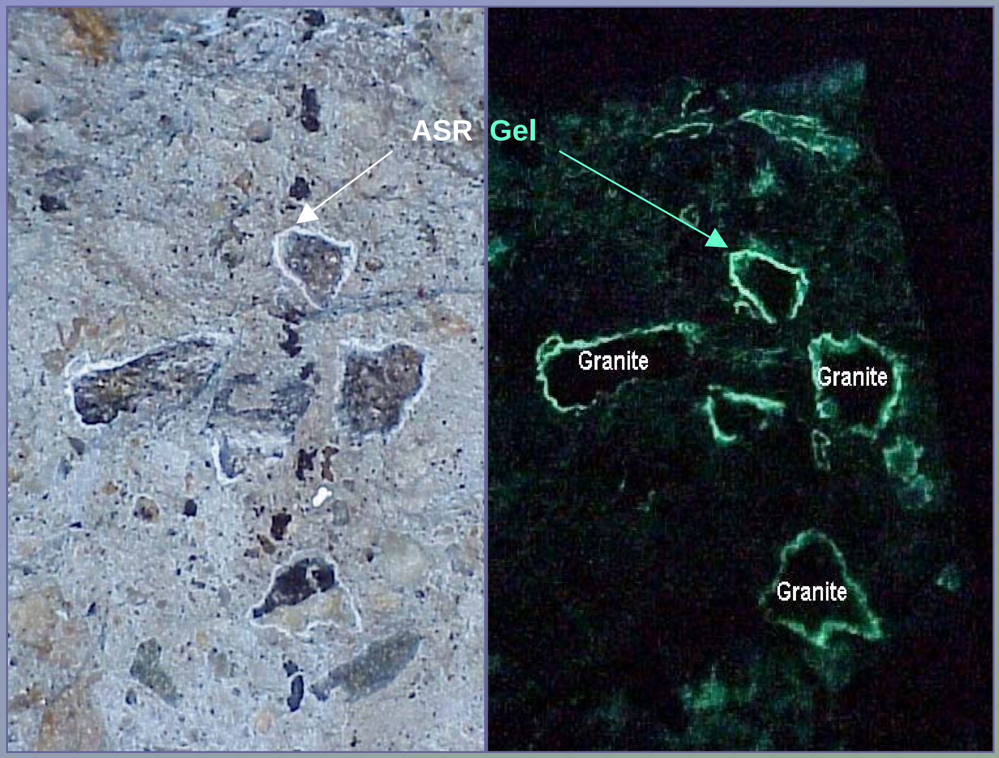
New Hampshire DOT

Research Record



Mitigation of Alkali-Silica Reactivity in New Concrete in New Hampshire – Phase 2

Minimum Amounts of Admixture(s) Needed to Significantly Minimize ASR

Final Report

Prepared by the New Hampshire Department of Transportation, in cooperation
with the U.S. Department of Transportation, Federal Highway Administration

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MINIMUM AMOUNTS OF ADMIXTURE(S) NEEDED TO SIGNIFICANTLY MINIMIZE ASR

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16. Abstract

A Phase 2 research study was undertaken to identify the types and amounts of admixture(s) needed to reduce Alkali-silica reactivity (ASR) expansion in new concrete made with reactive New Hampshire aggregates. The Phase 1 study found that twenty-five percent of the New Hampshire concrete aggregates tested under ASTM C1260-94 are potentially reactive (0.1% or greater elongation at 14 days) and identified ASR in over 40 percent of the concrete cores taken from existing bridge structures throughout the state.

The objectives of the Phase 2 research were the following:

- Evaluate different admixtures for their effectiveness in mitigating the development of ASR in new concrete in New Hampshire through ASTM C1260-94 accelerated mortar bar testing.
- Verify the minimum amounts of admixture(s) needed to reduce ASR expansion (to less than 0.1% at 14 days) in new concrete made with reactive NH aggregates
- Evaluate both mineral and chemical admixture(s) to include Fly Ash, Ground Granulated Blast Furnace Slag (GGBF) and Silica Fume
- Evaluate the ability of blended cement, ternary cement and high-reactivity metakaolin (HRM) to control expansion due to alkali-silica reaction (ASR)
- Conduct petrographic thin section analysis on mortar bars of selected Portland Cement Concrete (PCC) mixes to confirm the mitigation of Alkali-Silica Reactivity at the microscopic level

The Phase 2 research utilized the ASTM C1260-94 accelerated mortar bar test to identify the amounts of admixture(s) needed to reduce expansion in new concrete in New Hampshire to less than 0.1% elongation at 14 days. Several of the more highly reactive concrete aggregates in New Hampshire were utilized in the PCC mixes for the mortar bars. The research demonstrated that both chemical and mineral admixture(s), some combinations of admixtures, blended cement, ternary cement and high reactivity metakaolin (HRM) all have the ability to control (less than 0.1% elongation at 14 days) Alkali-Silica Reactivity in new concrete made with New Hampshire reactive aggregates. The development of ASR was not effectively mitigated with the admixture of silica fume when utilizing the ASTM C1260-94 test method. Petrographic thin section analysis on mortor bars from selected PCC mixes confirmed the ability of these products to mitigate the development of Alkali-Silica Reactivity (ASR).

17. Key Words

Alkali-silica reactivity, cement, expansion, ASR, mortar bar, potentially reactive, admixtures, elongation, mitigation
fly ash, ground granulated blast furnace slag, silica fume, blended cement, ternary, metakaolin

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MITIGATION OF ASR IN NEW CONCRETE IN NH – PHASE 2

EXECUTIVE SUMMARY

The second phase of the alkali-silica reactivity (ASR) research utilized the ASTM C1260-94 accelerated mortar bar test to identify the amounts of admixture(s) needed to reduce expansion in new concrete in New Hampshire to less than 0.1% elongation at 14 days. Several of the more highly reactive concrete aggregates in New Hampshire were utilized in the tested portland cement concrete (PCC) mixes. Chemical and mineral admixture(s), some combinations of admixtures, blended cement, ternary cement and high reactivity metakaolin (HRM) were shown to significantly reduce alkali-silica reactivity (ASR) expansion in new concrete made with reactive New Hampshire aggregates. ASR expansion was not effectively mitigated with the admixture of silica fume and blended cement was not successful in reducing expansion below 0.1% in mixes with the more highly reactive aggregates. Petrographic thin section analysis on mortar bars from selected PCC mixes confirmed the ability of these products to mitigate the development of ASR at the microscopic level.

INTRODUCTION

The Phase 1 alkali-silica reactivity (ASR) research *(1)* identified that 25 percent of the concrete aggregates in New Hampshire are potentially reactive (0.10% or greater elongation at 14 days) and that deleterious ASR expansion is present in a number of the existing New Hampshire Department of Transportation (NHDOT) concrete structures. The presence of expansive ASR gel within mortar bars made from potentially reactive aggregates was confirmed through petrographic thin section analysis (Photos 1 through 4). The uranyl acetate UV-light method confirmed the presence of ASR gel in varying amounts in many of the existing NHDOT bridges. Thin section analysis of the concrete cores taken from selected bridges verified the existence of expansive ASR gel at the microscopic level.

The rock types of the aggregates that tested potentially reactive in New Hampshire were identified as granite, rhyolite, quartzite, granitic gneiss, gneiss, amphibolite, phyllite and schist. In most cases, microcrystalline quartz was the constituent that contributed to the reactivity. The highest concentrations of reactive aggregates were generally along the Connecticut River Valley and the southern third of the state. However, based on the bedrock geology in New Hampshire, reactive aggregates could be encountered anywhere in the state.

ASR induced distress has resulted in costly repairs for some structures and has significantly reduced the service life of others. Construction costs for new concrete structures have risen significantly. Repairs to existing concrete structures can be expensive and difficult to execute. Mitigating the development of ASR in new concrete would extend the useful life of many concrete structures and could potentially result in significant long-term cost savings for the NHDOT.

There are a variety of ASR mitigation techniques for new cement that have been specified by other Transportation Agencies and organizations *(2)*. These procedures include the requirement to use low-alkali cement (less than 0.6% Na_2O equivalent alkali content), replacement of part of the cement with Class F fly ash, replacement of part of the cement with ground granulated blast-furnace slag (GGBFS), or a combination of fly ash and slag. Silica fume cement replacement, the addition of lithium salts, blended cement, ternary cement and partial replacement of cement by high-reactivity metakaolin (HRM) have also been utilized.

