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ALKALI-SILICA REACTION MITIGATION STATE-OF-THE-ART

by L.J. Malvar, NFESC

and Team Members
G.D. Cline, U.S. Navy, NFESC, Port Hueneme, CA
D.F. Burke, U.S. Navy, NFESC, Port Hueneme, CA
R. Rollings, U.S. Army, CRREL, Hanover, NH
T.W. Sherman, U.S. Army, TSMCX, Omaha, NE
J. Greene, U.S. Air Force, HQ AFCESA, Tyndall AFB, FL

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L.J. Malvar, G.D. Cline, D.F. Burke, R. Rollings, T. Sherman, J. Greene

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13. ABSTRACT (Maximum 200 words)

This report gathers the state-of-the-art in alkali silica reaction (ASR) in concrete, and ASR mitigation techniques, in preparation for a more detailed study to be submitted to Congress in response to Public Law 106-398 (HR 4205). Mitigation techniques from various states in the U.S., and from various countries and international organizations, were assessed and summarized. A set of recommended mitigation procedures was developed, which is being implemented in the current and upcoming Tri-Service guide specifications on concrete.

In particular, the recommended methodology requires the replacement of cement by Class F or N fly ash (25% to 40% by weight), or ground granulated blast furnace slag (GGBFS) Grade 100 or 120 (40% to 50% by weight), or a combination of both. The Class F or N fly ash should also have a maximum of 1.5% available alkali, a maximum 6% loss on ignition, and a maximum of 8% CaO.

In addition to mitigating ASR, these cement replacements are expected to: (1) reduce concrete costs, (2) significantly enhance the durability of concrete, (3) increase fly ash and GGBFS recycling, and (4) support the 1997 Kyoto protocol by significantly reducing CO_2 production. If 25% of all cement were to be replaced, total savings to the United States economy could be in excess of $1 billion every year.

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EXECUTIVE SUMMARY

This report gathers the state-of-the-art in alkali silica reaction (ASR) in concrete, and ASR mitigation techniques, in preparation for a more detailed study to be submitted to Congress in response to Public Law 106-398 (HR 4205). While Congress has authorized up to $5M to address this issue, none of that funding was available. Instead this report was sponsored by:

- The Naval Facilities Engineering Command (NAVFAC) through mission funding for the Pavements Technical Discipline Leader (first author)
- The N46 CNO RPM DemVal Program (PE 63725N) that covered the Navy testing and field applications at several Navy activities
- The NAVFAC Engineering Innovation and Criteria Office (EICO) that supported the development and implementation of this report's guidelines into Navy and Tri-Service Unified Facilities Guide Specifications (UFGS).

Mitigation techniques from various states in the U.S., and from various countries and international organizations, were assessed and summarized. A set of recommended mitigation procedures was developed, which is being implemented in the current and upcoming Tri-Service guide specifications on concrete.

The recommended methodology requires the replacement of cement by Class F or N fly ash (25% to 40% by weight), or ground granulated blast furnace slag (GGBFS) Grade 100 or 120 (40% to 50% by weight), or a combination of both. The Class F or N fly ash should also have a maximum of 1.5% available alkali, a maximum 6% loss on ignition, and a maximum of 8% CaO (calcium oxide). Methods for testing for ASR were also evaluated and a modified ASTM C 1260 is recommended.

In addition to mitigating ASR, these cement replacements are expected to: (1) reduce concrete costs, (2) significantly enhance the durability of concrete, (3) increase fly ash and GGBFS recycling, and (4) support the 1997 Kyoto protocol by significantly reducing CO_2 production. If 25% of all cement were to be replaced, total savings to the United States economy could be in excess of $1 billion every year.

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1. INTRODUCTION

1.1. PROBLEM

In 2001, Congress passed Military Authorization Bill - Public Law 106-398 (HR 4205) (Section 389), and Military Construction Appropriations Bill - Conference Report 106-710 for Public Law 106-246, 2001 (page 88). The Conference Report directs the Under Secretary of Defense for Acquisition, Technology, and Logistics to assess the overall condition of Department of Defense (DOD) facilities and infrastructure with respect to Alkali-Silica Reaction (ASR). Public Law 106-398 directs the Secretary of Defense, through the Service Secretaries, to assess the damage caused to aviation facilities by ASR, and explore available technologies capable of preventing, treating, or mitigating ASR. Service Secretaries may also conduct demonstration projects to test and evaluate technologies capable of preventing, treating, or mitigating ASR. The assessment is to be completed not later than 30 Sep 2006 at a total cost not to exceed $5,000,000. The Engineering Senior Executive Panel (ESEP) tasked a Tri-Service working group to develop a plan of investigation on this issue.

1.2. MAGNITUDE OF THE PROBLEM - AIRFIELDS

The main concern of Public Law 106-398 is the extent of ASR in hardened facilities and pavements, in particular in aviation facilities. The list below indicates the Tri-Service locations where ASR is or is suspected to be present.

1.2.1. Air Force Airfields

Many Air Force bases have reported ASR problems:

Air Combat Command (ACC)

- Seymour-Johnson AFB, NC – Severe.
- Langley AFB, VA – Moderate.
- Offut AFB, NC – No details.
- Holloman AFB – Problems exist on F-117 ramp and possibly several other pavements. Corps of Engineers (COE) investigation of ramp led to current projects using high quantities of Class F fly ash to help counter ASR.
- Cannon AFB, NM – Map cracking and compression of expansion joint.
- Beale AFB, CA – No details.
- Tonopah Test Range, NV – No details.

Pacific Air Force (PACAF)

- Osan AB, Korea – Reported by Air Force Civil Engineer Support Agency (AFCESA) evaluation team and suspected by local COE.

Air Force Material Command (AFMC)

- Plant 42, CA – Light to moderate.
- Kirtland AFB, NM – Moderate.
- Wright-Patterson AFB, OH – Light to moderate, reported by Base.
- Edwards AFB, CA – No details.
- Tinker AFB, OK – No details.

Air Mobility Command (AMC)

- Andrews AFB, MD – Information obtained years ago, including photos of a big ramp failure caused by the ASR expansion.
- Travis AFB, CA – There was evidence of ASR in several places back in 1995 and cores taken by Omaha reportedly confirmed ASR in the old pavements (~1949 vintage).
- Dover, DE – No details.

Air Force Space Command (AFSPC)

- Warren AFB, WY – Older concrete with ASR replaced, and no current problem.

U.S. Air Force Europe (USAFE)

- Torrejon AB, Spain – Returned to Spanish control.
- Aviano AB, Italy – None reported on the Base, but there are suspected ASR problems on the autostrasse just south of there (may be alkali-carbonate reaction rather than ASR).

Air National Guard (ANG)

- Pease AFB, NH – Severe.
- Channel Islands ANG Site, CA – No details.

Air Education and Training Command (AETC)

- Little Rock AFB, AR – No details.
- Vance AFB, OK – No details.

1.2.2. Army Airfields

- Biggs Army Airfield, TX – No details.
- Ft Bliss Army Airfield, TX – No details.
- Ft Campbell Army Airfield, KY – SOF apron and 501st Tactical Equipment Shop pavements show closure of expansion joints, spalling, cracking, and popouts.

1.2.3. Navy and Marine Corps Airfields

A program has been developed (FY02 start) to assess each Navy and Marine Corps airfield pavements for the presence of ASR during the 3-year cycle of Pavement Condition Index (PCI) surveys. At the present time, there is knowledge of ASR affected concrete pavements at:

- NAS Point Mugu, CA – Severe.
- NAS Fallon, NV – Severe.
- NOLF San Nicolas Island, CA – No details.
- MCAS Iwakuni, Japan – No details.
- MCAS Beaufort, SC – No details.
- MCAS Cherry Point, NC – No details.

1.3. MAGNITUDE OF THE PROBLEM – OTHER STRUCTURES

ASR is often apparent in large, old concrete structures such as dams. Several dams in the U.S. and elsewhere have ASR problems (see for example http://www.acres.com/aar/). A special issue on ASR reports problems on all types of structures in Canada (NRC, 2000). The Navy has found ASR in waterfront structures as well (Spencer and Blaylock, 1997).

1.4. PROBLEMS WITH CURRENT PRACTICE

Environmental Protection Agency (EPA) guidelines encourage the use of recycled materials such as fly ash and ground granulated blast furnace slag (GGBFS). Their use in concrete cannot be prevented, but since no minimum usage is set, often the concrete does not include these materials.

Even when fly ash is used, the current practice is to use low volume cement replacements, in the order of 15%. It will be shown that, in many cases, even with Class F fly ash, this low volume replacement can result in concrete with *worse* ASR problems than without cement replacement.

1.5. SCOPE

The objective of this report is to gather the state-of-the-art in ASR and ASR mitigation techniques in preparation for the more detailed study to be submitted to Congress. The more detailed study will include an assessment of all DOD airfield pavements, and further evaluation and development of the most promising ASR mitigation techniques determined herein.

2. BACKGROUND

2.1. ASR, AAR AND ACR

Alkali silica reaction (ASR) is the reaction between the alkali hydroxide in Portland cement and certain siliceous rocks and minerals present in the aggregates, such as opal, chert, chalcedony, tridymite, cristobalite, strained quartz, etc. The products of this reaction often result in significant expansion and cracking of the concrete, and ultimately failure of the concrete structure, including significant potential for foreign object damage to aircraft (see Helmuth et al., 1993, for details on the chemical reactions). Alkali aggregate reaction (AAR) is the reaction between the cement hydroxides and mineral phases in the aggregates, which may or may not be or siliceous origin. In this report no distinction is made between AAR and ASR.

