19
4	0.76	19.79	0.36	0.39	0.39	0.39
5	0.46	20.56	0.05	0.07	0.07	0.07
6	0.26	20.45	0	0	0.01	0.02
7	0.5	19.81	0.18	0.22	0.22	0.22
8	0.64	20.08	0.2	0.21	0.28	0.22
9	0.84	20.49	0.32	0.34	0.36	0.36
10	0.91	21.12	0.3	0.39	0.4	0.41
11	0.92	19.61	0.36	0.37	0.37	0.38
12	0.79	20.54	0.24	0.28	0.27	0.22
13	0.37	21.33	0	0.01	0.01	0.02
14	0.5	21.08	0.08	0.09	0.09	0.09
15	0.81	20.2	0.37	0.38	0.37	0.38
16	0.07	20.77	0.01	0.01	0	0.01
17	0.86	21.25	0.22	0.24	0.24	0.24
18	1	19.72	0.35	0.37	0.38	0.38
19	0.66	20.29	0.13	0.14	0.14	0.14
20	0.39	20.68	0.02	0.02	0.02	0.03
21	0.7	20.4	0.15	0.18	0.19	0.19

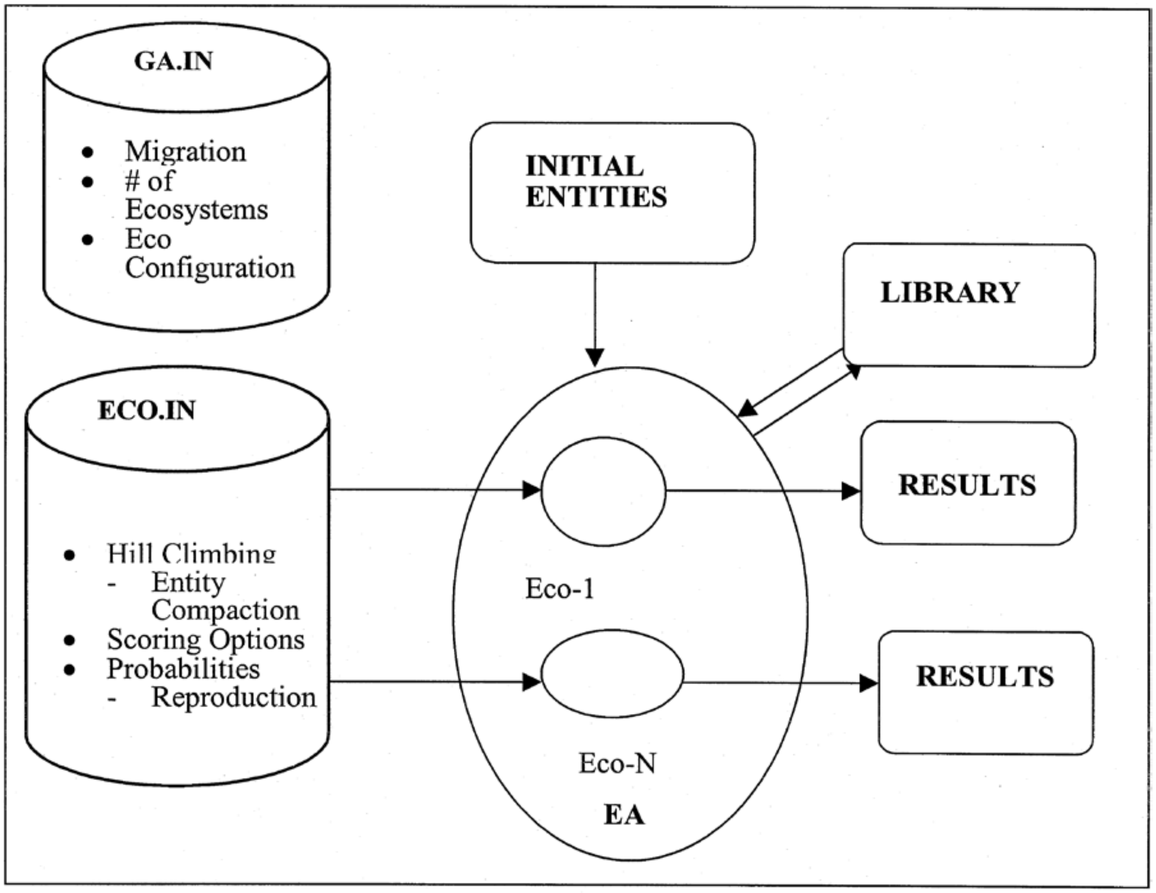

