

A microscopic view of concrete aggregate, showing various sized and colored particles (dark blue, brown, tan) embedded in a light-colored matrix.

**INVESTIGATION OF ALKALI-SILICA
REACTIVITY IN PORTLAND
CEMENT CONCRETE**

**PHASE I
VERMONT AGGREGATE
EVALUATION**



**Vermont Agency of
Transportation
Research, Development and
Technology Transfer Project
RSCH004-910**

1. Report No. FHWA-VT-RD-0301		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle INVESTIGATION OF ALKALI-SILICA REACTIVITY IN PORTLAND CEMENT CONCRETE, PHASE I VERMONT AGGREGATE EVALUATION				5. Report Date NOVEMBER 20, 2003	
				6. Performing Organization Code	
7. Author(s) JAMES R. WILD and THOMAS D. ELIASSEN				8. Performing Organization Report No.	
9. Performing Organization Name and Address VERMONT AGENCY OF TRANSPORTATION NATIONAL LIFE BLDG., DRAWER 33 MONTPELIER, VERMONT 05633				10. Work Unit No.	
				11. Contract or Grant No. RSCH007-910	
12. Sponsoring Agency Name and Address VERMONT AGENCY OF TRANSPORTATION NATIONAL LIFE BLDG., DRAWER 33 MONTPELIER, VERMONT 05633				13. Type of Report and Period Covered	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
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17. Key Words Alkali-Silica Reactivity, ASR, Mortar Bar, Petrographic Analysis, Thin Section, Cement, Expansion, Concrete, Aggregate, cracking.			18. Distribution Statement No Restrictions		
19. Security Classif. (of this report)		20. Security Classif. (of this page)		21. No.of Pages 88	22. Price

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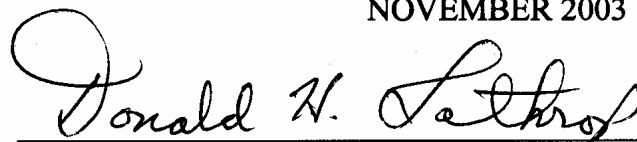
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NOVEMBER 2003

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ACKNOWLEDGEMENT

This project was approved by the Vermont Agency of Transportation Research Advisory Council and was funded as part of the State Planning and Research, Research and Development Work Program in cooperation with the Federal Highway Administration.

The authors would like to thank Chris Rea and Jerry McMahan, VTrans for their aggregate preparation and chemical analysis efforts, Margaret Thompson of Penn DOT for sharing her knowledge and sample slides and especially to Marc Fish and Dick Lane of New Hampshire DOT for their guidance and being there to answer the many questions we have had throughout the project.

TABLE OF CONTENTS

INTRODUCTION.....	1
ASR DEVELOPMENT	2
OBJECTIVES	3
GEOLOGY	3
ASR REACTIVE AGGREGATES	5
STUDY METHODOLOGY.....	5
Aggregate Selection Criteria.....	5
Mortar Bar Testing.....	6
Petrographic Analysis.....	7
RESULTS	8
Mortar Bar Testing.....	8
Petrographic Analysis.....	8
CONCLUSIONS	10
RECOMMENDATIONS.....	10
REFERENCES.....	11

FIGURES

Figure 1 Simplified geologic map of Vermont.....	4
Figure 2 Petrographic Microscope.....	7

TABLES

Table 1 Summary of Sample Properties.....	9
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APPENDICES

APPENDIX A - THIN SECTION SAMPLE PREPARATION
APPENDIX B – AASHTO T303-00 TESTING RESULTS
APPENDIX C - PHOTOMICROGRAPHS
APPENDIX D – MAP SHOWING AGGREGATE SAMPLE SOURCES AND MORTAR BAR EXPANSION VALUES