Alkali carbonate reaction (ACR) is the reaction between the cement hydroxides and certain dolomitic limestone aggregates, which can also result in deleterious expansion. This problem is relatively rare, and it is not specifically addressed here.

The ASR reaction needs several components to take place (ACI 221.1R, 1998):

- Alkali (usually supplied by the cement, although external sources can exist).
- Water (or high moisture content).
- Reactive aggregate.

High temperature usually accelerates the reaction, although in some cases lower temperatures have proven more detrimental.

2.2. ASR MITIGATION IN THE UNITED STATES

2.2.1. CALTRANS

In 1996, the California Department of Transportation (CALTRANS) completed a study to assess the use of mineral admixtures to mitigate alkali-silica reactivity (Glauz et al., 1996). Conclusions from this study were:

- ASR will increase proportionally to the cement alkali content.
- The ASTM C 150 limit of 0.6% alkali content (Na_2O equivalent) in Portland cement may be too high to mitigate ASR deleterious expansion.
- High calcium oxide (CaO) content in admixtures seems to promote ASR.
- Class F or N fly ash (ASTM C 618) is effective against ASR when replacing up to 30% of the Portland cement (by mass).
- Fly ash with more than 10% CaO is unsuitable for mitigating ASR.

- Natural pozzolanic materials with low lime content (<2% CaO) and low total alkali content (<3%) are very effective against ASR when replacing 15% of the Portland cement (by mass).
- Small amounts of silica fume are effective in inhibiting ASR expansion.
- Alkali ions from outside sources will contribute to ASR expansion.
- Tests in 1N (normal) NaOH solutions at 23ºC actually resulted in higher expansion than tests at 80ºC.
- A pozzolan that reduces expansion for a 1% alkali cement may not be effective with a 0.6% alkali cement.

Recommendations include using either a 15% fly ash replacement if the fly ash has less than 2% CaO and less than 3% total alkali, or 30% fly ash replacement if the CaO content is less than 10% and the total alkali content less than 3%.

From this study CALTRANS amended Section 90-4.08, "Required Use of Mineral Admixtures," of the standard specifications as follows:

90-4.08 REQUIRED USE OF MINERAL ADMIXTURES

- *Unless otherwise specified, mineral admixture shall be combined with cement to make cementitious material for use in Portland cement concrete.*
- *The calcium oxide content of mineral admixtures shall not exceed 10 percent and the available alkali, as sodium oxide equivalent, shall not exceed 1.5 percent when determined in conformance with the requirements in ASTM Designation: C618.*
- *The amounts of cement and mineral admixture used in cementitious material for Portland cement concrete shall be sufficient to satisfy the minimum cementitious material content requirements specified in Section 90-1.01, "Description," or Section 90-4.05, "Optional Use of Chemical Admixtures," and shall conform to the following:*

  A. *The minimum amount of cement shall not be less than 75 percent by mass of the specified minimum cementitious material content.*
  B. *The minimum amount of mineral admixture to be combined with cement shall be determined using one of the following criteria:*
     1. *When the calcium oxide content of a mineral admixture, as determined in conformance with the requirements in ASTM Designation: C618 and the provisions in Section 90-2.04, "Admixture Materials," is equal to or less than 2 percent by mass, the amount of mineral admixture shall not be less than 15 percent by mass of the total amount of cementitious material to be used in the mix.*
     2. *When the calcium oxide content of a mineral admixture, as determined in conformance with the requirements in ASTM Designation: C618 and the provisions in Section 90-2.04, "Admixture Materials," is greater than 2 percent, the amount of mineral admixture shall not be less than 25 percent by mass of the total amount of cementitious material to be used in the mix.*
     3. *When a mineral admixture is used, which conforms to the provisions for silica fume in Section 90-2.04, "Admixture Materials," the amount of mineral admixture shall not be less than 10 percent by mass of the total amount of cementitious material to be used in the mix.*

C. If more than the required amount of cementitious material is used, the additional cementitious material in the mix may be either cement, a mineral admixture conforming to the provisions in Section 90-2.04, "Admixture Materials," or a combination of both; however, the maximum total amount of mineral admixture shall not exceed 35 percent by mass of the total amount of cementitious material to be used in the mix. Where Section 90-1.01, "Description," specifies a maximum cementitious content in kilograms per cubic meter, the total mass of cement and mineral admixture per cubic meter shall not exceed the specified maximum cementitious material content.

It appears that, to allow for more Class F or N fly ashes to be used, a standard 25% replacement may be the easiest alternative. A maximum replacement of 35% is also indicated.

2.2.2. AASHTO, LEAD STATES and FHWA

From 1995 to 2000, the Lead State Team for ASR (New Mexico, North Carolina, Pennsylvania, South Dakota, Virginia, and partners from universities, industry, and the Federal Highway Administration – FHWA) established by the American Association of State Highway and Transportation Officials (AASHTO) was engaged in several projects to increase the awareness of ASR and develop guidelines and technologies for treating and preventing ASR. They prepared a draft guide specification for review by AASHTO (Lead States, 2000a). This specification was balloted and approved by AASHTO in August 2000. The Guide will be published in the next edition of the AASHTO Guide Specifications for Highway Construction (AASHTO, 2001).

In September 2000, the Alkali-Silica Reactivity Team transferred its responsibilities to the Subcommittees on Materials and Construction of AASHTO. The Team prepared a Transition Plan (http://leadstates.tamu.edu/asr/transition/) detailing the results of their work and recommendations for the future (Lead States, 2000b). The Lead States Team has made many significant accomplishments (most included in the Transition Plan), including:

- A survey of State Highway Agencies to assess the extent of ASR.
- An updated Strategic Highway Research Program (SHRP) "Handbook for the Identification of ASR in Highway Structures," SHRP-C-315. This handbook is available (with pictures) at http://leadstates.tamu.edu/asr/library/C315/.
- Draft AASHTO Guide Specification on ASR-Resistant Concrete available at http://leadstates.tamu.edu/ASR/library/gspec.stm.
- An updated SHRP ASR bibliography, adding an electronic format.
- A Q&A web forum with on-line training materials.
- An ASR glossary of terms.
- An aggregates databases and a list of resources.
- A list of ASR Lead State contacts, along with a bulletin board for technical assistance.
- Technical assistance to other State highway agencies and electric companies.

The draft AASHTO Guide Specification on ASR-Resistant Concrete proposes the following tests for aggregates:

- AASHTO T 303, which measures a mortar bar expansion at 14 days, limiting it at 0.08% for metamorphic aggregates, or 0.1% for all others.
- ASTM C 1293, which measures concrete prism expansion at 1 year, limiting it to 0.04%.

It should be noted that AASHTO T 303 is practically the same as ASTM C 1260, and that the limits indicate a requirement for innocuous aggregates. Several Lead States use alternately one or the other.

Methods to prevent ASR in new concrete include the use of:

- Low alkali and/or blended cements.
- Minimum 15% Class F fly ash or 25% GGBFS cement replacement. Some of the Lead States use 15% to 25% Class F fly ash, or 25% to 50% GGBFS replacement. Virginia requires 20% Class F fly ash, or 30% to 50% GGBFS.
- Lithium admixtures (lithium nitrate, carbonate, hydroxide, or hydroxide monohydrate).

2.2.3. New Mexico State Highway and Transportation Department

The State of New Mexico has some of the most reactive aggregates in the U.S., and its specifications are of special importance.

Section 510 on Portland Cement Concrete from the New Mexico State Highway and Transportation Department (NMSHTD) requires aggregates to be tested via AASHTO T 303 or ASTM C 1293, and uses expansion limits of 0.1% and 0.04% for each test, respectively. Aggregates with less expansion are assumed innocuous. A list of innocuous (non-reactive) aggregates can also be obtained from the Central Materials Laboratory.

Class F fly ash is required if either fine or coarse aggregate shows reactivity, otherwise Class C fly ash is permitted. Both fly ashes are required to have less than 10% CaO, less than 1.5% available alkalis, and a loss on ignition (LOI) of less than 3%. If the aggregate is potentially reactive, then the following minimum admixtures (among others) should be incorporated into the concrete:

- 20% of Class F fly ash by weight of cement.
- 25% to 50% GGBFS by weight of cement.
- Lithium Nitrate – 4.6 L/m^3 (0.55 $gal/yard^3$) of solution per kg (pound) of cement sodium equivalent.

The effectiveness of the admixture is to be determined using AASHTO T 303 with an expansion limit of 0.1% at 14 days.

A recent study conducted for the NMSHTD (McKeen et al., 1998) concluded that 25% to 27% Class F fly ash replacement was sufficient for most of the reactive aggregates studied. Class C fly ash and blends of Class F and Class C did not provide enough expansion reduction.

The City of Albuquerque (2000) requires the use of 20% Class F fly ash whether or not the aggregates are found to be reactive.