Figure 3.1 Evolutionary algorithm

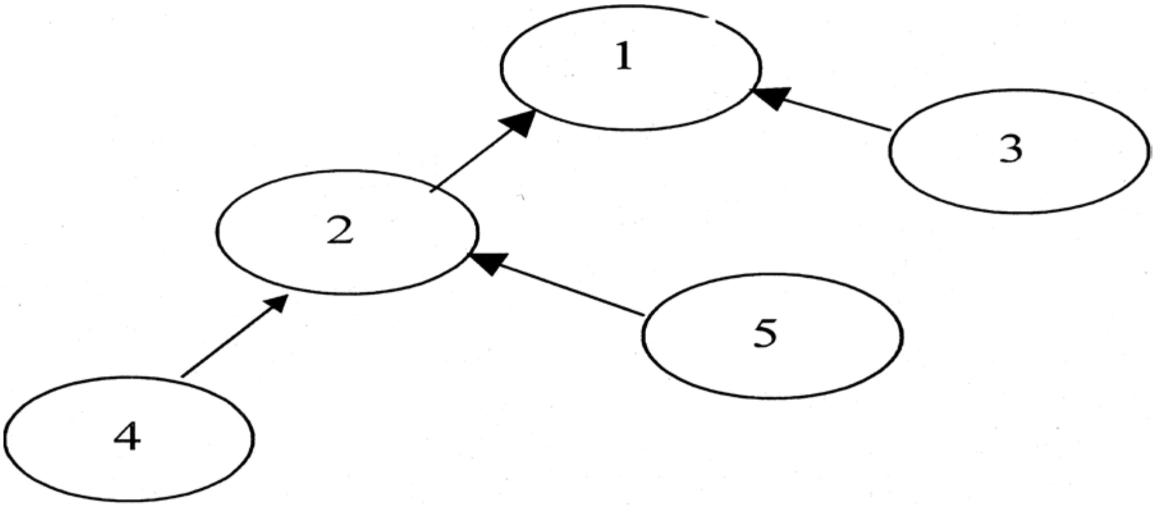

Figure 3.2 Hierarchal migration

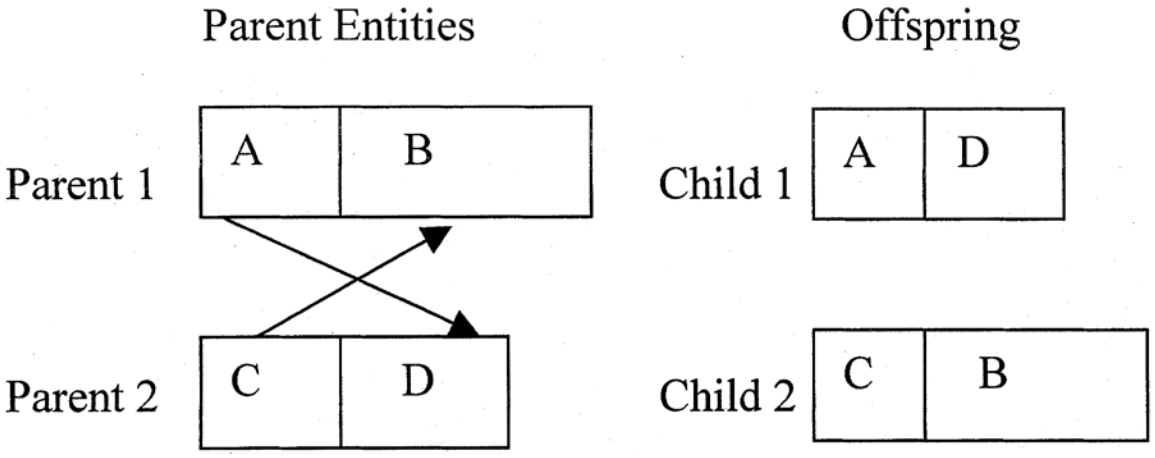

Figure 3.3 Sexual Crossover

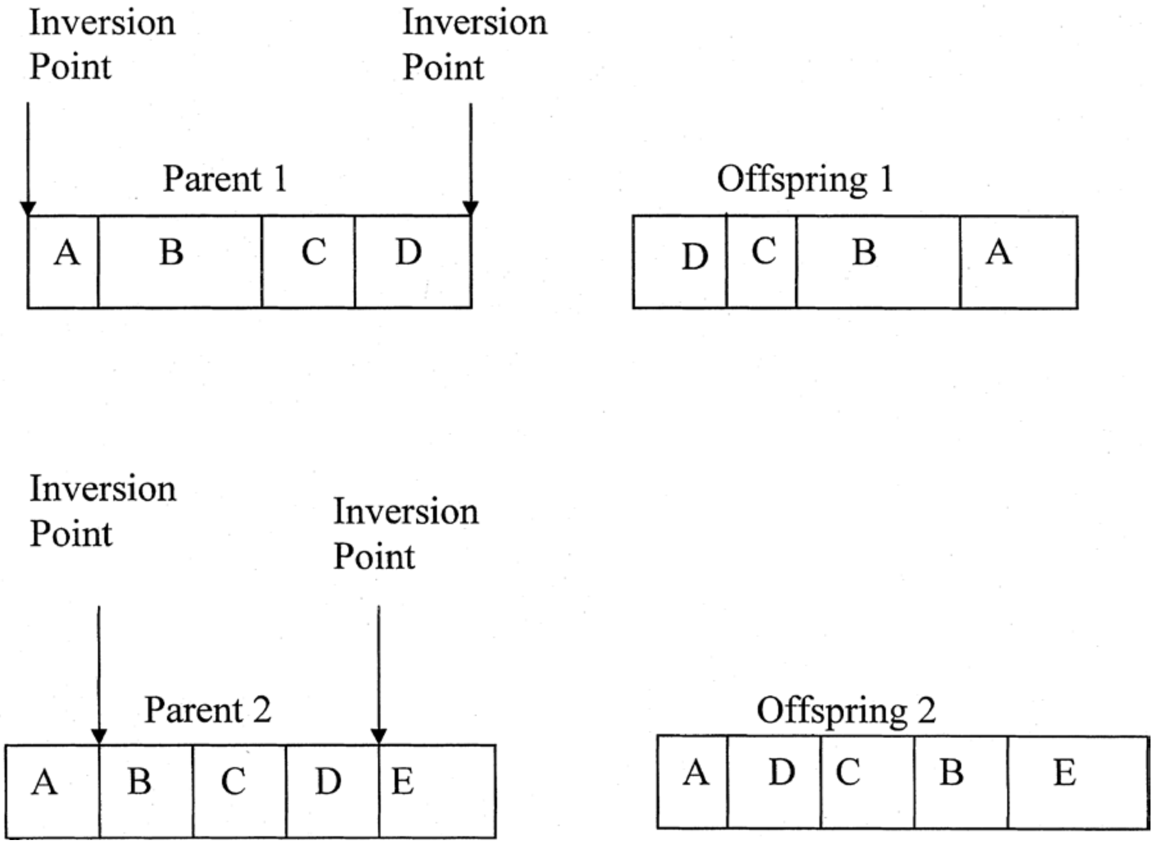

Figure 3.4 Asexual Crossover

3.3.2 Application to the ASR Condition

The evolution algorithm (EA) used in this study combines genetic algorithm with techniques from genetic programming, hill climbing, a heuristic search for the coefficients, and machine learning. Figure 3.1 shows the EA algorithms. The EA algorithm supports multiple ecosystems with multiple integration and intermarriage strategies. The ecosystem topologies include queue, circular queue, and hierarchy. Hierarchical migration and intermarriage was used for the analysis as shown in Figure 3.2. Intermarriage is achieved by allowing mating between partners from different ecosystems. Ecosystems are independent closed environments where the population lives and reproduces. Multiple ecosystems may be created by allowing populations with a different configuration setup to evolve independently and concurrently. A number of selection strategies are available for the choice of migrants and foreign marriage.