OBJECTIVES

The objectives of this research were the following:

1. Evaluate different admixtures for their effectiveness in mitigating the development of ASR in new concrete in New Hampshire through ASTM C1260-94 *(3)* accelerated mortar bar testing.

2. Verify the minimum amounts of admixture(s) needed to reduce ASR expansion (to less than 0.1% at 14 days) in new concrete made with reactive New Hampshire aggregates.

3. Evaluate both mineral and chemical admixture(s) to include Fly Ash, Ground Granulated Blast Furnace Slag and Silica Fume.

4. Evaluate the ability of blended cement, ternary cement and high-reactivity metakaolin to control expansion due to alkali-silica reactivity.

5. Conduct petrographic thin section analysis on mortar bars of selected Portland Cement Concrete mixes to confirm the mitigation of ASR at the microscopic level.

MATERIALS

The chemical composition of the cements, the admixtures, the blended cement, the ternary cements and the HRM used in this research study are presented in Table 1. Type II Portland cement with a total alkali content of 0.55% was used as the standard cement. The standard aggregate utilized throughout the research study had a 14-day expansion of 0.074% and was a manufactured, fine concrete aggregate composed primarily of gneiss and granite. The known reactive aggregates used for this research included a fine concrete aggregate from Lebanon, NH, a coarse concrete aggregate from Westmoreland, NH, and both fine and coarse aggregates from Columbia, NH (Table 2). The ASTM C1260 test method focused primarily on the Lebanon fine aggregate. Based on C1260 accelerated mortar bar testing conducted during the Phase I ASR study, this aggregate material was identified as one of the most reactive aggregates in New Hampshire. It was assumed that the admixture replacement levels sufficient to mitigate ASR with this aggregate would be effective in mitigating ASR problems with other less reactive aggregates in the state. The percent of expansion at 14-days ranged from 0.150% to 0.290% for the reactive aggregates utilized in this study.

Fly Ash, GGBFS, Silica Fume, blended cement, ternary cements and HRM were evaluated in this study for their effectiveness in mitigating the development of ASR in Portland Cement Concrete made with reactive New Hampshire aggregates. The ASTM C1260 test method is not considered appropriate for evaluating the effectiveness of lithium compounds, therefore lithium admixtures were not tested in this study *(4,5,6)*.

The alkali content of the cement is not suppose to have any influence on the results of the mortar bar expansion tests, but some studies have indicated there may be exceptions *(7)*. Therefore, both low and high alkali cements (1.17% total Na_2O equivalent content) were utilized with different levels of admixtures as a comparison.

TEST PROCEDURES (METHODOLOGY)

This research utilized the ASTM C1260 accelerated mortar bar test method to evaluate the ability of different admixtures to mitigate the development of ASR in PCC mixes made with known reactive aggregates from New Hampshire. The C1260 test method has been found to be a good indicator of pozzolan or slag cement replacement levels to sufficiently mitigate ASR in new concrete *(4,8,9)*. The C1260 accelerated mortar bar test is generally considered severe, but is typically utilized for its quick results and its ability to identify slow reacting aggregates. A test series consisted of three sample aggregates with a non-reactive standard aggregate and two reactive test aggregates. Each sample aggregate test consisted of four 1” x 1” x 11.25” mortar bars. The mortar bars for each aggregate sample were immersed in 1N sodium hydroxide solution in individual containers. The three containers were placed in a water bath to maintain the storage temperature at 80 degrees centigrade during the test period. Admixtures were tested over a range of replacement levels to determine the minimum amount required to limit expansion in PCC mixes with reactive aggregates to less than 0.10% at 14 days. In addition, some admixtures were tested with both low and high alkali cements. A total substitution of the standard cement was made when testing blended and ternary cements.

A polarized-light microscope was used to conduct a petrographic analysis on selected mortar bars to confirm the mitigation of ASR at the microscopic level. Standards utilized as a guide in the petrographic examinations included Petrographic Methods of Examining Hardened Concrete *(10)*, Standard Guide for Petrographic Examination of Aggregates for Concrete ASTM C295-98 *(11)* and Standard Practice for Petrographic Examination of Hardened Concrete ASTM C856-95 *(12)*.

RESULTS AND DISCUSSION

A 20% class F fly ash cement replacement reduced the ASTM C1260 expansion to below 0.1% for PCC mixes made with either low or high alkali cement and the highly reactive Lebanon aggregate. A 20% Class F fly ash cement replacement with the Lebanon aggregate resulted in a reduction in the ASR expansion of 80% and 77% for PCC mixes made with low and high alkali cements, respectively (figures 1 and 2). A 15% Class-F fly ash cement replacement successfully mitigated ASR in a mix made with a less reactive aggregate from Columbia, NH. The CaO content of the Class F fly ash utilized in this research was 4.1%.

A 35% Class C fly ash cement replacement reduced the AASTM C1260 expansion to below 0.1% for PCC mixes made with high alkali cement and the highly reactive Lebanon aggregate. Class C fly ash cement replacement levels of 20% and 25% resulted in 14-day expansions of 0.178% and 0.154%, respectively (figure 3). The CaO content of the Class C fly ash was 26.4%, significantly higher than the CaO content in the Class F fly ash. Class C fly ashes typically contain 10% to 40% CaO by mass and usually require higher dosages by mass of concrete than Class F fly ashes to mitigate ASR.

It is common practice for organizations to specify 15 to 25% fly ash cement replacement as part of their standard PCC specifications *(2)*. The lime content changes the effectiveness of the fly ash to mitigate ASR. A higher CaO content in admixtures tends to increase the occurrence of ASR *(13)*. Many organizations restrict the maximum CaO content of fly ash to 8% or less.

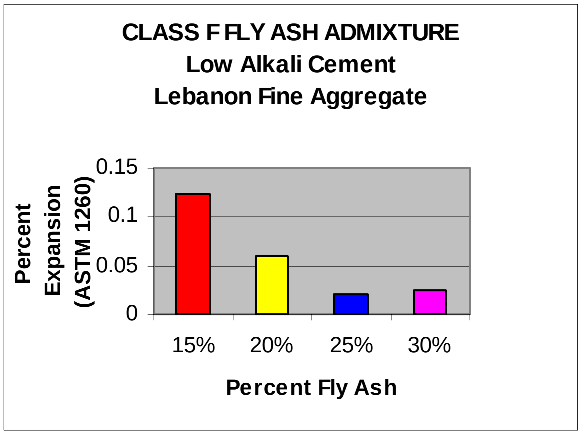

Figure 1 - Percent expansion vs. class F fly ash content (Low alkali cement).

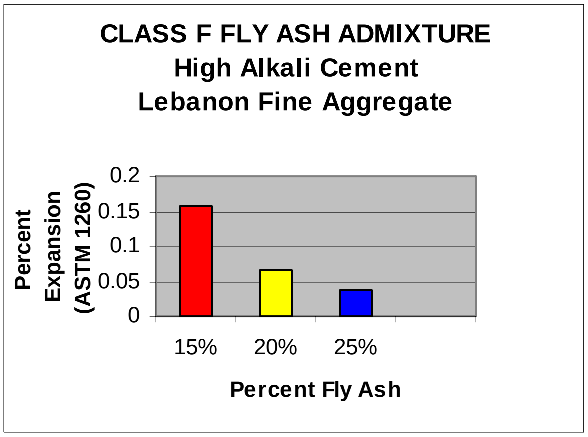

Figure 2 – Percent expansion vs. class F fly ash content (High alkali cement)

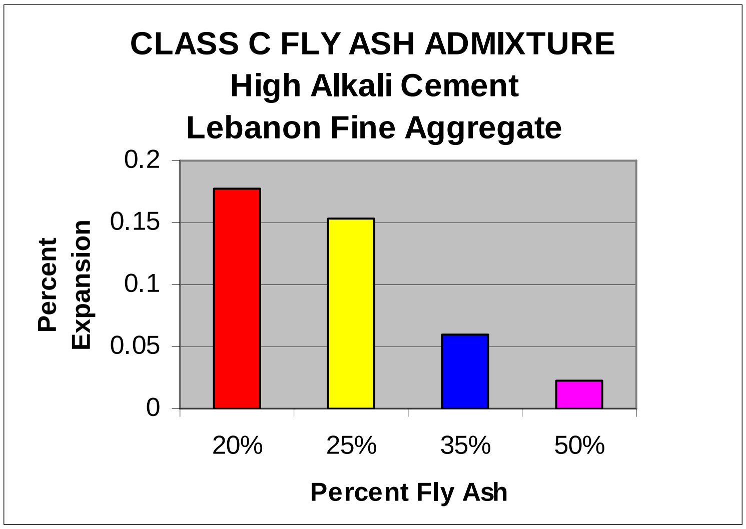

Figure 3 – Percent expansion vs. class C fly ash content

A 50% Ground Granulated Blast-Furnace Slag (GGBFS) cement replacement was successful in reducing the ASTM C1260 expansion to below 0.1% for Portland Cement Concrete made with the Lebanon aggregate and low alkali cement. A 50% GGBFS cement replacement reduced ASR expansion by 67% and 59% in PCC mixes (Lebanon aggregate) with low and high alkali cements, respectively (figures 4 and 5). A 60% GGBFS cement replacement was needed to successfully mitigate ASR when utilizing high alkali cement with the Lebanon aggregate (figure 5). Mixes with less reactive aggregates only required a 40% GGBFS cement replacement to successfully mitigate ASR.