2.2.4. Washington State Department of Transportation

In the State of Washington either ASTM C 1260 or AASHTO T 303 are recommended, with an expansion limit of 0.1%. Recommended mitigation procedures include low-alkali cement, fly ash, and lithium. However, the aggregate is considered non-reactive if either ASTM C 1293 or C 295 are satisfied, with an expansion limit of 0.04% in the first, and deleterious material limits in the second, as follows:

- Optically strained, microfractured, or microcrystalline quartz 5% max
- Chert or chalcedony 3% max
- Tridymite or cristobalite 1% max
- Opal 0.5% max
- Natural volcanic glass 3% max

Hence, it appears that in Washington State, it is sufficient that only a single test out of the three (ASTM C 1260, C 1293, or C 295) needs to be satisfied for the aggregate to be accepted without any mitigating measure. This approach seems risky, for example in the case where two out of the three tests would indicate deleterious performance.

2.2.5. Portland Cement Association

The Portland Cement Association (PCA) has published a guide specification for concrete subject to ASR (PCA IS415, 1998) where it requires ASTM C 1260 (limit 0.1%) and ASTM C 295 (same limits as Washington State above). Aggregate considered potentially reactive can be further evaluated using ASTM C 1293, with a limit of 0.04%, and no known field reactivity. Any aggregate having shown reactivity in service is considered reactive regardless of test results. Potentially reactive aggregates shall be used in concrete in one of three ways:

1) Use a combination of pozzolan or slag with Portland or blended cement and show effectiveness of the combination.
2) Use a blended cement and show its effectiveness.
3) Limit the alkali content in cement and other concrete ingredients to levels proven to limit reactivity in field conditions (using the same aggregate).

Effectiveness can be proven in two ways:

1) Via ASTM C 1260 if the expansion is less than the limit of 0.1%.
2) Via ASTM C 441 if the test mixture with the admixture results in less expansion than a control mixture made with low-alkali cement with total Na_2O equivalent alkali content between 0.5% and 0.6%.

2.2.6. Federal Aviation Administration

The Federal Aviation Administration (FAA) addresses Portland cement concrete pavements in Item P-501 (FAA, 1999). It requires that aggregates be tested using either ASTM

C 1260 or a set of tests that includes ASTM C 295, ASTM C 289, and ASTM C 227. It also mentions that C 289 test results may not be correct, and that C 227 should be conducted for at least 6 months, or preferably 1 year. Item P-501 indicates that total cementitious materials (slag and fly ash) can replace cement in the proportion of 25% to 55%. However, for fly ash alone, they recommend 10% to 20% replacement only. Item P-501 also indicates that the minimum 28-day flexural strength is 600 psi for airport pavements.

2.2.7. American Concrete Institute

The American Concrete Institute (ACI) has produced several documents on ASR and ASR mitigation. Some highlights from these documents are indicated below.

ACI Committee 221 completed a state-of-the-art report in 1998 (ACI 221.1R). In particular, this Committee indicated that:

- Although a maximum of 0.6% Na_2O equivalent alkali is often used for cement, a limit of 0.4% is preferable (this lower limit may also prevent ACR).
- A low calcium oxide (CaO) content is desirable for fly ash, and Class F fly ash generally contains less than 5% CaO.
- GGBFS grades 100 and 120 are recommended for ASR mitigation.
- If densified pellets of silica fume are not well dispersed while mixing, they may act like reactive aggregate and cause cracking due to ASR (Pettersson, 1992).
- An expansion limit of 0.08% is suggested for ASTM C 1260.
- Aggregates with lower particle size produce less expansion.

ACI Committee 232 completed a guide on the use of fly ash in concrete (ACI 232.2R, 1996). Some highlights:

- 50 million tons of fly ash were produced in the United States in 1991 (ACAA, 1992) and only 10% to 12% of that total was used in concrete.
- Small increases in the dosage rate for air-entraining admixtures is often necessary to insure that the required percentage of entrained air will be obtained.
- Precast concrete often requires 3500 to 5000 psi compressive strength at form removal time, which can be 10 to 12 hours after pouring (requiring cement contents of 600 to 750 lbs/yd^3). (Note that this may require only partial cement replacement, or lowering the water to cementitious materials ratio, or otherwise altering the original mix.)

ACI Committee 233 completed a guide on the use of GGBFS in concrete (ACI 233R, 1995). Some highlights:

- 13 million tons of GGBFS were produced in 1991 in the United States.
- A 40% to 50% GGBFS cement replacement usually provides the greatest strength gain at 28 days.
- Small increases in the dosage rate for air-entraining admixtures is often necessary.
- Grade 120 slag cement replacements result in lower strengths in the first 3 days, but greater strengths after 7 days (compared to mix without replacement).

- Grade 100 slag cement replacements result in lower strengths in the first 21 days, but greater strengths after that.
- Grade 80 slag gives lower strengths at all ages.
- Stable long-term strength gain beyond 20 years has been documented.
- A minimum 40% GGBFS cement replacement is needed to mitigate ASR (see also Appendix X3 of ASTM C 989, 1997), and seems to mitigate ACR as well.
- Precast mixes with Grade 120 slag cement replacement can get 1-day compressive strengths higher than without replacement.

2.3. ASR MITIGATION IN OTHER COUNTRIES

2.3.1. Canadian Standards Association

The Canadian Standards Association (CSA) has promoted the development of CSA A23.2-25A and CSA A23.2-14A, which are similar to ASTM C 1260 and C 1293, respectively. However, the limit expansion in CSA A23.2-25A is 0.15% (CSA A23.2-27A, 2000; Fournier et al., 2000b), greater than the 0.1% allowed by ASTM C 1260, although Appendix B of CSA A23.1 recommends using the 0.1% limit as well.

In terms of the fly ash used, CSA A23.2-27A indicates that low lime (CaO) contents below 8% are preferred.

For highly reactive aggregates, CSA A23.2-27A recommends at least 25% to 30% low lime fly ash, or at least 50% GGBF slag cement replacement.

2.3.2. RILEM

RILEM (Réunion Internationale des Laboratoires d'Essais et de recherche sur les Matériaux et les constructions, or International Association for Building Materials and Structures) is a non-profit, non-governmental technical association whose vocation is to contribute to progress in construction. It was started in Europe and produces worldwide technical standards for concrete. RILEM Technical Committee TC 106-AAR on Alkali Aggregate Reaction has published two recommendations for detection of potential alkali reactivity of aggregates: TC 106-2 (the ultra accelerated mortar-bar test) (RILEM TC 106-2, 2000) and TC 106-3 (method for aggregate combinations using concrete prisms) (RILEM TC 106-3, 2000).

RILEM TC 106-2 is similar to ASTM C 1260 and AASHTO T 303 (all these methods are based on the South African National Building Research Institute, or NBRI, accelerated test method). The annex indicates that aggregates with more than 2% by mass of porous chert and flint are not recommended (they can give misleading results and get inappropriate approval). They use ASTM C 1260 specimen sizes (2.5 by 2.5 by 285 cm), although other sizes have been used in the past (RILEM TC 106-2, 2000; Jensen and Fournier, 2000).

RILEM TC 106-3 is similar to ASTM C 1293 but the specimens are wrapped in cotton cloth and sealed inside polythene lay-flat tubing.

In TC 106-2, aggregates are considered non-expansive for expansion less than 0.1% at 14 days, potentially expansive if between 0.1% and 0.2%, and expansive otherwise (RILEM TC 106-AAR, 2000). In TC 106-3, aggregates are considered non-expansive for expansion less than 0.04% to 0.05% at 14 days (no final specification limit has been adopted), potentially expansive if less than 0.15%, and expansive otherwise (RILEM TC 106-AAR, 2000; Nixon and Sims, 2000).

2.3.3. BRE and BSI

The British Research Establishment (BRE) recommends the use of low-alkali cement (less than 0.6% Na_2O equivalent) and gives lists of innocuous and reactive aggregates. Test method DD 218, now replaced by BS 812-123 (1999) from the British Standards Institution (BSI), is used to indicate the expected reaction, which is categorized as:

- Expansive if more than 0.2% expansion after 12 months.
- Possible expansive if between 0.1% and 0.2%.
- Probably non-expansive if between 0.05% and 0.1%.
- Non-expansive if less than 0.05%.

2.3.4. The Netherlands

In the Netherlands, CUR-Recommendation 38 indicates that if cement replacement in the amount of at least 25% by mass of fly ash, or 50% by mass of GGBFS is implemented, then the potential reactivity of the aggregates is of no concern (Heijnen and Larbi, 1999).

2.3.5. Australia

The Queensland Department of Main Roads (1999) requires 20% fly ash cement replacement in all prestressed roadway concrete. All other concrete meeting the minimum 20% requirement is exempt of additional testing for reactivity. Fly ash with a maximum total alkali content of 2%, and a maximum available alkali content of 0.5%, is required. For GGBF slag the corresponding contents are 1%, and 0.5%, respectively.

3. TEST METHODS

Several test methods have been used for detection of ASR potential. The following is an assessment of the methods most used currently.