3.3.3. Operators

There are two types of crossover operators, sexual and asexual crossover. The sexual crossover takes two randomly chosen individuals (parents) as input and combines them to generate two children. Figure 3.3 shows the sexual crossover. Asexual crossover operation exchanges part of the same individual. Figure 3.4 shows asexual crossover. The following types of asexual activities are implemented: inversion and mutation. Members of the next generation are selected from previous generations with a probability associated with their fitness. Fitter strings (expressions) receive more copies in the next generation because of the higher probability of selection, ‘survival of the fittest’. In the algorithm used, when the genetic algorithm discovers a new best expression, the EA uses hill-climbing to improve the expression. Newly discovered best expressions are then subjected to a heuristic search for optimization. All these stochastic events are linked to user configurable probabilities.

3.2.4 Development of EA Model

ASR data generated from Roy et al. (2003) as shown in Table 3.2 was used for the EA analysis. Three ecosystems were selected; each with an ecology size of 20. The subset of operators applied to this problem is addition, subtraction, multiplication, and division. Hill climbing was introduced after 1000 reproductions. Reproduction parameters were as follows. Sexual reproduction was done 90% of the time, and mutation was done only 30% of the time. During sexual reproduction, instructions were mated 80% of the time. Only coefficients (local constant) were mated 10% of the time. The migration probability was 10%, and the intermarriage probability was also 10%.

The relationship between two week expansion and Na_2O equivalent value was first tested. The predicted value and true value regression model gave an R- squared value of only 44 %. The 8 week expansion value was then analyzed. The results from the 8-week expansion value and Na_2O equivalent value resulted in the following relationship.

ASR expansion (%) = Na_2O eqv. / 2.89

The predicted value from the relationship was plotted with the true value. The regression plot gave the following relationship and the R-squared value was around 80%. Figure 3.5 shows the plot.

Predicted expansion = 0.106061 + 0.527494* true expansion

R-squared= 80%.

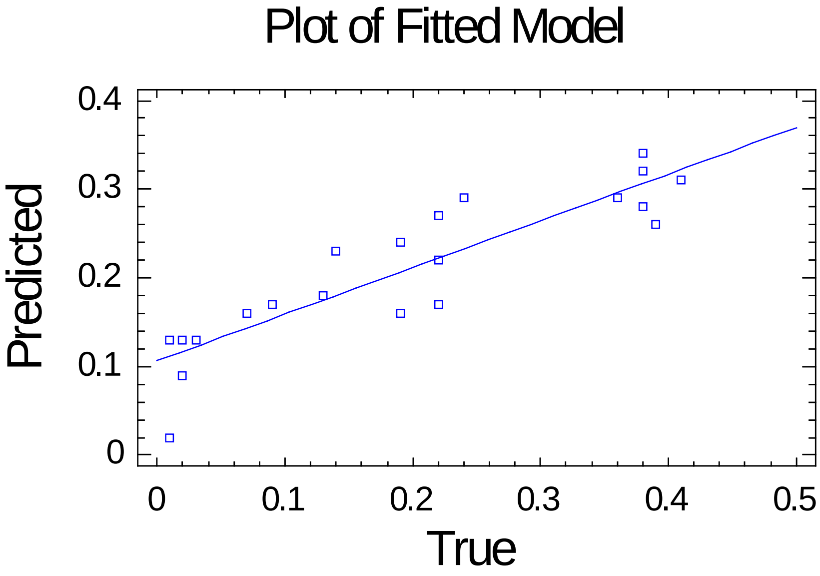

Figure 3.5 Plot of predicted vs true ASR expansion

3.4 ASR Rating

3.4.1 Rating

A method for determining rating of ASR was developed by DelDOT personnel. The method was to generate an approximate ASR reaction rate to predict concrete pavement life. ASR rating was developed using ASR test T-299. By using ASR test T-299, it is possible to track the progression of the ASR with time. The required time frame for the process would be twenty years. But it was decided that by looking at pavements in various stages of ASR and using pavement lives, it is possible to develop a reasonable approximation of ASR reaction rate [Zipf 2003].

The results by the indicator and core analysis were divided into three broad categories. 1. None to low ASR, 2. moderate ASR and 3. advanced ASR. These three were subdivided into a high and low giving a total of six ratings. It is believed that using these ratings and given sufficient number of years, it is possible to plot a reaction rate curve. Table 3.3 shows the rating table of ASR.