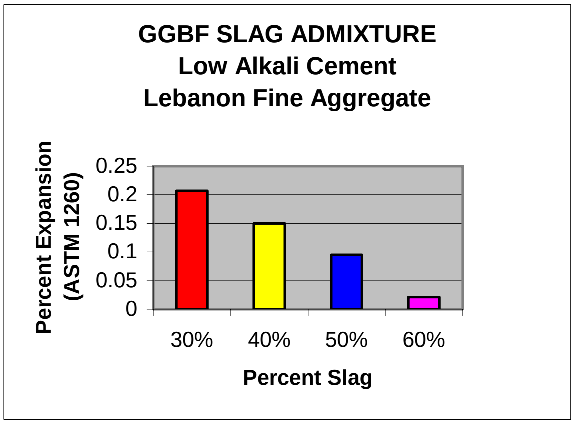

Figure 4 – Percent expansion vs. slag content (Low alkali cement)

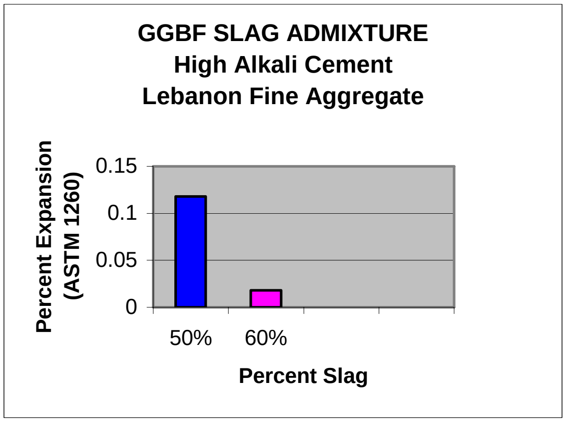

Figure 5 – Percent expansion vs. slag content (High alkali cement)

Silica fume cement replacement at amounts ranging from 4 to 15% with the Lebanon aggregate resulted in an increased expansion, rather than a decrease (figure 6). It has been stated that if silica fume is not evenly dispersed in the cement mix, it can react with the alkali in the cement to induce ASR *(13)*. It is suspected that this may be the reason for the increase in expansion observed in the tests.

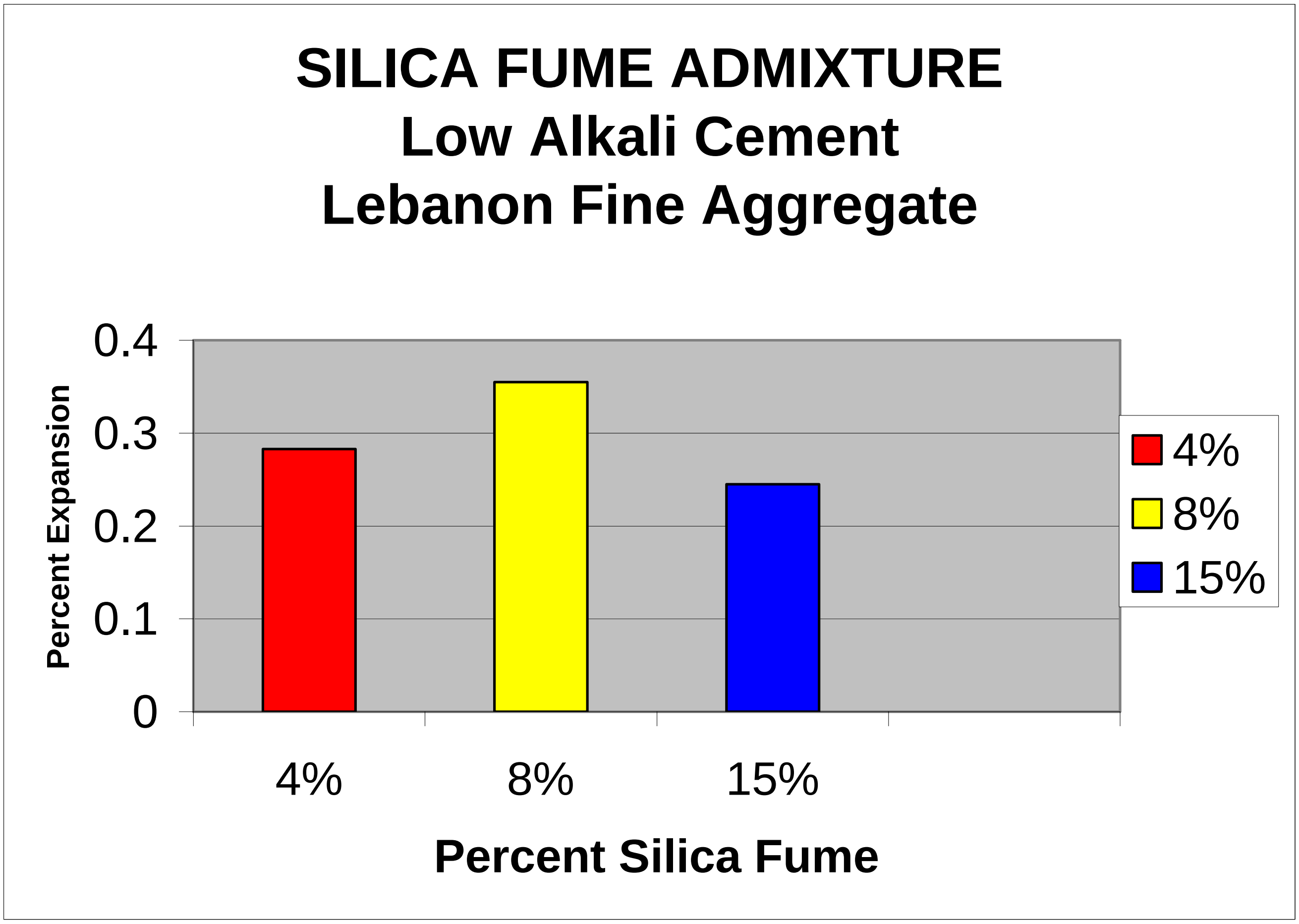

Figure 6 – Percent expansion vs. silica fume content (Low alkali cement)

Several combinations of silica fume with fly ash or slag were tested. Only the combination consisting of 4% silica fume and 20% fly ash was successful in reducing the 14-day expansion to below 0.1% with the Lebanon aggregate. The reduction in the ASR expansion for this combination was 84%. Blended silica fume cement did not adequately reduce expansion in PCC mixes with the highly reactive Lebanon aggregate, but was successful in mitigating ASR when used with the less reactive Columbia fine aggregate. Two commercially produced ternary cements were tested with the Lebanon aggregate and the less reactive Columbia aggregate. The reduction in the ASR expansion with the ternary cements ranged from 78% to 92 % (figure 7). The ternary cements were successful in mitigating ASR expansion and reducing the elongation of the mortar bars below 0.1% at 14-days.

Metakaolin as a cement replacement was tested in mixes utilizing the Lebanon aggregate *(14)*. A reduction in the ASR expansion with a 15% metakaolin cement replacement was 89% and 85% for low and high alkali cements, respectively (figure 7).