3.1. ASTM C 1260 / AASHTO T 303 / CSA A23.2-25A

ASTM C 1260 (or its equivalents AASHTO T 303 and CSA A23.2-25A) – the accelerated mortar bar test (AMBT) – is perhaps the most widely used test method (also similar to RILEM TC 106-2). It is often modified to assess the specific concrete mix to be used. The accepted maximum expansion for innocuous aggregates is 0.1% (14 days after the zero reading, or 16 days after casting) for both United States methods, or 0.15% in Canada (per CSA A23.2-27A, although 0.1% is recommended in Appendix B of CSA A23.1). However, these limits have in some cases been lowered to 0.08% for metamorphic aggregates (Lead States, 2000b). This is also consistent with Note X1.1 of ASTM C 1260 that indicates that "*some granitic gneisses and metabasalts have been found to be deleteriously expansive in field performance even though their expansion in this test was less than 0.1% at 16 days after casting*" (see Lane, 2000a). ACI 221.1R (1998) also suggests using a 0.08% limit. Grosbois and Fontaine (2000) suggested 0.08% or even 0.06%.

ASTM C 1260 is an accelerated test using a mortar bar. It is somewhat conservative in that it provides excess NaOH in the 1N solution in which the specimen is immersed, and high temperature (80ºC or 176ºF). In reality no external NaOH source may exist, and the reaction may terminate earlier. On the other hand, ASTM C 1260 is useful for identifying slowly reacting aggregates (which may not be identified by other methods) (PCA IS413, 1997). Aggregates found innocuous with ASTM C 1260 are very likely to perform well in the field.

In this test, the solution is supposed to provide a sufficient external source of alkali to complete any reaction, and the alkali content of the cement is supposed to have little or no influence. However, different cements have sometimes yielded different results (Simon and Wathne, 2000), and a modified ASTM C 1260 is often completed where the actual concrete composition, including pozzolan admixtures, is used (PCA IS415, 1988; Appendix B of CSA A23.1, 2000). In the modified method, an expansion limit of 0.1% has been recommended (Appendix B of CSA A23.1, 2000).

3.2. ASTM C 1293 / CSA A23.2-14A

In ASTM C 1293 (and its Canadian equivalent CSA A23.2-14A) – the concrete prism test (CPT) – concrete prism samples are kept in a moist (100% relative humidity) environment at a temperature of 38ºC (100.4ºF) for up to 1 year. Typically maximum expansions of 0.04% are required with this test. These two methods are also similar to RILEM TC 106-2, although the samples are handled differently in the latter.

ASTM C 1293 is perhaps in theory a more realistic method than ASTM C 1260, but it has two drawbacks: (1) the samples are tested only to 1 year in a non-accelerated environment, and (2) it may be difficult to ascertain that the aggregates used for the samples 1 year ago are representative of the ones being used in the current project. This method is less conservative than ASTM C 1260, and more likely to allow some potentially deleterious aggregates.

3.3. COMPARISON BETWEEN ASTM C 1260 AND ASTM C 1293

Some studies have assessed the relative performance of ASTM C 1260 and C 1293 and are summarized below.

Grosbois and Fontaine (2000) show comparisons of the two methods for various aggregate types. For carbonate aggregates, C 1260 did not appear conservative enough, and a 0.08% threshold (or even 0.06%) would have been more appropriate. For sandstones, both methods seemed to predict similar reactivity. For igneous and metamorphic rock, in two cases C 1260 seemed to predict the reactivity (which contradicts the Leads States assessment). The authors indicate that lowering the threshold in the accelerated mortar bar test to 0.08% is a common proposal (they found that 0.06% would insure that all aggregate found reactive with C 1293 would have been found reactive with C 1260, but that would penalize other aggregates found non-reactive with C 1293). The authors appear to accept the CPT (ASTM C 1293) as the reference test.

Fournier et al. (2000a) also use the CPT as the reference test and indicate that the AMBT (ASTM C 1260) is a good screening test.

In New Brunswick, Canada, a study showed the AMBT to conservatively indicate reactivity while the CPT did not in 46% of the cases tested (Strang, 2000). However, given that for example about 70% of the structures built between 1930 and 1950 show reactivity, it is difficult to assess which test was more accurate.

Although some of the previous works seem to accept that the CPT will give the best results, there is evidence that aggregates that appeared innocuous with the CPT actually showed field reactivity (Jensen and Fournier, 2000). Of course, field experience is the ultimate standard, and the CPT was not accurate. In Norway, the CPT method is not used (Jensen and Fournier, 2000).

3.4. ASTM C 227

This method is similar to ASTM C 1293 in terms of specimen exposure (100% relative humidity and 38ºC). However, unless specifically required at later dates, the expansion is reported at 14 days, which is too short of a time. ASTM C 33 Appendix XI (Methods for Evaluating Potential Reactivity of an Aggregate) indicates that the expansion is considered excessive if it exceeds 0.05% at 3 months, or 0.10% at 6 months – even this extended period is still considered too short. The FAA requires running it for at least 6 months, and preferably for 1 year (FAA, 1999). In general, this test method may not produce significant expansion, especially for carbonate aggregate (PCA IS413, 1997) and has been deemed unreliable (Wigum et al., 1997). This method is currently being superseded by either C 1293 or C 1260.

3.5. ASTM C 295

This method is a petrographic analysis that can detect alkali-silica reactive constituents, such as opal, cristobalite, tridymite, siliceous and intermediate volcanic glass, argillites, phyllites, metamorphic graywackes and quartz, etc. The maximum amount of these components can then be limited (e.g. see Washington State Department of Transportation specifications). Problems with this test method are: (1) the list of reactive aggregates that are limited may be incomplete, and (2) the test is very dependent on the reliability of the operator performing the test.

3.6. ASTM C 289

Also dubbed the Chemical Method, where samples of crushed and sieved aggregates are reacted with an alkaline solution at 80ºC (176ºF) and the dissolved silica is measured. This method may not be reliable for many aggregates (PCA IS413, 1997; FAA, 1999; ACI 221.1R, 1998; Wigum et al., 1997), although it may serve as a good indicator for some types of aggregates, and in some cases it is still being used (Freitag et al., 2000).

4. BENEFICIAL ADMIXTURES

4.1. ADVANTAGES OF CLASS F FLY ASH

Class F (low calcium) fly ash in replacement amounts around 25% has been shown to significantly mitigate the effects of ASR, even in marine environments (for water/cement ratios below 0.6) (Malhotra et al., 1994; Bérubé et al., 2000; McKenn et al., 1998). In a study by Touma et al. (2000) on several reactive aggregates, 25% Class F fly ash cement replacement reduced the ASTM C 1260 expansion from more than 0.9% to 0.12% in one case, and less than 0.1% in all other cases. This 25% Class F fly ash cement replacement also resulted in less expansion than 35% Class C fly ash cement replacement in all cases (while Class C fly ash has some of these advantages as well, it has often shown to either not reduce or even aggravate the ASR problem, e.g. see PCA IS413, 1997). Similar significant reductions in expansion were found by Barringer (2000) and McKeen et al. (1998) using 24% to 27% Class F fly ash cement replacement and reactive New Mexico aggregates. Several other reports confirm the effectiveness of Class F fly ash in ASR mitigation at replacement levels usually between 15% and 45% (ACI 232.2R, 1996; Langley, 2000; Rogers et al., 2000; Fournier, 1999), although levels below 25% may not be effective unless low-lime fly ash is used with 10% or less CaO (Malhotra et al., 1994; Rogers et al., 2000; Glauz et al., 1996).

The lime content affects the effectiveness of Class F fly ash to mitigate ASR. CALTRANS requires a maximum CaO content of 10%, and lowers the required fly ash if the CaO content is below 2% (Glauz et al., 1996). In Canada, CSA A23.2-27A shows a preference for a maximum CaO content of 8%. Generally, Class F fly ash contains less than 5% CaO by mass (ACI 221.1R, 1998), may be up to 8% (Keck, 2001). It is recommended that a maximum CaO content of 8% be used.

Class F fly ash has also been reported to mitigate expansion caused by delayed ettringite formation in steam-cured concrete (Zacarias et al., 1999).

In addition to mitigating ASR reaction, Class F fly ash (ASTM C 618) has the following advantages:

- Reduced construction costs.
- Savings in Portland cement production.
- Reduced heat of hydration and reduced permeability.
- Enhanced durability of waterfront structures.
- Higher long term strengths.
- Reduction in CO_2 generation.
- Higher fly ash recycling.
- Conformity with Resource Conservation and Recovery Act (RCRA) affirmative procurement regulations and DOD affirmative procurement policy.
- Increased resistance to high temperatures from jet blast.

Some of these advantages are detailed below, and apply to GGBFS as well.

Reduced construction costs. Cement is the most expensive constituent of concrete. A cubic yard of 5000-psi ready-mix concrete costs $68.25 (for Los Angeles, ENR 5 Oct 98). Up to $21, or 30%, of the cost is due to the cement itself. Hence replacement of 25% of the cement by fly ash can result in total concrete savings around 4% (also 4% savings for 50% GGBGS cement replacement). This can be significant when extended to all DOD construction. Within the Navy, more than $500 million in MILCON funds are spent annually on new construction and repairs. Improved concrete quality will also result in improved durability that will reduce maintenance costs and increase performance life.

Savings in Portland cement production. Global cement production in 1995 was 1.4 billion tons and is expected to rise to almost 2 billion tons per year by 2010 (Malhotra 1999). Significant reduction in cement production could be accomplished if all projects incorporated 25% fly ash (or 50% GGBFS) cement replacement. In the United States, 87.3 million tons of cement were produced in 1999 (http://www.global-cement.dk/files/facts.htm). Since cement costs $81.83 per ton (ENR http://www.enr.com/cost/cost2.asp), and fly ash for use in concrete costs from $20 to $45 per ton (at the site, source: American Coal Ash Association), savings to the Navy are estimated at $4 million per year (estimated 0.4 million tons yearly cement usage). Total savings to the United States economy could be in excess of $1 billion every year.