ABSTRACT

Alkali-silica reactivity (ASR) is of concern world wide and has gained more attention in recent years as a problem to concrete durability. Throughout the State of Vermont, many of our transportation structures show signs of potential ASR activity. Vermont's neighboring states have or are currently investigating ASR and finding it to be wide spread. Given the results of our neighboring states investigations, we suspected that much of the cracking that we are seeing in our structures could be attributed to ASR. The goals of this research were to: 1) Evaluate aggregate from select existing sources for ASR potential in portland cement concrete. 2) Investigate existing structures for presence of ASR. 3) Determine appropriate mitigation or remediation options to prevent further ASR distress in both new and existing structures. This report presents the results of the first phase of study. Eleven coarse aggregate sources were selected for the initial part of this research. Of those selected, five were found to be at or above the suggested percent expansion limit threshold for ASR potential. Petrographic analysis was performed to assess for cracking and gel formations that are characteristic of ASR activity. Based on petrographic analysis, it was found that seven of the eleven sources showed signs of ASR development. Based on conclusions reached in this study recommendations were made that include further screening and initiation of the second phase of the study.

INTRODUCTION

The increasing concern world-wide for alkali-silica reactivity (ASR) in concrete structures has led the State of Vermont to question whether there is an ASR problem related to aggregate used in Agency projects. Nearby states have completed ASR studies and have demonstrated that New England aggregates indeed show the potential for ASR development. In an attempt to assess the susceptibility of Vermont aggregates to the development of ASR a three phased study has been proposed.

The first phase of this study, which is the subject of this report, consists of the evaluation of mortar bars constructed with coarse aggregate from selected locations throughout the state. The mortar bars were subjected to controlled conditions conducive for the development of ASR and measured for elongation after a pre determined time in accordance with AASHTO test method T303-00 (Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica-Reaction). Thin sections

were prepared from the bars and evaluated utilizing a petrographic microscope for signs of ASR development.

The second phase will consist of identifying structures throughout the state that contain aggregate identified in Phase I as potentially reactive and evaluating samples from those structures for the presence of ASR. A third phase will consist of determining appropriate mitigation/remediation options designed to prevent further ASR distress in existing structures constructed with susceptible aggregate and methods to prevent ASR in new concrete.

Prior to this research, the State of Vermont Agency of Transportation had not performed any type of formal testing for ASR. The Agency shares some common concrete aggregate sources with the State of New Hampshire. New Hampshire had previously tested these shared concrete aggregate sources and found that some of them exhibited ASR potential. There are also some concrete aggregate sources that we share with the State of New York. New York has had an ASR program in effect for a number of years and found that some of those shared sources also showed ASR potential. The potential ASR problem is further compounded by the fact that most of the cements that are available in the northeast are higher in alkali than is recommended in AASHTO M85 (Standard Specification for Portland Cement). The use of deicing salts provides an additional potential source of alkali. ASR is not the only factor for decreased concrete durability, but is believed to be a major contributor to the problem.

Construction costs have risen dramatically for new concrete structures. Repairs to existing concrete structures and replacement of unsound structures become increasingly more difficult and costly due to the increased traffic volumes and permit acquisitions. Considering Vermont's commitment to responsible asset management, it has become more important than ever to construct structures that have future volume capacity, durability and design life. An important factor in increasing durability and design life is the mitigation of the ASR distress.

ASR DEVELOPMENT

Alkali-Silica Reactivity is a chemical reaction in which hydroxyl groups liberated from sodium and potassium oxides in solution react with certain susceptible aggregates in concrete to form an alkali-silica gel. This hygroscopic gel swells resulting in expansion of the concrete. The expansion within the concrete leads to the development of cracks which in turn provides increased moisture further accelerating ASR based expansion and the deterioration of the structure.

In order for ASR to develop, three key components must be in place. These components are:

1. The presence of aggregate containing minerals susceptible for the development of ASR,
2. Total alkali content in the concrete greater than 5 pounds per cubic yard, and
3. The presence of sufficient moisture.

Cements that are available in the eastern portion of North America have alkalis that exceed the recommended maximum of 0.60 mg/l along with sufficient available moisture to help drive the reactivity. Moisture is available from direct rainfall (39-44 in/yr) and condensation of atmospheric moisture onto colder concrete structures.

OBJECTIVES

The objectives of this study are to identify possible alkali-silica reactive (ASR) concrete aggregate currently used in Agency structures, evaluate the extent of affected transportation structures by ASR, and recommend remediation actions for existing structures and mitigation options for new concrete. The project tasks were as follows:

1. Screen selected aggregate sources for alkali-silica reaction (ASR) potential in Portland cement concrete.
2. Investigate existing structures for presence of ASR.
3. Determine appropriate mitigation/remediation options to prevent further ASR distress.