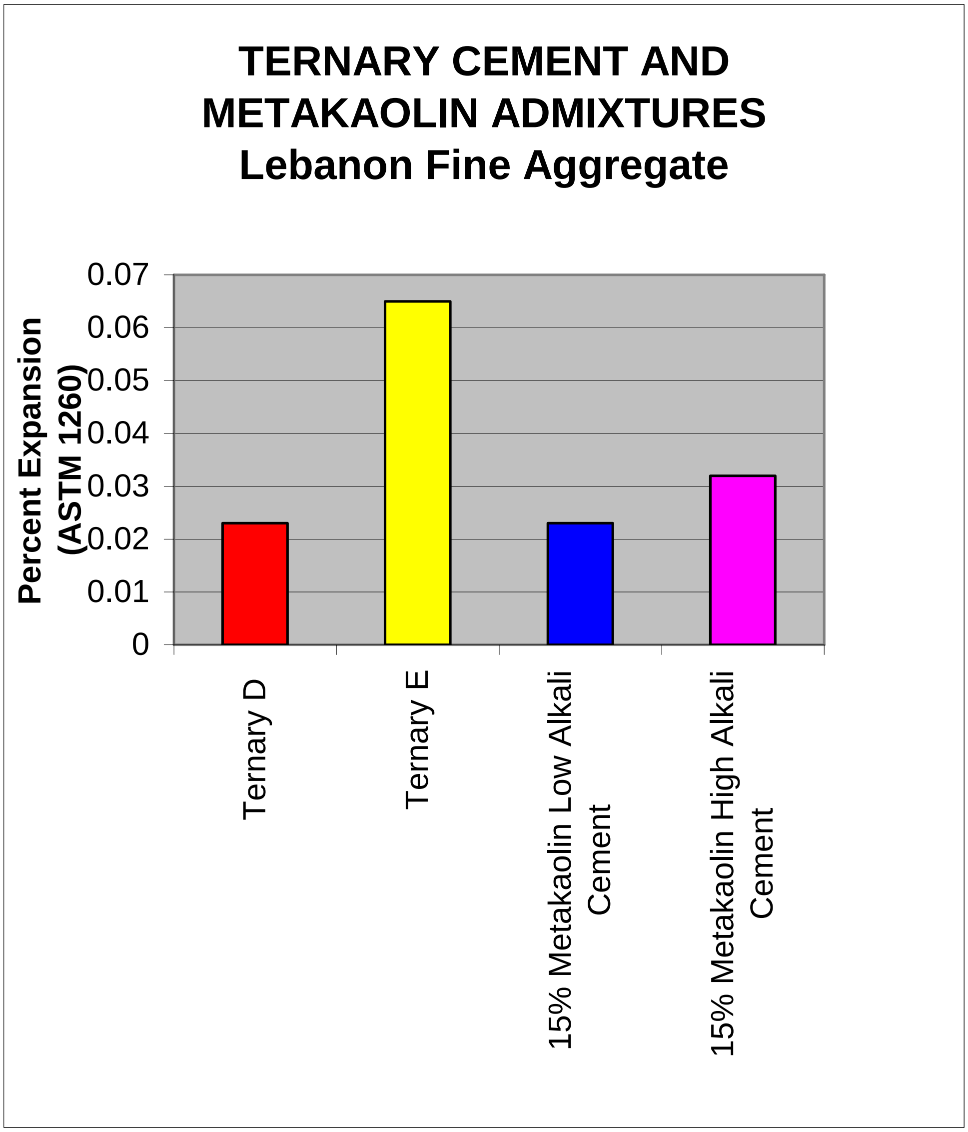

Figure 7 – Percent expansion vs. ternary cements and 15% metakaolin content (Low and high alkali cements)

The alkali content of the cement is supposed to have very little to no effect on the mortar bar expansion when using the ASTM C 1260 accelerated immersion test method *(13)*. There is disagreement in research conducted by others on the effect of the alkali content of cements on mortar bar expansion when using the ASTM

C 1260 test method. A study conducted by Rangaraju and Sampura indicated that alkali content of cement has a distinct influence on the expansion levels observed in the ASTM C1260 test method *(7).*
In our study, when comparing the PCC mixes made with the same level of admixtures and the same aggregates, in most cases there was a slight increase in expansion with the higher alkali cement (figure 8). The only exception was PCC mixes made with 60 % slag as an admixture. When GGBF was used as an additive at 60 % replacement there was a slight decrease in expansion with the higher alkali cement in comparison to the low alkali cement.

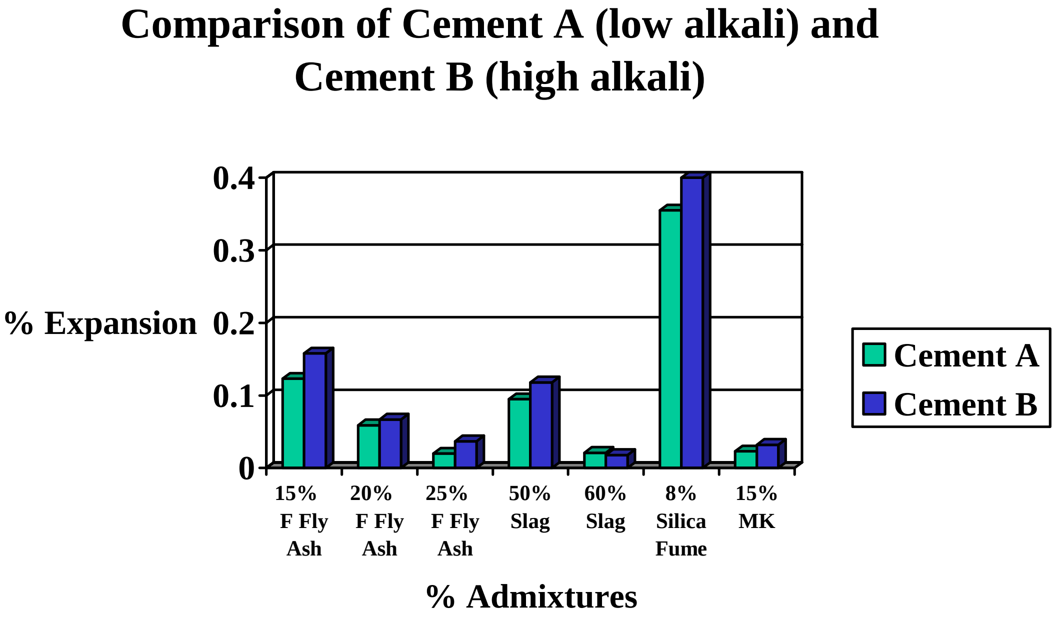

Figure 8 – Percent expansion of mortar bar (ASTM 1260) with reactive aggregate and different amounts of admixtures at 14 days for low and high alkali cements.

CONCLUSIONS AND RECOMMENDATIONS

The ASTM C1260 accelerated mortar bar testing and petrographic thin section analysis (Photos 5 through 8) have shown that ASR expansion in portland cement concrete made with New Hampshire reactive aggregates can be successfully mitigated with admixtures. Cement replacement of 20% Class F fly ash or 50 % GGBF slag with low alkali cement reduced the expansion of the mortar bars to less than 0.1% at 14-days. Our research showed that both the ternary cements and 15% cement replacement with metakaolin were effective in mitigating ASR. Research by others has shown that the use of metakaolin as a cement replacement admixture can result in a significant reduction in expansion *(14)*. The silica fume blended cement when used with the less reactive Columbia fine aggregate was successful in reducing expansion below 0.1%. When silica fume blended cement was used with the highly reactive Lebanon aggregate it reduced the expansion, but not below the 0.1% level. The replacement of cement with silica fume, ranging from 4 to 15%, actually increased the expansion in mixes made with the highly reactive Lebanon aggregate. This may have been due to poorly mixed and undispersed grains of silica fume that reacted with the alkalis in the cement.

Cement replacement levels at 15 to 40% for class F fly ash and at 25 to 70% for GGBFS are typically used by the industry for mitigating ASR or for improving certain properties of the cement *(13,15).* The amount of cement replacement by admixtures to mitigate ASR in New Hampshire is within the limits typically utilized by other DOT’s and organizations. It required a substantially higher dosage (35%) of class C fly ash to mitigate the same reactive aggregate.