Reduced heat of hydration, reduced permeability, and enhanced durability. Class F fly ash, in particular, reduces the concrete permeability (this reduction is lesser for Class C, see Ellis, 1992), reduces the heat of hydration (resulting in less shrinkage cracking), and therefore slows down the ingress of chloride ions, increasing durability. Class F fly ash also increases the sulfate resistance of concrete (Class C decreases it) (Ellis, 1992).

Higher long term strengths. Fly ash has pozzolanic properties, and long-term strengths are usually higher with fly ash (or GGBFS) cement replacement than without it. However, for straight replacement with Class F fly ash, the early strength is usually lower, which can be a drawback for prefabrication. This can be compensated by changing the water-cement ratio. Alternatively, while a 25% cement replacement is still desired in these applications, it is possible that part of the 25% would be cement replacement, while the rest would be fly ash addition, in order to maintain high early strength (e.g. see modified replacement in Malhotra et al., 1994; Naik and Ramme, 1989; Illinois, 2001). This would still result in a less expensive, more durable, and more-environmentally friendly concrete.

Reduction in CO_2 generation. Experts on global warming link 7% of the world's carbon dioxide emissions to the procurement of Portland cement, a main concrete component (Malhotra, 1999). In the United States, cement production accounts for about 2.4% of total industrial and energy related CO_2 emissions (Intergovernmental, 1996) and for 61% of industrial non-energy related carbon dioxide emissions. By significantly decreasing the amount of total cement used in construction, DOD would be able to reduce cement consumption and the associated CO_2 emission. Each ton of cement that is eliminated would reduce carbon dioxide emissions by about 1 ton as well (Malhotra, 1999; Mehta, 1998). If all projects worldwide were to incorporate 25% to 30% fly ash replacement, CO_2 emissions from cement fabrication could be reduced by the same amount every year, and total world CO_2 emissions could decrease by 2%. This would be a significant contribution towards meeting the 1997 Kyoto Protocol to the United Nations, where nations intend to reduce their CO_2 emissions by at least 5% below 1990 levels in the commitment period 2008 to 2012 (see text of Protocol in the internet at: http://www.cnn.com/SPECIALS/1997/global.warming/stories/treaty/index.html).

Higher fly ash recycling. Recycling of fly ash and silica fume, both industrial by-products, will reduce the need for disposal of these waste materials into landfills. Today only 10 percent of the 60 million tons of fly ash annually produced in the United States is used in concrete (Rosenbaum, 1998). If 25% of all cement produced in the United States was replaced with fly ash, about 22 million tons could be used. This does not even account for the imported cement.

Conformity with RCRA and DOD affirmative procurement regulations. The Office of Federal Environmental Executive (OFEE) is responsible for evaluation affirmative procurement materials. RCRA Section 6002 provides that federal agencies must establish an affirmative procurement program for procuring items containing recovered materials to the maximum practical extent. Items listed by the Environmental Protection Agency (EPA) in 40 CFR 247.12(c) include cement and concrete containing either fly ash or GGBF slag (http://www.epa.gov/epaoswer/non-hw/procure/rman1.htm#technical). Requirements for procuring recovered materials are also described in Executive Order 13101 and Navy EQ recommendation 3.1.13.a. Reuse/Recycling of Hazardous/Polluting Materials. Increasing the content of fly ash in concrete would enhance conformity to these environmental requirements.

Increased resistance to high temperatures from jet blast. Another interesting benefit for airfield pavements is that using slag and fly ash as partial cement replacement materials has been shown to increase the pavement resistance to high thermal gradients and temperatures from jet exhaust (Robins and Austin, 1995).

According to ASTM C 595, fly ash blended cements could have up to 40% cement replacement by weight, but in practice 15% to 25% replacements are more common, and previously recommended (ACI 211.4R, 1993). The Navy, Army, and Air Force already allow for up to 25% or 30% cement replacement with Class F fly ash, e.g. for airfield pavements (see for example Army TM 5-822-7 and UFGS 02751N prior to changes consequent to this report). However, while this use is allowed, no minimum cement replacement is usually required, and consequently no fly ash is usually included. It is recommended that a minimum Class F fly ash cement replacement of 25% be required, with a maximum CaO content of 8%.

4.2. STRENGTH GAIN RATE WITH CLASS F FLY ASH

While mixes incorporating fly ash cement replacement typically show higher long-term strengths (e.g. at 90 days), it is known that the strength gain rate is initially lower than for regular mixes without replacement. NFESC currently has an on-going Demonstration and Validation (DEMVAL) effort to demonstrate the use of high volume fly ash cement replacement (30% or more). One of the objectives of this effort is to assess this strength gain rate. Towards this goal, several laboratory demonstrations have been completed at different locations (corresponding to the various NAVFAC Engineering Field Divisions). In particular:

- Two nominal 3500 psi and 5000 psi mixes were tested with and without 30% of Class F fly ash cement replacement in Virginia (Tables 1 and 2). This fly ash had a very low 0.6% CaO content.
- Several mixes were tested with 0% to 40% Class F fly ash cement replacement for Pier D, Naval Station Bremerton, Washington (Tables 3 and 4). This fly ash had a 10% CaO content and actually showed a pessimum around 15% replacement (see Table 4), i.e. worse measured expansion per ASTM C 1260.

These mixes show that the compressive strength at 28 days with Class F fly ash cement replacement is between 80% and 95% of the strength without replacement. Replacement appeared to have an even lesser effect on the flexural strength at 28 days. Similar ratios for both compressive and flexural strengths at 28 days can be found elsewhere (Malhotra et al., 1994; Galeota et al., 1995). Some States Departments of Transportation (DOTs) use replacement ratios in an attempt to maintain the strength gain rate, e.g. the Illinois DOT replaces each bag of cement with 1.5 bags of Class F fly ash (Illinois, 2001). It should be noted that in this, like in other DOTs, it is only permitted that 0% to 15% of the cement should be replaced, which practically insures *worse* expansion for Class F fly ashes with CaO contents near 10%.

In summary, it appears that either direct substitution or partial substitution can be made to yield either a similar compressive and/or flexural strength at 28 days.

4.3. ADVANTAGES OF CLASS N FLY ASH

Although Class N fly ashes have been less used, a comprehensive study by CALTRANS (Glauz et al., 1996) shows that Class N fly ashes, with the same limitations in composition as the ones indicated for Class F fly ash, provide the same advantages as Class F fly ash. That study also shows that some very good Class N fly ashes exist with a CaO content below 2%, almost no alkalies, and an LOI of less than 4%. It is recommended that Class N flay ash be allowed, with the same restrictions as for Class F.

4.4. ADVANTAGES OF GGBFS

Ground granulated blast furnace slag (GGBFS) (ASTM C 989) offers similar advantages to Class F fly ash, but only when used in higher quantities (e.g. Malhotra et al., 1994; Rogers et al., 2000; Ramachandran, 1998). For example, in blended cements, while typical replacements for fly ash are in the range of 15% to 40%, for GGBFS they are in the range of 25% and 70% (ASTM C 595). Typically 35% to 50% is used (e.g. see UFGS 02571N). A 40% GGBFS cement replacement can provide benefits similar to a 25% fly ash replacement (BRE, 1999). In the Netherlands, 25% fly ash is considered equivalent to 50% GGBFS (Heijnen and Larbi, 1999). GGBFS has been successful in mitigating ASR (Hooton et al., 2000; Malhotra et al., 1994). A minimum 40% GGBFS cement replacement has been recommended to mitigate ASR (see ASTM C 989, Appendix X3, and ACI 233R, 1995). GGBFS Grades 100 or 120 are preferred to Grade 80 (ACI 221.1R, 1998; ACI 233R, 1995; Brewer, 2000). GGBFS grades 100 and 120 are also the ones recommended for ASR mitigation (ACI 221.1R, 1998).

Pavements with GGBFS also exhibit a lighter color. The use of more reflective concrete can reduce energy absorption, lead to pavements with longer lives, reduce temperature levels, and reduce lighting requirements. The site http://eetd.lbl.gov/HeatIsland/Pavements from Lawrence Berkeley Labs has information about the subject and describes the benefits of reflective pavements.

Over 13 million tons of GGBFS are produced annually in the United States, mostly in the East coast (ACI 232.2R, 1996), and mostly Grade 100 or 120.

4.5. STRENGTH GAIN RATE WITH GGBFS

GGBFS is not a pozzolan, rather it is a hydraulic cement. For Grades 100 and 120, GGBFS will result in higher strengths at 28 days (and later), although the early strength may be lower. ACI 232.2R (1996) reports the following:

- Grade 120 slag cement replacements result in lower strengths in the first 3 days, but greater strengths after 7 days (also, precast mixes with Grade 120 slag cement replacement can get 1-day compressive strengths higher than without replacement, see Brewer, 2000).
- Grade 100 slag cement replacements result in lower strengths in the first 21 days, but greater strengths after that.
- Grade 80 slag gives lower strengths at all ages – Grade 80 is not recommended for ASR mitigation (see ACI 221.1R, 1998).