Table 3.3 ASR Rating [Zipf 2003]

Rating	Description
0 (None)	There is no ASR present. This is usually for a new pavement. There will be a faint background glow using uranyl acetate indicator. But there will be no hot spots.
1(Low)	Very light ASR by indicator. There is a probability of few reactive aggregates. Visually neither the concrete nor the pavement shows any ASR.
2(Average)	Typical for a 20-year low reactive pavement. ASR by indicator shows a number of hot aggregates or hot spots. There will be visible rimming around some of the coarse aggregate. There may be a few small (2-3 mm) gel pockets. There is to be no sign of distress in pavement.
3(Moderate)	The ASR is more advanced than ASR rating #2. There are more reactive aggregates. Physically the cement matrix is sound. The pavement will start to see signs of early distress, such as map cracking. But there will be no major deterioration.
4(Heavy)	This is where first evidence of deterioration is observed. Visually there are a number of fractured aggregates. There can be erosion of cement past from around some of the coarse aggregates near the surface. With indicator there are fine gel filled hairline cracks in the matrix.
5(Severe)	The reaction is quite advanced. There is major erosion of the cement matrix from around the aggregate. The silica gel is eroding out of the hairline cracks. The pavement is starting to deteriorate to the point where it will need replacing

3.4.2 ASR Reaction Rate

Given several years data, it is possible to plot the ASR rating against time. From the curve it is possible to determine the ASR reaction rate. Since DelDOT does not check pavements on a regular basis, one is limited to a single data point, the core being tested for ASR. It was therefore decided that ASR reaction rate is a straight line and the two points for drawing the line would be the time the core is tested, t, and the time the pavement is initially rated 0 i.e. $t = 0$. The following equation was given:

ASR Reaction Rate= ASR Rating #/ $(t_t - t_o)$
t_t = date cored (all time is years)
t_0 = date pavement placed
ASR Rating 3= Rating of core at t_t

Once the ASR Reaction Rate is determined, one can use it to obtain an approximate prediction for the remaining number of years by the following equation.

Years Remaining = (5.0-ASR rating #) / ASR reaction Rate

Chapter 4

CONCLUSIONS

4.1 General Remarks

1. ASR affect properties of concrete such as concrete compressive strength, modulus, tensile strength, flexural strength, structural behavior of concrete, shear strength of beams and tensile bond strength of reinforcement in concrete. Researchers seem to agree that ASR reduces concrete modulus and tensile strength but does not have any influence on the structural behavior of concrete. Also ASR increases the shear strength and reduction in bond strength of reinforcement in concrete beams. The influence of ASR on compressive strength is rather unclear because of contradictory results obtained by different researchers.
2. ASR is affected by factors such as the alkali limit of cement, the reactive silica component in the aggregate, relative humidity and temperature, effect of restraint, mix design and effect of gel reaction product. The alkali limit suggested by most of the researchers is Na_2O equivalent of 0.60% maximum. Sometimes less than 0.40% Na_2O can however cause deleterious effects. It is generally accepted that the expansion of ASR varies directly with the percentage of relative humidity. Conflicting views are however expressed regarding the effect of temperature. It also appears that steel reinforcement restrains expansion parallel to the direction of reinforcement. The behavior of the gel in concrete is still not well understood and further research in this area is needed.
3. Different guidelines for preventing ASR in new and old concrete structures are used by different states in US, Canada and countries around the world.
4. Although there has been much research carried out on the role of admixtures in controlling ASR, there are still some aspects that are not well understood. The research papers studied reveal the effects of admixtures such as fly ash, silica fume, calcined natural pozzolans, ground-granulated blast furnace slag (GGBFS), metakaolin, pulverized fuel ash, rice husk ash and lithium based admixtures. It is

generally accepted that appropriate use of fly ash can prevent ASR. However, for highly reactive aggregates, high replacement levels can negatively impact on early strength, and the low volume of fly ash can also worsen the ASR problem. A minimum replacement level is therefore required. Silica fume has also been considered to be favorable. There are however conflicting views regarding the product form of silica fume. GGBFS suffer from the same problem with early strength as fly ash. It appears that the use of ternary blend is considered to be most effective in controlling ASR.

The use of pulverized fuel ash, rice ash and metakaolin is relatively new and needs to be further investigated. The lithium based admixture concept is also new and gaining popularity. The study reveals the use of LiOH, $LiNO_3$, LiF, $LiCO_3$ and lithium bearing admixtures. LiOH has been able to reduce the expansion of concrete; however, inadequate dosage may worsen ASR expansion. LiF and $LiCO_3$ can also cause effects similar to those of LiOH. $LiNO_3$ as a neutral salt free from the effect of inadequate dosage is suggested for use in the mitigation of ASR.