GEOLOGY

Aggregates used for structural concrete on Vermont Agency of Transportation (VTrans) projects are acquired from both sand and gravel pits and from rock quarries. Currently the Agency uses aggregate from 28 different producers throughout Vermont and immediately adjacent areas of New Hampshire and Massachusetts in its structural mixes. The New Hampshire and Massachusetts locations are very close to the Vermont border and for convenience, reference to the location of aggregates used in the study will be considered as being from within the State of Vermont.

Natural sand and gravel aggregates in Vermont are derived predominantly from glacial deposits. These glacial deposits include kames, deltas and eskers. The glacial deposits vary widely in particle size and the mineral composition varies dependent upon the source rock from which the material was abraded. Because the glaciers traversed the state in a predominantly north to south direction, deposits tend to reflect the bedrock geology present northerly of the deposit location.

The rock types found in glacial deposits from the central and eastern portions of the state consists predominantly of granite, gneiss, schist, phyllite and quartzite. The minerals quartz and feldspar are abundant with varying amounts of associated igneous and metamorphic minerals such as hornblende, mica and chlorite. In the Champlain and Rutland valleys, glacial deposits may contain limestone, dolomite or sandstone.

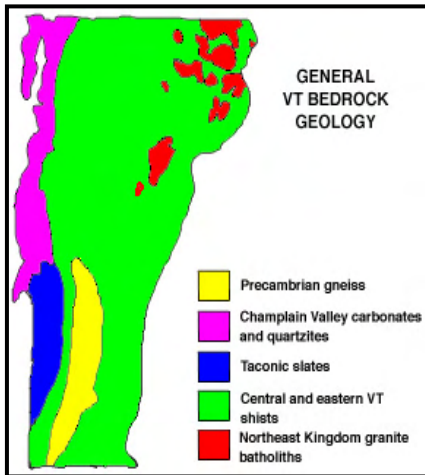


Figure 1 presents a simplified geologic diagram of the State of Vermont. The geology of the state is characterized by northeast trending zones of bedrock geology that reflects the sedimentary, metamorphic and igneous rock types found in the state. The bedrock aggregate sources throughout Vermont vary widely in rock type, crystal grain size, mineral composition, grade of metamorphism and degree of weathering.

Figure 1 Simplified geologic map of Vermont

Sedimentary type rocks such as limestone and dolomite are quarried at locations in the western valley deposits that stretch from Bennington to the Canadian border along the western part of the state. These deposits tend to be somewhat homogeneous and do not differ significantly in chemical composition or physical properties.

Metamorphic rocks such as meta-limestones, gneisses, quartzites and amphibolites and igneous rocks such as granite, granodiorite and quartz monzonites are quarried from locations in the central and eastern portions of the state. Metamorphic rocks in Vermont have been subjected to repeated episodes of metamorphism and structural alteration during at least two major mountain building events in the geologic past. This has resulted in the development of masses of rock that are heterogeneous in nature and differ, sometimes significantly, in mineralogical makeup. This heterogeneous nature of metamorphic rocks lead to aggregate sources that may show a wide variation of quality as an aggregate source is quarried over a broad area.

The metamorphic rocks schist, slate and phyllite are not desirable rock types for aggregate as the soft platy mineral makeup of the rock makes for a poor engineering material. Although not desirable, these rock types do show up in some quarried material. As long as they do not make up a significant proportion of the material their negative affect on the engineering properties of the aggregate is minimal.

ASR REACTIVE AGGREGATES

It is well established that some mineral and rock types are considered ASR reactive.

Some of the most susceptible are:

- Chert
- Opal
- Chalcedony
- Volcanic Glass

These aggregate types are considered to be rapidly alkali silica reactive. None of these are found in Vermont in significant quantities that would contribute to the development of ASR.