In summary, because of its cementitious properties, GGBFS (Grades 100 and 120) appears to result in equal or higher strengths at 28 days. Hence it is recommended that 28-day strength requirements be specified for mixes using GGBFS.

4.6. PESSIMUM EFFECTS AND MINIMUM REPLACEMENTS

As indicated earlier, low cement replacements around 15% for fly ash have been common. It should be noted that for any fly ash, a pessimum effect (i.e. more expansion instead of less) can be observed which gets worse as the CaO content increases (Malhotra et al., 1994; Rogers et al., 2000). This pessimum effect is very pronounced for Class C fly ash (which typically has CaO contents between 10% and 30%), and is also present with Class F fly ash (which typically has CaO contents between 0% and 10%). For Class F fly ash with 10% CaO, the pessimum effect often occurs for replacements around 15%, and the minimum replacement to reduce the expansion to an acceptable level is around 30% (see example in Table 4). What this indicates is that standard practice replacements of 15% may have resulted in concretes with worse expansion!

This pessimum effect is also reflected in the CALTRANS specification, which allows for 15% replacement only if the Class F fly ash CaO content is less than 2%, and requires 25% replacement for CaO contents between 2% and 10%. It is recommended that a Class F or N fly ash with 8% CaO or less be used, and that a minimum replacement of 25% be used. If the fly ash has a CaO content between 8% and 10%, it could be allowed provided that the minimum replacement is increased to 30%.

For GGBFS, minimum replacements of 35% (Cheung and Foo, 1999) and 40% (ASTM C 989, Appendix X3) have been suggested to mitigate ASR. It is recommended that a minimum replacement of 40% be used.

4.7. ADVANTAGES OF LITHIUM SALTS

Lithium salts can be added to the concrete mix to counter the reactivity of the aggregates (Durand, 2000; Lane, 2000b; Stokes et al., 2000a; Thomas et al., 2000; Thompson, 2000; McKeen et al., 1998). Lithium can reduce the concrete expansion but the amount of lithium compound needed can be high and varies depending on the aggregate (Durand, 2000; Thomas et al., 2000). Lithium has also been recommended in several guidelines (Lead States, 2000b).

It should be noted, however, that lithium hydroxide (LiOH) and lithium carbonate (Li_2CO_3) have been found to increase the expansion of alkali-carbonate reactive rock, and some lithium compounds in insufficient quantities can actually increase the expansion (pessimum effect) (Lead States, 2000a; Appendix B of CSA A23.1, 2000). Lithium hydroxide is also a hazardous material. Lithium nitrate ($LiNO_3$) does not exhibit a pessimum effect, is safe to handle, and is recommended (Lead States, 2000a; Appendix B of CSA A23.1, 2000).

In theory, lithium salts can also be applied topically to existing structures or pavements experiencing ASR and slow down or complete the reaction (Stokes et al., 2000b; Johnston et al., 2000). In practice, the lithium may not penetrate sufficiently into the structure and may not be able to mitigate the reaction but superficially, resulting in continuing decay of the structure. Methods of driving lithium ions using electrical fields are being studied to improve penetration (Whitmore and Abbott, 2000). If the pavement is cracked enough, the salts may penetrate deeply, but the concrete may be too decayed anyway. Hence, topical applications of lithium to existing structures are not recommended until further research shows conclusive benefits.

4.8. ADVANTAGES AND DISADVANTAGES OF SILICA FUME

Silica fume has also been proven to mitigate ASR, for example 10% silica fume cement replacement has been reported to reduce expansion to a level close to 20% Class F fly ash (Touma et al., 2000). Silica fume can also increase the concrete strength and lower its permeability. However, several recent uses of silica fume have resulted in high profile problems in the Navy:

- In Hawaii, a NAVSTA Pearl Harbor bridge is experiencing deleterious expansion as a result of poor silica fume dispersion during the mixing. Similar experiences were reported by Pettersson (1992) in Sweden (see also ACI 221.1R, 1998), and also by

Diamond (1997) who stated that "silica fume can induce ASR rather than mitigating it." Silica fume particles have a diameter around 0.1 μm, unfortunately, silica fume is prone to lumping (ACI 234R, 1996). Apparently undispersed or undispersable grains in lump sizes from 40 μm to 800 μm (up to 3000 μm in the bridge) can react with the cement alkalis just like reactive aggregates (see additional references in Diamond, 1997).

- In Yuma, premature drying of a silica fume bonding layer in a bonded pavement overlay may have resulted in the layer acting as a bond breaker instead, indicating other potential problems (such as the need for different amounts of water in the mix).

Other difficulties in the usage of silica fume have been reported elsewhere (Al-Amoudi et al., 2001). Finally, cost is also an issue, since silica fume is much more expensive than cement, fly ash, or slag (around 45 cents/pound, versus 4 cents/pound for cement, versus 1 to 2 cents/pound for fly ash, and about 3 cents/pound for slag). In summary, care should be taken when using silica fume, or it should be avoided in favor of other pozzolanic admixtures.

If silica fume is used, the following precautions should be taken (see also ACI 234R, 1996): (1) it should be used in slurry form to facilitate dispersion, (2) shreddable bags should be avoided, (3) extra mixing is recommended, and (4) proper curing must be followed.

4.9. AIR ENTRAINMENT

Air entrainment has been reported to also somewhat mitigate the deleterious expansion from ASR (ACI 221.1R, 1998; Ramachandran, 1998). The expanding gel that forms with ASR has been observed to fill the air voids, reducing the internal pressures created. This, however, could reduce the resistance to freeze-thaw, so that a level of air entrainment higher than initially planned may be desirable to address both issues.

Many Class F fly ashes may require a higher dosage of air-entraining mixtures to obtain specified air contents (ACI 211.1, 1997).

5. MITIGATION PROCEDURES

5.1. SUMMARY OF MITIGATION PROCEDURES

5.1.1. Cement

Low alkali cement (ASTM C 150) with less than 0.6% alkali content (equivalent sodium oxide) should be required. However, use of low alkali cement is not, by itself, sufficient to control ASR (PCA IS413, 1997), and additional measures are required, as indicated below. For potentially reactive aggregates, a maximum cement alkali content of 0.4% is recommended, if available (e.g. see ACI 221.1R, 1998, as well as North Carolina DOT and Virginia DOT specifications in Lead States, 2000).

5.1.2. Admixtures

In the previous section, the benefits of Class F or N fly ash (ASTM C 618) and GGBFS (ASTM C 989) cement replacement were indicated. It is recommended that minimum replacements of 25% for Class F or N fly ash be required for all concrete work. While very high replacements have been used in some special applications (such as dams), for typical Navy use it is recommended to limit the maximum replacement to 40% at this time. This is in part due to increased difficulties with concrete finishing, and lower strength gain rates at higher volume replacements. The fly ash should also have a maximum of 1.5% available alkali, a maximum 6% loss on ignition, and a maximum of 8% CaO (although less than 2% would be preferable) (PCA IS413, 1997; Glauz et al., 1996; CSA A23.2-27A, 2000). Contents of CaO between 8% and 10% could be allowed if the minimum replacement is 30% (by weight).

If the aggregates have been proven to be innocuous via ASTM C 1260, it has been suggested that Class C fly ash (or a blend of Class F and Class C) could be allowed instead of Class F fly ash, with the same restrictions (e.g. see New Mexico, 2000). However, the restrictions on Class C fly ash composition (ASTM C 618) allow for much more unknown materials than Class F, in particular high contents of CaO (beyond 10%), significantly increasing the potential for adverse effects. At the present time Class C fly ash is not recommended.

For GGBFS, Grade 120 or 100 should be used (Grade 120 is preferred) to effectively control ASR (ACI 221.1R, 1998). Replacements between 40% and 50% are recommended.

Lithium admixtures have shown potential to mitigate ASR, however, only lithium nitrate is recommended since it is safe to handle and does not show a pessimum effect. AASHTO (Lead States, 2000a, 2000b) has taken the lead in this area, and their progress will be monitored.

5.1.3. Aggregate Selection

The best way to prevent ASR is to use non-reactive aggregates. This can be done by using aggregate that has historically performed well, or aggregate shown to be non-reactive by either ASTM C 1260, C 1293, or C 295. It should be noted that historical performance may be difficult to demonstrate since in many cases deterioration only occurs after 15 years or more (Lead States, 2000b). If the concrete contains low-alkali cement and ASR-reducing admixtures, it is possible that it can accommodate slightly reactive aggregates without significant expansion. It is recommended that this be verified using the actual mix in ASTM C 1260 (modified version). Note that reduction in the maximum aggregate size appears to somewhat reduce the expansion due to ASR and even ACR (PCA IS413, 1997).

5.2. RECOMMENDED MITIGATION PROCEDURES

As an example, UFGS 02751N has been reviewed following the previous mitigation procedures, and excerpts of this specification with proposed corrections in bold type are shown below.