5. The following tests are generally conducted for determining ASR: petrographic analysis, ASTM C227, ASTM C126, ASTM C1293, ASTM C441, AASHTO T303. It appears that there are conflicting views regarding which test is most accurate.
6. Based on the evolutionary algorithm, the relationship between ASR% expansion at eight weeks and Na2O equivalent was obtained as ASR expansion = Na2O eqv/2.89. The plot of predicted value and true value gave a regression model with an R-squared value of 80 percent.

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REFERENCES

1. Adams,N. and Stokes, D.B. (2002), “Using Advanced Lithium Technology to Combat ASR in Concrete”, Concrete International Vol 24 No 8 page 99-102

2. Ahmed, T., Burley E. and Ridgen, S. (1998), “The Static and Fatigue Strength of Reinforced Concrete Beams Affected by Alkali-Silica Reaction”, ACI Materials Journal Vol 95 No 4 P 376-388

3. Ahmed, T., Burley, E. and Ridgen,S. (1998), “Effect of Alkali-Silica Reaction on Tensile Bond Strength of Reinforcement in Concrete Tested under Static and Fatigue Loading”, ACI Materials Journal Vol 96 No 4 P 419-428

4. Alkali-silica reactivity lead state team (2000), “Transition plan for AASHTO”.

5. Aquino,W., Lange, D.A. and Olek, J. (2001), “The Influence of Metakaolin and Silica Fume on the Chemistry of Alkali-Silica Reaction Products”, Cement and Concrete Composites 23 P 485-493

6. Barger, G.S., Ahnsen, E.R., Wood, M.R., Neary, T., Beech, D.J, and Jaquier, D. (2001), “Production and Use of Calcined Natural Pozzolans in Concrete”, Cement, Concrete and Aggregates Vol 23, No 2 P 73-80

7. Barringer, W.L. (1999), “Using Accelerated Test Methods to Specify Admixtures to Mitigate Alkali-Silica Reactivity”, Cement, Concrete and Aggregates Vol 21 No 2 P 165-172

8. Berube, M.A., Dorion, J.F., Duchesne, J. and Fournier, B., Vezina, D. (2002), “Laboratory and Field Investigations of the Influence of Sodium Chloride on Alkali-Silica Reactivity”, Cement and Concrete Research (article in press)

9. Boddy, A.M, Hooton, R.D., Thomas, M.D.A. (2000), “The Effect of Product Form of Silica Fume on its Ability to Control Alkali–Silica Reaction”, Cement and Concrete Research 30 P 1139-1150

10. Carpenter, A.J., and Cramer, S.M. (1999), “Mitigation of Alkali-Silica Reaction in Pavement Patch Concrete that Incorporates Highly Reactive Fine Aggregate”, Transportation Research Record No 1668 P 60-67

11. Diamond, S. (1997), “Alkali Silica Reactions - Some Paradoxes”, Cement and Concrete Composites 19, 391-401.

12. Diamond, S. (1999), “Unique response of $LiNO_3$ as an Alkali Silica Reaction-Preventive Admixture”, Cement and Concrete Research 29 P 1271-1275

13. Doran, D.K. (chairman of Task Group) (1992), “Structural effects of alkali Aggregate Reaction”, The Institute of Structural Engineers

14. Fan, S. and Hanson, J.,M. (1998), “Effect of Alkali Silica Reaction Expansion and Cracking on Structural Behavior of Reinforced Concrete Beams”, ACI Structural Journal Vol 95 N0 5. P 498-505

15. Fan, S. and Hanson, J.M. (1998), “Length Expansion and Cracking of Plain and Reinforced Concrete Prisms Due to Alkali-Silica Reaction”, ACI Materials Journal Vol 95 No 4 P 480-487

16. Hasparky, N.P., Monteiro, P.J.M. and Carasek, H. (2000), “Effect of Silica Fume and Rice Husk on Alkali-Silica Reaction”, ACI Materials Journal Vol 97 No 4

17. Hill, E.D. (1996), “Alkali Limits for Prevention of Alkali-Silica Reaction: A Brief Review of Their Development”, Cement Concrete and Aggregates Vol 18 No 1 P 3-7

18. Jones, A.E.K. and Clark, L.A. (1998), “The Effects of ASR on the Properties of Concrete and the Implications for Assessment”, Engineering Structures Vol. 20 No 9, 785-791.