The type of fly ash, its total alkali content, the chemical composition and the amount added to the concrete mix all have an impact upon the effectiveness in controlling ASR expansion *(4)*. Class F fly ashes that meet the requirements in ASTM C 618 *(16)* are generally more effective in mitigating expansive reactivity than Class C fly ashes. In general, Class F fly ashes have higher silicon dioxide and lower lime contents, which improve the ability to control expansive ASR *(4)*. Although Class C fly ashes have some similar advantages to Class F fly ashes, they often do not reduce or in some cases have aggravated the ASR problem. Even in cases where Class C fly ash has mitigated ASR, it has required higher dosages by mass of cementing material (30% or higher). If the amount of fly ash used exceeds 25% by mass, the concrete becomes susceptible to scaling. Class C fly ashes typically contain 10 to 40% CaO by mass. Therefore, Class C fly ash should not be utilized as an admixture for mitigating ASR in PCC *(13)*. The physical and chemical requirements in both ASTM C 618 *(16)* and ASTM C 311 *(17)* should be specified for fly ashes used to control ASR. In summary, the fly ash should have a maximum 1.5% available alkali, a maximum 6% loss on ignition and a maximum 8% CaO content *(13)*.

Some admixtures can have beneficial effects in portland cement when used in certain amounts. Both fly ash and GGBF slag can increase the long-term strength of concrete. In contrast to the beneficial effects, there is a risk of adverse effects if the cement admixture replacement levels are too low. The required minimum admixture level when using class F fly ash can also be influenced by the CaO content. A CaO content of 8% or less has been specified by some agencies. Higher CaO content results in greater expansion. Depending on the amount of CaO, the minimum fly ash replacement level could range between 25 and 30%. There is a similar effect with ground granulated blast furnace slag. A 40% minimum GGBFS cement replacement has been recommended by some organizations. Another factor to consider is the potential problem with deicer salts. The susceptibility of concrete structures to salt scaling can increase, if the cement replacement levels exceed 25% for fly ash and 50% for GGBFS *(13)*. The minimum levels of fly ash or slag needed to mitigate ASR for most aggregates in New Hampshire seem to fall within a range that avoids the increased expansion caused by low replacement levels of these admixtures and the deicer salt scaling problem caused by admixtures levels that are too high.

Although the alkali content of the cement should not influence the expansion of mortar bars during the ASTM C 1260 test, PCC mixes made with high alkali cement often resulted in higher expansion than the same mixes with low alkali cement. In most cases, higher levels of admixtures were required to successfully mitigate ASR in PCC mixes made with the higher alkali cement.

The use of low alkali cement (Na_2O equivalent alkali content less than 0.6%) to mitigate ASR in New Hampshire is not considered a viable option. Most of the cements available in this region have high alkali content. In addition, NHDOT research indicates using low alkali cement alone may not effectively mitigate the development of ASR.

Lithium compound admixtures have been shown to be effective in mitigating ASR *(18)*. Lithium nitrate ($LiNO_3$) is the preferred compound because it is safe to handle. The ASTM C1260 accelerated mortar bar test has been shown not to be a suitable method in assessing the ability of lithium compounds to reduce expansion due to ASR *(4,5)*. Therefore, lithium compounds were not evaluated in this research study.

The type of aggregate and the alkali level in the concrete, both affect the minimum levels of admixtures needed to successfully mitigate ASR. Based on the research findings, cement replacement with Class F fly ash may be the most effective and cost beneficial method for the NHDOT to mitigate ASR in new concrete. In addition to mitigating ASR, there is a potential cost savings and an increase in the long-term strength of the concrete when utilizing Class F fly ash as a cement replacement. The GGBFS cement replacement levels to mitigate ASR in the state's most reactive aggregates is at a level that may result in scaling problems. It is recommended that other admixtures be utilized in lieu of GGBFS replacement levels of 50% or higher. Both ternary cements and metakaolin were found to be effective in mitigating ASR in new concrete made with reactive New Hampshire aggregates.

IMPLEMENTATION PLAN

Equipment purchased under both the Phase 1 and Phase 2 research studies will need to be maintained and upgraded as necessary to continue in house ASR testing capability. A NHDOT specification shall be written stating the minimum amounts of admixtures to be used in new concrete mixes that utilize reactive aggregates.

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APPENDIX A – TABLES

TABLE 1 Chemical composition of cements and admixtures

Oxide Analysis	Cement A (Type II) Standard %	Cement B (Type II) High Alkali %	Cement C Blended %	Cement D Ternary %	Cement E Ternary %	Cement F (Type III) High Alkali %	Class F Fly Ash %	Class C Fly Ash %	Slag %	Silica Fume %	HRM %
SiO_2	21.7	20.3	25.5	35.6	25.8	23.3	55.4	30.4	36.1	94.7	7.4
Al_2O_3	4.5	5.2	4.9	6.2	6.3	2.5	14.0	22.9	10.7	0.4	47.0
Fe_2O_3	3.2	2.6	2.2	2.8	1.5	2.3	3.1	5.91	1.2	0.09	0.19
MgO	3.3	3.3	2.3	1.8	5.4	3.9	0.8	4.79	5.5	0.04	0.03
SO_3	3.1	3.3	3.6	3.6	3.1	3.3	1.3	2.26	0.7	0.22	0.14
CaO	64.8	61.9	59.6	46.3	54.7	61.8	4.1	26.4	41.2	0.31	0.025
K_2O	0.43	1.3	0.9	0.81	0.83	1.6	0.35	0.39	0.28	0.13	0.42
Na_2O	0.27	0.30	0.23	0.02	0.03	0.28	0.21	0.49	0.25	0.07	0.29
SrO	0.09	-----	-----	0.07	0.16	0.04	-----	0.34	-----	-----	0.01
Mn_2O_3	0.03	0.08	0.06	0.05	0.29	0.14	0.01	0.026	0.32	0.01	------
ZnO	0.01	0.02	0.01	0.03	0.02	0.02	0.01	0.03	.003	0.07	0.003
Cr_2O_3	0.04	0.01	0.01	0.01	0.01	0.003	0.01	0.01	0.01	0.004	0.003
Ignition Loss	1.17	1.16	1.67	2.14	1.24	0.89	1.77	0.61	1.05	2.90	1.01
Insoluble Residue	0.18	0.28	2.13	2.14	1.53	0.89	70.15	21.46	0.37	31.6	34.59
Na_2O Eq	0.55%	1.17%	0.83%	0.55%	0.57%	1.33%	0.44%	0.74%	0.43%	0.15%	0.57%

TABLE 2 Percent expansion of mortar bars with reactive aggregates at 14-days

Type of Aggregate	Source	% Expansion at 14-days
Amphibolite/gneiss/meta-rhyolite (fine)	Lebanon, NH	0.290%
Quartzite/amphobolite/gneiss/phyllite (coarse)	Westmoreland, NH	0.179%
Phyllite/schist (fine) Phyllite/schist (coarse)	Columbia, NH Columbia, NH	0.193% 0.150%

TABLE 3-A Percent expansion of mortar bars with reactive aggregate and different amounts of admixtures at 14-days (Lebanon, NH – fine)

Cement	% Admixture(s)	% Expansion at 14-days
Cement A (low alkali)	15% Fly ash	0.123%
Cement A (low alkali)	20% Fly Ash	0.059%
Cement A (low alkali)	25% Fly Ash	0.020%
Cement A (low alkali)	30% Fly Ash	0.024%
Cement B (high alkali)	15% Fly Ash	0.158%
Cement B (high alkali)	20% Fly Ash	0.067%
Cement B (high alkali)	25% Fly Ash	0.037%
Type III	25% Fly Ash	0.049%
Cement B (high alkali)	20% Class C Fly Ash	0.178%
Cement B (high alkali)	25% Class C Fly Ash	0.154%
Cement B (high alkali)	35% Class C Fly Ash	0.060%
Cement B (high alkali)	50% Class C Fly Ash	0.022%
Cement A (low alkali)	30% Slag	0.207%
Cement A (low alkali)	40% Slag	0.150%
Cement A (low alkali)	50% Slag	0.095%
Cement A (low alkali)	60% Slag	0.021%
Cement B (high alkali)	50% Slag	0.118%
Cement B (high alkali)	60% Slag	0.018%
Type III	50% Slag	0.055%
Cement A (low alkali)	4% Silica Fume	0.283%
Cement A (low alkali)	8% Silica Fume	0.355%
Cement A (low alkali)	15% Silica Fume	0.245%
Cement B (high alkali)	8% Silica Fume	0.410%
Cement A (low alkali)	4% Silica Fume/15% Fly Ash	0.142%
Cement A (low alkali)	4% Silica Fume/20% Fly Ash	0.046%
Cement A (low alkali)	4% Silica Fume/30% Slag	0.248%
Cement C (blended)	NA	0.119%
Cement D (ternary)	NA	0.023%
Cement E (ternary)	NA	0.065%
Cement A (low alkali)	15% metakaolin	0.023%
Cement B (high alkali)	15% metakaolin	0.032%

Note: Red indicates 14-day mortar bar expansions of 0.1% or greater.