PART 2 PRODUCTS

2.1 MATERIALS

2.1.1 Cementitious Material

2.1.1.1 Cement

ASTM C 150 Type [I] [II] [I or II] [III, for high early strength concrete] [IV] [V] with maximum alkali content of 0.60%. Cement certificates shall include test results in accordance with ASTM C 150, including Equivalent Alkalies indicated in the Optional Chemical Requirements

> ***Note: A maximum alkali content of 0.40% is more desirable but not required.***

2.1.1.2 Fly Ash

ASTM C 618 Class F or N except that the maximum allowable loss on ignition shall be 6%, maximum available alkalies content shall be 1.5%, and maximum calcium oxide (CaO) content 8%*. Fly ash certificates shall include test results in accordance with ASTM C 618, including available alkalies indicated in the Supplementary Optional Chemical Requirements.*

> ***Note: A maximum calcium oxide content of 2% is more desirable but not required.***
> ***Note: A maximum calcium oxide content between 8% and 10% can be allowed if the amount of cement replacement is at least 30%.***

2.1.1.3 Slag

ASTM C 989 Ground Granulated Blast Furnace Slag (GGBFS) Grade 120 or Grade 100. Certificates shall include test results in accordance with ASTM C 989.

Note: GGBFS Grade 120 is more desirable, but Grade 100 is allowed.

2.1.2 Water

ASTM C 94/C 94M.

2.1.3 Aggregates

2.1.3.1 Alkali Reactivity Test

> ***Note 1****. While not wholly conclusive, petrographic examination (ASTM C 295)* ***and the Chemical Test Method (ASTM C 289) are*** *valuable indicators. However, chemical test results may not be correct for aggregates containing carbonates of calcium, magnesium or ferrous iron, such as calcite, dolomite, magnesite or siderite; or silicates of magnesium such as serpentine.* ***The Concrete Prism Test (ASTM C 1293) is also a valuable indicator. However, none of the methods above constitutes a substitute for the modified ASTM C 1260.***

> ***Note 2****. The most important aggregates and minerals known to be deleteriously reactive with the alkalies in Portland cement are listed in ASTM C 33* ***(and ASTM C 294).*** *However, this list is not inclusive, and particles having a glassy or micro-crystalline structure should be considered suspect. Reactive aggregates are widespread in the United States, being especially common in the western half and southeastern portions. However, generalizations concerning area distribution of reactive aggregates should not be relied upon for important work. Contract documents for important concrete projects should include provisions for preventing such aggregate being used, if possible, or requiring their use exclusively with low-alkali cements, suitable blended cements,* ***and supplementary cementitious materials*** *as available and as required to avoid deleterious effects on the concrete.*

Fine and Coarse aggregates to be used in all concrete shall be evaluated and tested by the Contractor for alkali-aggregate reactivity in accordance with ASTM C 1260. ***The coarse and fine aggregates shall be evaluated in a combination which matches the contractors' proposed mix design (including the required Class F or N fly ash, or GGBF slag), utilizing the modified version of ASTM C 1260 indicated below.*** *Test results of the combination shall have a measured expansion of less than 0.08 percent at 16 days. Should the test data indicate an expansion of greater than 0.08 percent, the aggregate(s) shall be rejected and the contractor shall submit new aggregate sources for retesting or may submit additional test results* ***incorporating additional Class F or N fly ash, or GGBF slag, or Lithium Nitrate*** *for consideration.*

ASTM C 1260 shall be modified as follows to include one of the following options:

a. Utilize the contractor's proposed low alkali Portland cement and ***Class F or N fly ash*** *in combination for the test proportioning. The laboratory shall use the contractor's proposed percentage of cement and fly ash.*

b. Utilize the contractor's proposed low alkali Portland cement and ground granulated blast furnace (GGBF) slag in combination for the test proportioning. The laboratory shall use the contractor's proposed percentage of cement and GGBF.

c. Utilize the contractor's proposed low alkali Portland cement and ***Class F or N fly ash*** *and ground granulated blast furnace (GGBF) slag in combination for the test proportioning. The laboratory shall use the contractor's proposed percentage of cement, fly ash and GGBF.*

> ***Note: It is recommended that the coarse and fine aggregates also be evaluated separately, in accordance with the standard ASTM C 1260, to ascertain the specific reactivity of each aggregate.***

2.2 CONCRETE MIX DESIGN

2.2.1 Contractor-Furnished Concrete Mix Design

Contractor-furnished mix design concrete shall be designed ***in accordance with ACI 211.1 [and ACI 211.4R]*** *except as modified herein, and the mix design shall be as specified herein under paragraph entitled "Submittals." The concrete shall have a minimum flexural strength of 4481 kPa 650 pounds per square inch at* ***28 days****. The air content shall be 5.5 plus or minus 1.5 percent. Maximum size aggregate for slip forming shall be 38 mm 1.5 inches. The minimum cement factor and slump shall be ...*

The cement factors given in the foregoing table are minimum; if they are not sufficient to produce concrete of the flexural strength required, they shall be increased as necessary, without additional compensation under the contract. The cement factor shall be calculated using cementitious material, including ***Class F or N fly ash, and/or GGBF slag****.* ***Use a cement replacement (by weight) of 25%-40% Class F or N fly ash, or 40%-50% GGBF slag, or a combination of the two. In the combination, each 5% of Class F or N fly ash that is subtracted from the minimum 25% requirement shall be replaced by 8% GGBF slag.***

> ***Note: If a Class F or N fly ash with a calcium oxide content between 8% and 10% is used, the amount of cement replacement must be between 30% and 40%.***

5.3. AFFECTED TRI-SERVICE SPECIFICATIONS

5.3.1. Navy

The Naval Facilities Engineering Command (NAVFAC) is responsible for maintaining building materials guide specifications for the U.S. Navy. Current NAVFAC Guide Specifications covering concrete include:

- NFGS 02751 – superseded by UFGS 02751N (see below)
- NFGS 02752 – superseded by UFGS 02752N (see below)
- NFGS 03311 – Marine Concrete,
- NFGS 03300 – Cast in Place Concrete,
- NFGS-03371 – Shotcrete,
- NFGS-03410 – Precast Structural Concrete,
- NFGS-03412 – Precast Prestressed Structural Concrete,
- NFGS-03450 – Precast Architectural Concrete,
- NFGS-03480 – Concrete Poles,
- NFGS-03520 – Lightweight Concrete Roof Insulation,
- NFGS-03930 – Concrete Rehabilitation.

All these specifications are being revisited to include the recommendations in this report, as well as to integrate them into Tri-Service Unified Facilities Guide Specifications (UFGS).

5.3.2. Army and Air Force

The Army and Air Force have recently published various joint specifications and practices, in addition to previous service-specific ones. Several are being integrated into Tri-Service UFGS. Among them:

- Army TM 5-822-7/Air Force AFM 88-6 (8) – Standard Practice for Concrete Pavements
- TM5-805-1/AFM88-3 – Standard Practice for Concrete for Military Structures.

5.3.3. Tri-Service

- UFGS 02751N (5/01) Concrete Pavement for Airfields and other Heavy Duty Pavements
- UFGS 02753A (7/01) Concrete Pavement for Airfields and other Heavy-Duty Pavements
- UFGS 02752N (1/01) Portland Cement Concrete Pavement for Roads and Site Facilities
- UFGS 02754A (7/01) Concrete Pavements For Small Projects
- UFGS 02395N (9/99) Prestressed Concrete Fender Piling
- UFGS 02454A (2/98) Precast Concrete Piling
- UFGS 02459N (9/99) Cast-In-Place Concrete Piles
- UFGS 02455A (11/97) Cast-In-Place Concrete Piles, Steel Casing

- UFGS 02456N (1/01) Prestressed Concrete Piles
- UFGS 02458A (2/98) Prestressed Concrete Piling
- UFGS 02459A (2/98) Piling: Composite, Wood And Cast In-Place Concrete
- UFGS 02588N (9/99) Concrete Poles
- UFGS 02755A (7/01)Roller Compacted Concrete (RCC) Pavement
- UFGS 02770A (8) Concrete Sidewalks And Curbs And Gutters
- UFGS 02780 (1/98) Concrete Block Pavements
- UFGS 03300 (5/01) Cast-In-Place Structural Concrete
- UFGS 03300N (9/99) Cast-In-Place Concrete
- UFGS 03311 (9/99) Marine Concrete
- UFGS 03340A (6/97) Roof Decking, Cast-In-Place Low Density Concrete
- UFGS 03371 (5/95) Shotcrete
- UFGS 03372 (11/94) Preplaced-Aggregate Concrete
- UFGS 03373 (8/95) Concrete For Concrete Cutoff Walls
- UFGS 03410N (3/00) Plant-Precast Structural Concrete
- UFGS 03410A (5/98) Precast/Prestressed Concrete Floor and Roof Units
- UFGS 03412N (9/99) Plant-Precast Prestressed Structural Concrete
- UFGS 03413A (5/98) Precast Architectural Concrete
- UFGS 03414A (3/89) Precast Roof Decking
- UFGS 03415A (1/96) Precast-Prestressed Concrete
- UFGS 03450 (9/99) Plant-Precast Architectural Concrete
- UFGS 03511A (9/96) Gypsum Plank Decking (Contractor's Option)
- UFGS 03520N (9/99) Lightweight Concrete Roof Insulation
- UFGS 03700 (7/92) Mass Concrete
- UFGS 03701 (2/94) Roller-Compacted Concrete For Mass Concrete Construction
- UFGS 03900 (12/97) Restoration of Concrete in Historic Structures
- UFGS 03930 (9/99) Concrete Rehabilitation
- UFGS 13208N (9/99) Wire-Wound Circular Prestressed-Concrete Water Tank

5.4. CONCURRENT EFFORTS

NFESC currently has an on-going Demonstration and Validation (DEMVAL) effort to demonstrate the use of high volume fly ash cement replacement (30% or more). Another objective of this effort is to familiarize the Engineering Field Divisions (EFDs) and Engineering Field Activities (EFAs) with the use of high volumes of fly ash. Several successful applications have been completed to date:

- F/A-18 parking aprons were completed at NAS Oceana using lightweight aggregate and 30% Class F fly ash replacement (FY00).
- A simulated aircraft carrier deck was completed on a runway at NAS Point Mugu (FY00) using 30% Class F fly ash replacement (Burke and Malvar, 2000). The concrete

exceeded the requirements of 5000 psi compressive strength and 650 psi flexural strength at 56 days.