19. Lane, D.S. and Ozylidrim, C. (1999), “Preventive Measures for Alkali –Silica Reactions (Binary and Ternary Systems)”, Cement and Concrete Research, Vol 29, Issue 8, 1281-1288

20. Lumley, J.S. (1997), ASR “Suppression by Lithium Compounds”, Cement and Concrete Research Vol 27 No 2 P 235-244

21. Malvar, L.J., Cline, G.D., Burke, D.F., Rollings, R., Sherman, T.W. and Greene, J.L. (2002), “Alkali-Silica Reaction Mitigation: State of the Art and Recommendations”, ACI Materials Journal,Vol 99, No5, P 480-490

22. Mo X., Yu, C. and Xu, Z. (2002), “Long-Term Effectiveness and Mechanism of LiOH in Inhibiting Alkali-Silica Reaction”, Cement and Concrete Research (article in press)

23. Monette, L.J., Gardner, N.J and Grattan-Bellew P.J. (2002), “Residual Strength of Reinforced Concrete Beams Damaged by Alkali-Silica Reaction-Examination of Damage Rating Index Method”, ACI Materials Journal Vol 99 No 1 P 42-50

24. Olafsson, H. (1986), The Effect of Relative Humidity and Temperature on Alkali Expansion of Mortar Bars, Concrete Alkali-Aggregate Reactions", Proceedings of the 7th International Conference, Ottawa, Canada, p-461-465

25. Ramlochan, T., Thomas, M. and Gruber, K.A. (2000), "The Effect of Metakaolin on Alkali-Silica Reaction in Concrete", Cement and Concrete Research 30 P 339-344

26. Roy, D.M., Tikalsky, P.J., Scheetz, B.E., Rosenberger, J., Cavalline, T. and Arjunan, P. (2003), "Influence of Portland cement Characteristics on Alkali Silica Reactivity", TRB 2003 Conference Proceedings

27. Saccani, A., Bonora, V. and Monari, P. (2001), Laboratory Short-Term Evaluation of ASR, A Contribution", Cement and Concrete Research Vol 31 P 739-742

28. Sahu, S., Badger, S. R., Osgood, B., and Thaulow, N. (2001), "Petrographic Analysis of Concrete Deterioration by Feature Relocation", Transportation Research Record Vol 1775 P 21-27

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

30. Shehata, M.,H. and Thomas, M.D.A (2002), "Use of Ternary Blends Containing Silica Fume and Fly Ash to Suppress Expansion Due to Alkali –Silica Reaction in Concrete",Cement and Concrete Research 32 p 341-349

31. SHRP-C-342 (1993), "Alkali-Silica Reactivity, an Overview of Research"

32. Sibbick, R.G. and Page, C.L. (1995), "Effects of Pulverized Fuel Ash on Alkali-Silica Reaction in Concrete", Construction and Building Materials Vol 9 No 5 P 289-293

33. Struble, L.J, and Pade, C. (2000), "Proposed New Test Procedure for Measuring Alkali-Silica Expansion Produced by Hydraulic Cement", Cement, Concrete and Aggregates Vol 22, No 01 P 48-54

34. Swamy, R.N. (1992) "The Alkali-Silica Reaction in Concrete", Blackie and Son Limited

35. Touma, W.E., Fowler, D.W, Carrasquillo, R.L, Folliard, K.J, and Nelson, N.R. (2001) “Characterizing Alkali-Silica Reactivity of Aggregates Using ASTM 1293, ASTM 1260, and Their Modifications”, Transportation Research Record Vol 1757 P 157-165

36. Thomas, M.D.A, and Stokes, D.B. (1999), “Use of a Lithium-Bearing Admixture to Suppress Expansion in Concrete Due to Alkali-Silica Reaction”, Transportation Research Record No 1668 P 54-59

37. Zhan, C., Wang, A., Tang, M. and Zhang N. (1999) “Influence of Dimension of Test Specimen on Alkali-Aggregate Reactive Expansion”, ACI Materials Journal Vol 96 No 2

38. Zipf, K. (2003), “Alkali-Silica Reaction (ASR) Rate, Preliminary Work”, Delaware Department of Transportation