TABLE 3-B Percent expansion of mortar bars with reactive aggregate and different amounts of admixtures at 14-days (Columbia, NH – fine)

Cement	% Admixture(s)	% Expansion at 14-days
Cement B (high alkali)	20% Fly Ash	0.040%
Cement B (high alkali)	40% slag	0.073%
Cement C (blended)	NA	0.072%
Cement D (ternary)	NA	0.015%
Cement E (ternary)	NA	0.041%

TABLE 3-C Percent expansion of mortar bars with reactive aggregate and different amounts of admixtures at 14-days (Columbia, NH – coarse)

Cement	% Admixture(s)	% Expansion at 14-days
Cement A (low alkali)	15% Fly Ash	0.060%
Cement B (high alkali)	15% Fly Ash	0.058%
Cement A (low alkali)	50% Slag	0.028%
Cement B (high alkali)	50% Slag	0.024%

TABLE 3-D Percent expansion of mortar bars with reactive aggregate and different amounts of admixtures at 14-days (Westmoreland, NH – coarse)

Cement	% Admixture(s)	% Expansion at 14-days
Cement A (low alkali)	25% Fly Ash	0.046%
Cement B (high alkali)	25% Fly Ash	0.052%
Cement A (low alkali)	50% Slag	0.006%
Cement B (high alkali)	50% Slag	0.014%

APPENDIX B – PHOTOMICROGRAPHS

MORTAR BAR PHOTOMICROGRAPHS

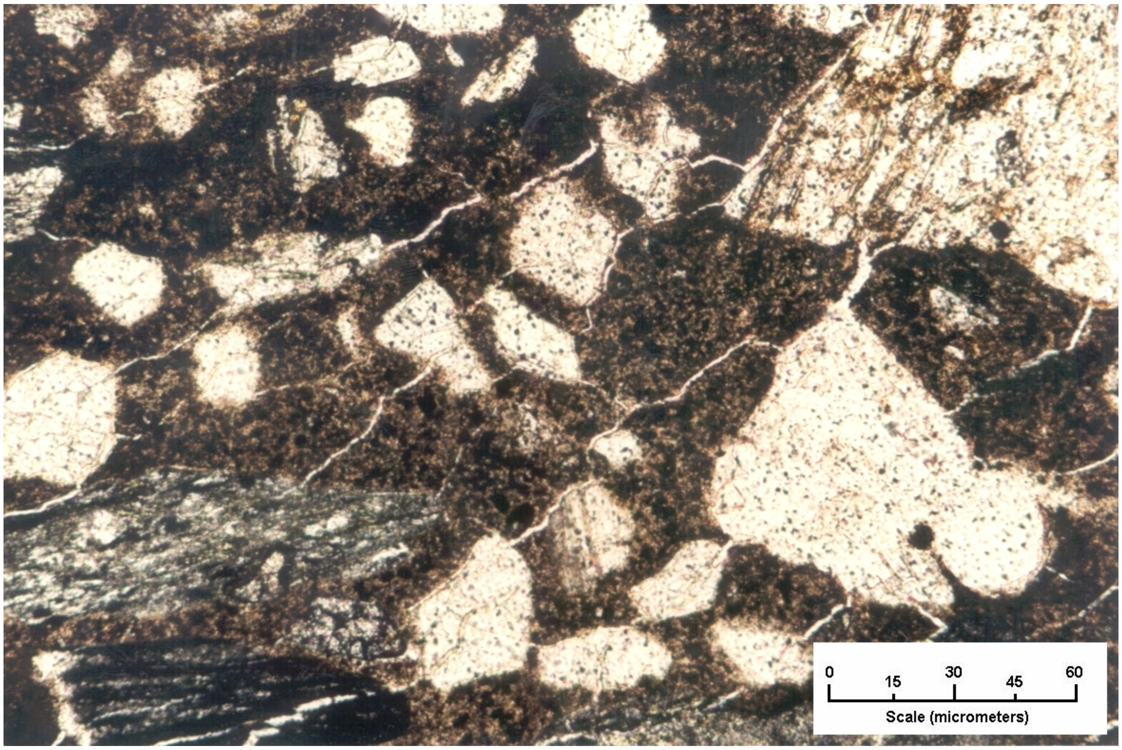

Photo 1 - Micro cracks extending from aggregate particles (igneous and metamorphic rocks), through cement paste and into other aggregate particles, plane light, 50X, fine aggregate, Lebanon, NH (no additives).

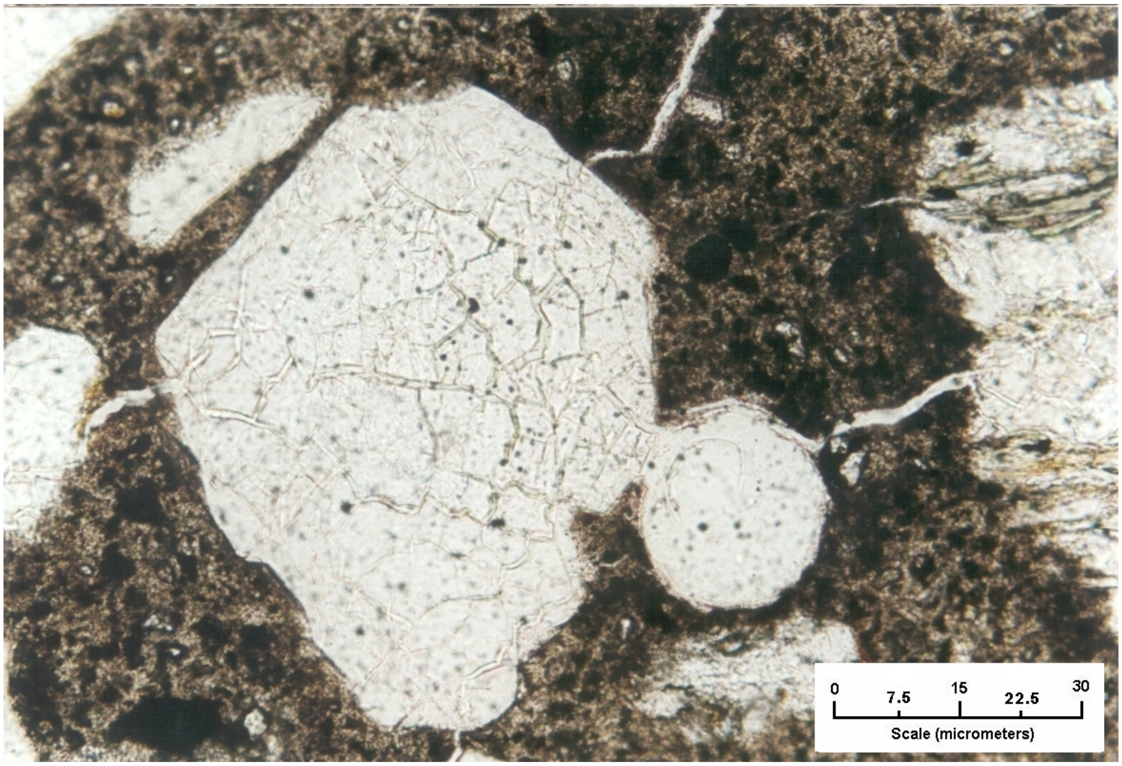

Photo 2 - Micro cracks extending from granite and quartz particles into cement paste, plane light, 100X, fine aggregate, Lebanon, NH (no additives)

MORTAR BAR PHOTOMICROGRAPHS (continued)