- An arresting gear anchor was completed at NAS Miramar using 30% Class F fly ash replacement (FY00). At 56 days, the concrete compressive strength was 6000 psi, and the flexural strength 710 psi, again in excess of the same requirements.
- A demonstration and validation project is looking at wrapping piles experiencing ASR with fiber reinforced composites. The aim is to show the capability of the wraps, or jackets, to contain the expansion and maintain or enhance the pile structural capability by confining the concrete. Previous studies have shown that pressures from ASR gels rarely exceed 10 MPa (1450 psi) (CSA A864, 2000).

The EFDs have also already independently completed several successful applications of high volume fly ash or GGBF slag replacement:

- The Atlantic Division has used 40% Class F fly ash cement replacement (as well as GGBFS cement replacement) in airfield pavements with 650-psi concrete flexural strength at 28 days (e.g. Taxiway extension, Chambers Field, Naval Station Norfolk, VA, August 01).
- The Southern Division has used GGBFS as a replacement for cement since the early 1980s. Typically this replacement is 50% of the total cementitious materials. One of the latest projects was an apron at NAS Jacksonville, FL. Specifications called for a 650-psi flexural strength concrete. Contractor proposed 260 lbs type I cement and 260 lbs of blast furnace slag. The average 7-day breaks for this mix was 619 psi and the 28-day break average was 841 psi. Similarly, the Southern Division has also been using fly ash in their mixes for a long time. They recently awarded a couple of apron expansion projects in the Southwest Texas area that specified 650-psi flexural strength concrete with 25% type F fly ash.

The U.S. Army, Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL) is also developing an Engineering Technical Letter (ETL 02-XX: Alkali Aggregate Reaction in Portland Cement Concrete Airfield Pavements, by R. Rollings) for use in Air Force airfields. This ETL will incorporate the above Tri-Service recommendations for ASR mitigation.

6. CONCLUSIONS

A review of the state-of-the-art on ASR mitigation has been completed. From this review a set of recommendations has been formulated that can be used to update both the Navy and the more recent Tri-Service guide specifications that address concrete. In particular, it is recommended to include a cement replacement of 25% to 40% low calcium Class F or N fly ash, or 40% to 50% GGBF slag (Grade 100 or 120), or a combination thereof, in all concrete. The Class F or N fly ash should also have a maximum of 1.5% available alkali, a maximum 6% loss on ignition, and a maximum of 8% CaO. Methods for testing for ASR have also been evaluated and a modified ASTM C 1260 has been recommended.

In addition to mitigating ASR, these cement replacements are expected to: (1) reduce concrete costs, (2) significantly enhance the durability of concrete, (3) increase fly ash and GGBFS recycling, and (4) support the 1997 Kyoto protocol by significantly reducing CO_2 production. If 25% of all cement were to be replaced, total savings to the United States economy could be in excess of $1 billion every year.

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Table 1. Laboratory Investigation, Virginia Field - Nominal 3500 psi Mix

MIX	3500 PSI CONTROL	3500 PSI REPLACEMENT
Cement, lbs/yard^3 (kg/m^3)	564 (335)	395 (234)
Class F fly ash, lbs/yard^3 (kg/m^3)$^+$	0 (0)	165 (98)
Coarse aggregate, lbs/yard^3 (kg/m^3)*	1850 (1098)	1850 (1098)
Fine aggregate, lbs/yard^3 (kg/m^3)*	1131 (671)	1079 (640)
W/(C+FA)	0.47	0.44
Slump, inches (cm)	5 (12.7)	4.5 (11.4)
Air, %	7.3	6.4
Maximum temperature, ºF (ºC)	74 (23.3)	73 (22.8)
Unit weight, pcf (kg/m^3)	139 (2224)	139.6 (2234)
Compressive strength, psi (MPa)		
1day	1250 (8.6)	790 (5.5)
7 days	3870 (26.7)	3010 (20.8)
14 days	4420 (30.5)	3860 (26.6)
28 days	4900 (33.8)	4580 (31.6)
60 days	5530 (38.1)	5840 (40.3)
90 days	5850 (40.3)	6360 (43.9)
Flexural strength, psi (MPa)		
28 days	850 (5.86)	835 (5.76)
60 days	895 (6.17)	910 (6.28)
90 days	910 (6.28)	935 (6.45)
Initial set (minutes)	400	445
Final set (minutes)	475	560
Rapid chloride permeability ASTM C 1202 (Coulombs)		
64 days	7350	3243
90 days	4586	1957

$^+$ This fly ash had a very low 0.6% CaO content.
* Saturated, surface dry weight.

Table 2. Laboratory Investigation, Virginia Field Mix - Nominal 5000 psi Mix

MIX	5000 PSI CONTROL	5000 PSI REPLACEMENT
Cement, lbs/yard^3 (kg/m^3)	705 (418)	493 (292)
Class F fly ash, lbs/yard^3 (kg/m^3)$^+$	0 (0)	212 (126)
Coarse aggregate, lbs/yard^3 (kg/m^3)*	1850 (1098)	1850 (1098)
Fine aggregate, lbs/yard^3 (kg/m^3)*	1014 (602)	948 (562)
W/(C+FA)	0.38	0.38
Slump, inches (cm)	3.75 (9.5)	4.25 (10.8)
Air, %	5.5	5.5
Maximum temperature, ºF (ºC)	80 (26.7)	78 (25.6)
Unit weight, pcf (kg/m^3)	142.4 (2278)	142 (2272)
Compressive strength, psi (MPa)		
1day	2730 (18.8)	1940 (13.4)
7 days	4730 (32.6)	3570 (24.6)
14 days	5480 (37.8)	4390 (30.3)
28 days	6160 (42.5)	5520 (38.1)
60 days	6790 (46.8)	6730 (46.4)
90 days	7120 (49.1)	7240 (49.9)
Flexural strength, psi (MPa)		
28 days	940 (6.48)	965 (6.66)
60 days	1005 (6.93)	1035 (7.14)
90 days	1045 (7.21)	1070 (7.38)
Initial set (minutes)	230	270
Final set (minutes)	319	382
Rapid chloride permeability ASTM C 1202 (Coulombs)		
64 days	5825	2975
90 days	3975	1792

$^+$ This fly ash had a very low 0.6% CaO content.
* Saturated, surface dry weight.

Table 3. Laboratory Investigation, Pier D Replacement, Naval Station Bremerton, Washington.

FLY ASH	COMPRESSIVE STRENGTH psi (MPa)				FLEXURAL STRENGTH psi (MPa)		
(%)*	1-day	7-day	28-day	180-day	7- day	28-day	180-day
0	2787 (19.2)	4490 (31.0)	5580 (38.5)	5885 (40.6)	575 (4.0)	565 (3.9)	615 (4.2)
10	1993 (13.7)	3933 (27.1)	4860 (33.5)	5440 (37.5)	550 (3.8)	610 (4.2)	640 (4.4)
15	2183 (15.1)	4583 (31.6)	5603 (38.6)	6250 (43.1)	605 (4.2)	650 (4.5)	705 (4.9)
20	2137 (14.7)	4240 (29.2)	5070 (35.0)	5730 (39.5)	570 (3.9)	590 (4.1)	640 (4.4)
25	1590 (11.0)	3603 (24.9)	4580 (31.6)	5180 (35.7)	540 (3.7)	510 (3.5)	610 (4.2)
30	1477 (10.2)	3680 (25.4)	4267 (29.4)	4640 (32.0)	495 (3.4)	590 (4.1)	605 (4.2)
35	1590 (11.0)	3603 (24.9)	4580 (31.6)	4713 (32.5)	440 (3.0)	560 (3.9)	610 (4.2)
40	1477 (10.2)	3680 (25.4)	4267 (29.4)	4467 (30.8)	440 (3.0)	520 (3.6)	560 (3.9)

* This fly ash had a 10% CaO content.

Table 4. Laboratory Investigation, Pier D Replacement, Naval Station Bremerton, Washington.

FLY ASH (%)[+]	SET (minutes)		28-DAY EXPANSION* ASTM C 1260 (%)	RAPID CHLORIDE PERMEABILITY ASTM C 1202 (Qs, Coulombs)	
	Initial	Final		60-day	180-day
0	252	333	+ 0.128	7939	8561
10	227	274	+ 0.168	8305	3445
15	217	269	+ 0.221	6150	4219
20	209	259	+ 0.138	6879	3537
25	207	256	+ 0.111	7250	4405
30	220	279	+ 0.070	7744	3078
35	233	294	+ 0.088	6241	3091
40	250	318	+ 0.042	5906	3870

[+] This fly ash had a 10% CaO content and shows a pessimum around 15% replacement.
* Readings were taken beyond the standard 14 days.