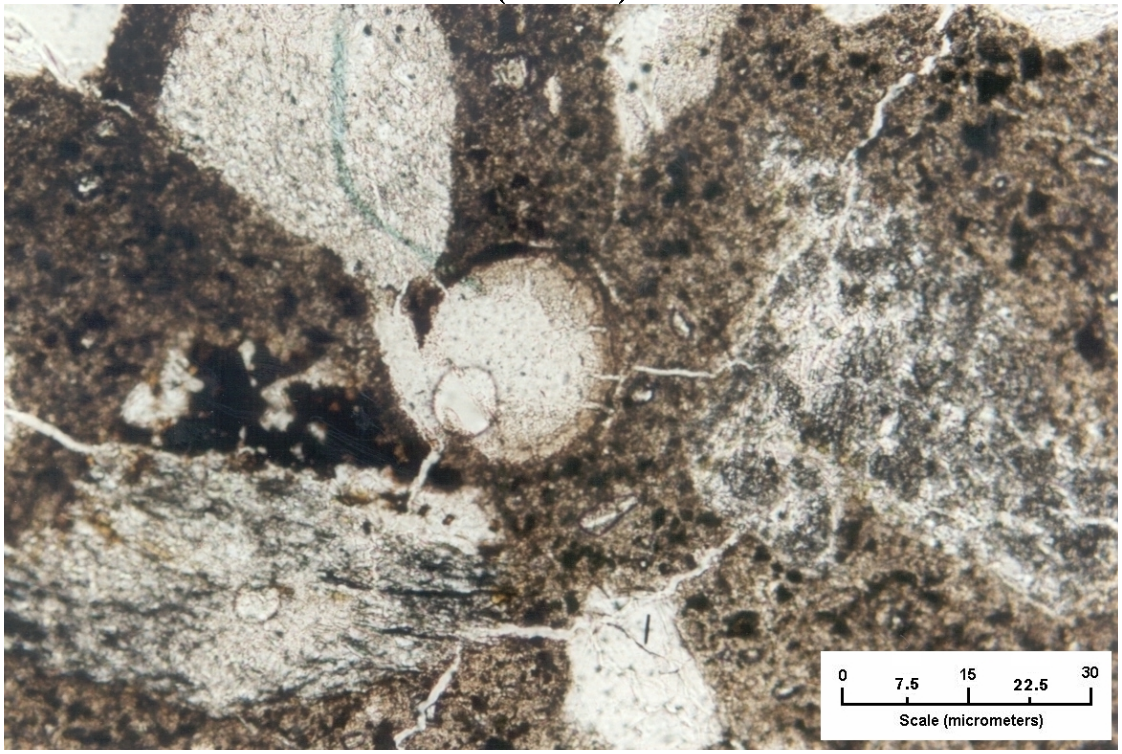

Photo 3 - Micro cracks extending from aggregate particles into cement paste and into ASR gel filled void, plane light, 50X, fine aggregate, Lebanon, NH (no additives).

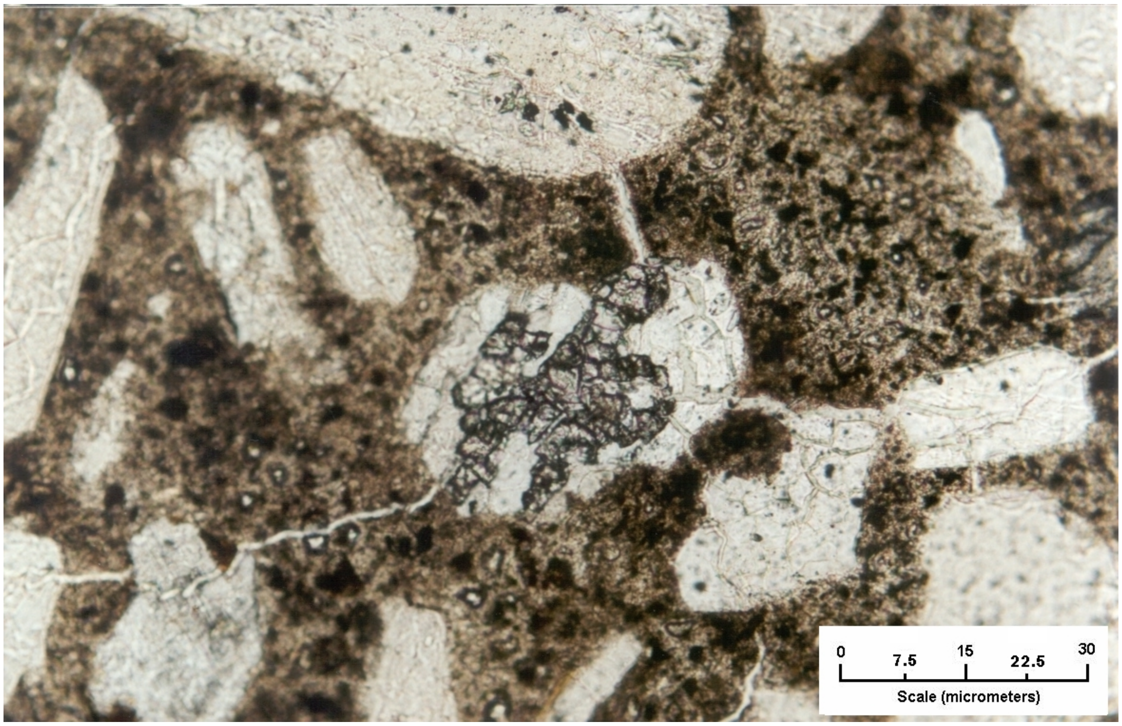

Photo 4 - Micro cracks extending from chemically altered quartz particle, into and through cement paste, into other quartz and granite particles, fine aggregate, Lebanon, NH (no additives).

MORTAR BAR PHOTOMICROGRAPHS (continued)

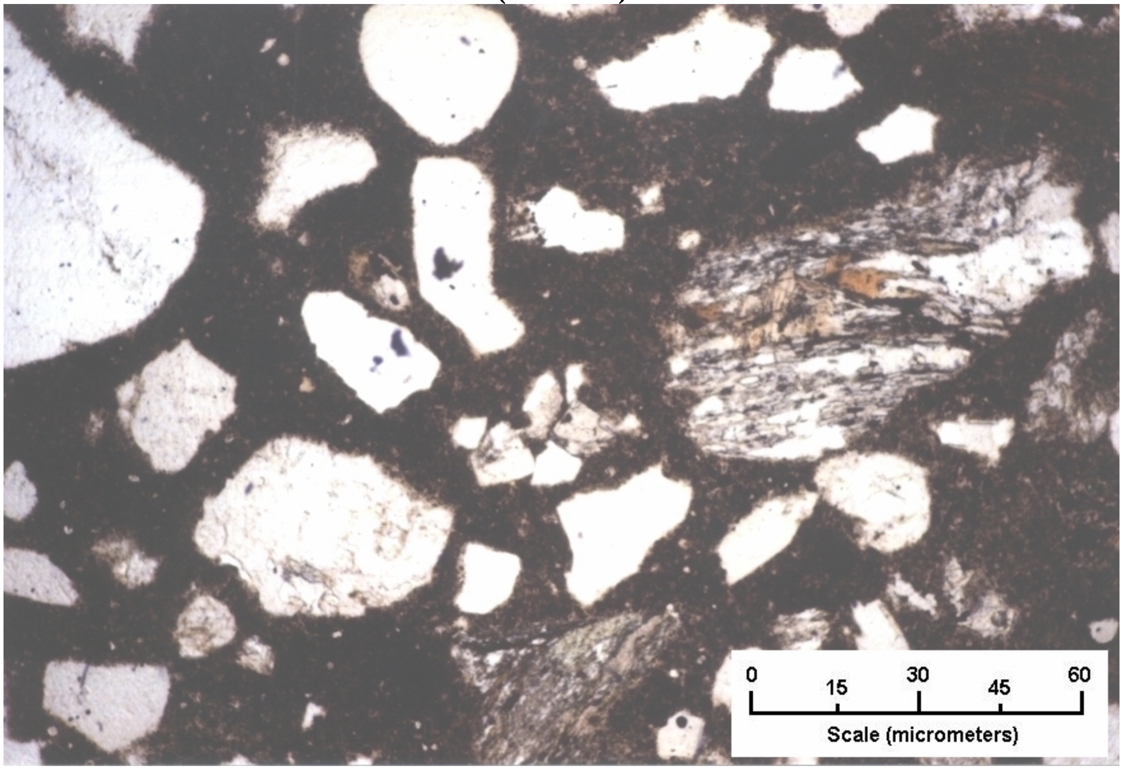

Photo 5 - No micro cracks in aggregate particles or cement paste, plane light, fine aggregate Lebanon, NH (20% Fly Ash)

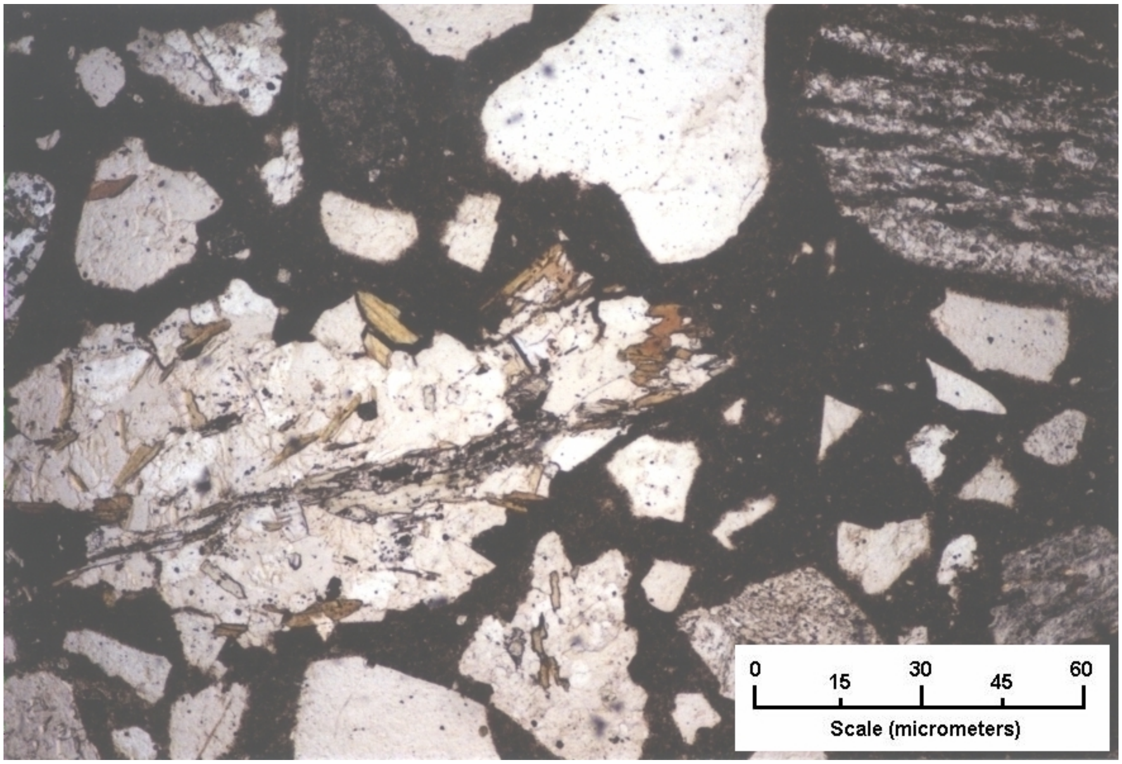

Photo 6 - No micro cracks in aggregate particles or cement paste, plane light, fine aggregate Lebanon, NH (50% Slag)

MORTAR BAR PHOTOMICROGRAPHS (continued)

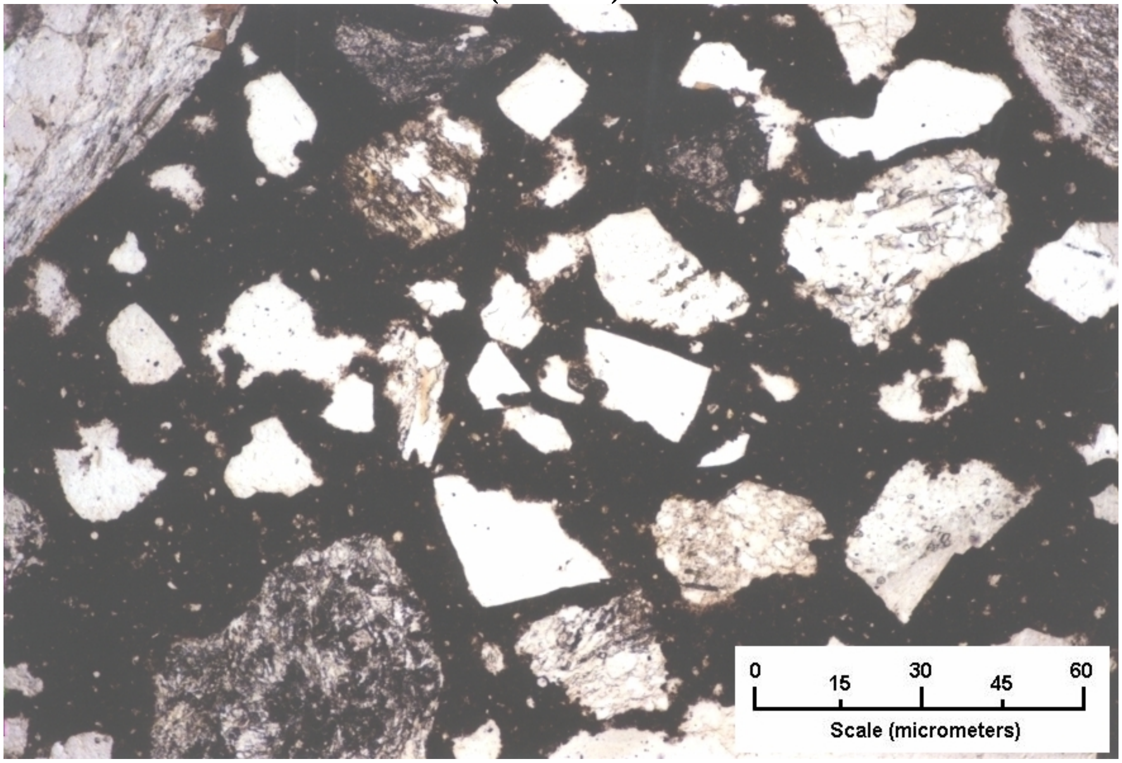

Photo 7 - No micro cracks in aggregate particles or cement paste, plane light, fine aggregate Lebanon, NH (Ternary Cement)

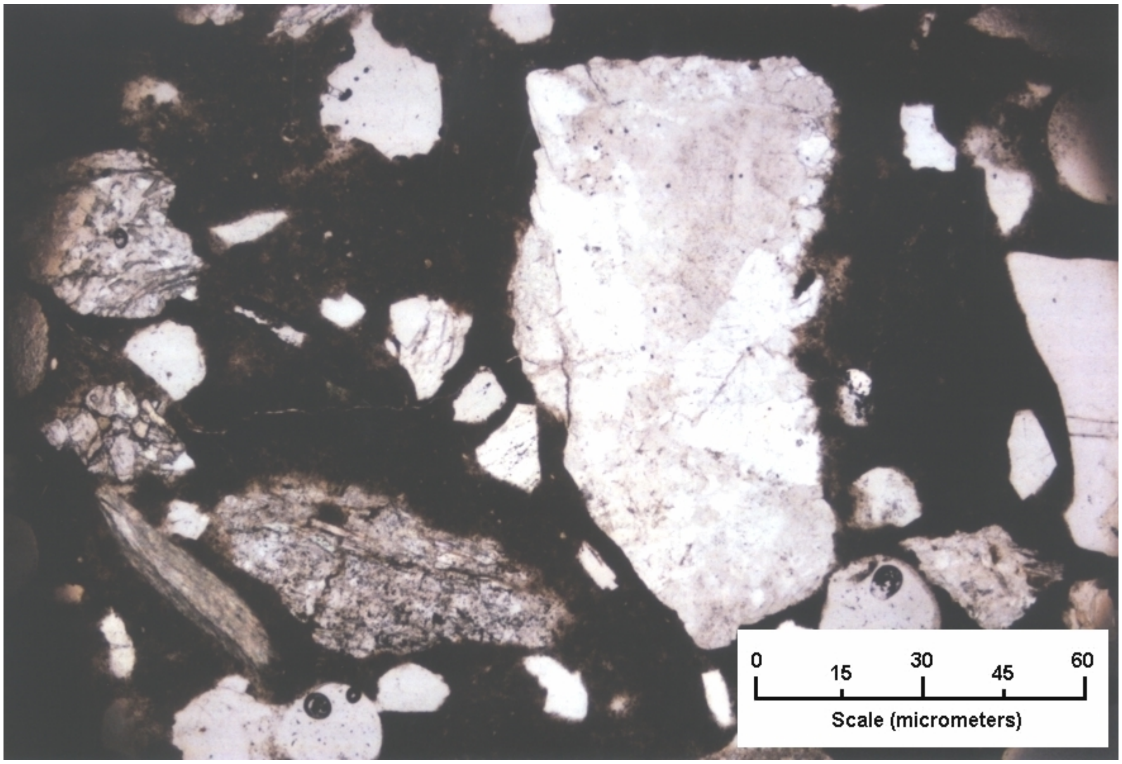

Photo 8 - No micro cracks in aggregate particles or cement paste, plane light, fine aggregate, Lebanon, NH (15% metakaolin)