It has also been found that other metastable silicates such as argillite, greywacke, phyllite, hornfels, rocks containing strained quartz, some granites and cataclastic rocks (rocks that have undergone brittle shear as the result of intense folding or faulting) can be potentially reactive. These aggregates tend to take a longer period of time to develop ASR and as such have been referred to as “Slow/Late-Expanding Alkali Silicate/Silica Reaction” aggregates. Many of these aggregate types are found in Vermont and surrounding states.

While porous and hydrous silica aggregates such as opal, chert, chalcedony and volcanic glass usually react rapidly with the alkali in the cement, well crystallized dense forms of quartz (found in metamorphic rocks) show slow reactions that lead to delayed expansion of the concrete.

Parameters such as crystal shape, texture and surface area play important roles in an aggregate's susceptibility to the development of ASR. Jensen (1993) stressed that slowly expansive alkali silica reactive aggregates should be evaluated based on micro-structural analysis and known field experience rather than on rock types.

Microcrystalline quartz and strained quartz have been identified as ASR susceptible. They are common constituents originating from the break down of metamorphic rocks. Individual concrete aggregate producers in the state often utilize multiple sources of both crushed and bank-run materials. Some manufacturers of aggregate materials blend different rock types during the production of their crushed stone products. In summary, the types and composition of the aggregates can vary significantly within a single source and between sources across the state.

STUDY METHODOLOGY

Aggregate Selection Criteria

It is well known that chert, opal, chalcedony, flint, volcanic glasses, microcrystalline quartz and strained quartz can be susceptible to alkali silica reactivity. Factors that affect an aggregate's susceptibility to ASR are the crystal phase of the silica, porosity, crystal

particle size and strain within the crystal. Metamorphic rocks are the predominant type of rock in Vermont with sedimentary rock occurring in the Champlain and Rutland valleys and igneous rocks in the north central to northeastern portion of the state. Chert, opal, chalcedony, flint and volcanic glasses either do not occur or do not occur in sufficient amounts in Vermont to contribute to the ASR susceptibility of Vermont aggregates. Strained quartz, however, is common due to the cataclastic nature of the metamorphic rocks found in the state. Strained quartz has been found to be susceptible to the development of ASR.

Seventeen major aggregate sources recently supplying Vermont construction projects were examined for possible inclusion in this study. A total of eleven aggregate sources were determined appropriate for evaluation based on the following criteria:

1. The aggregate should represent a regular, consistently producing source,
2. The pits/quarries should have been in operation for 10 years or more,
3. Aggregate from the pit/quarry should have been used in the past in structural concrete on VTrans projects and expected to be available for future projects,
4. The mineral composition of the aggregate should contain rock types/mineralogy that is suspected as being susceptible to ASR development and
5. Each source should be representative of distinct geological provinces of the State of Vermont.

Annually, the Vermont Agency of Transportation collects samples from aggregate sources for testing and evaluation for suitability in Portland cement concrete. It was determined to use winter aggregate program samples that had previously been collected by the Agency's Portland Cement Concrete Unit. It was also determined that only coarse aggregate would be evaluated at this time. Of the eleven sources evaluated, three are representative of the western side of the state (Champlain and Rutland Valleys), three in the north central portion of the state and five along the Connecticut River valley.

Mortar Bar Testing

For the first phase of this research, it was decided that only coarse aggregate for concrete would be tested from pits or quarries that have been open for at least 10 years and are still producing coarse aggregate for concrete. An effort was also made to select coarse aggregate sources that would represent different geological areas of the state.

The selected coarse aggregate sources were tested in accordance with AASHTO test method T303-00, Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction. This test procedure was chosen for its ability to give results within 16 days of mortar bar fabrication. The cement chosen was Blue Circle Cement because of its conformance to reference cement characteristics. Six bags were purchased from S.T. Griswold Concrete Company in Williston Vermont. The mill report that represented this cement stated a total alkali of 0.62%.

Three mortar bars were molded for each coarse aggregate sample and de-molded 24 hours later. The bars were stored in water maintained at 176 +/- 3 degrees Fahrenheit for the first 24 hours after demolding. After the initial measurement was taken, the 3 bars for each sample were placed into containers filled with 1N sodium hydroxide solution maintained at the same temperature as the water. Measurements of the bars were taken at 0 (initial measurement), 3, 5, 7, 10, 13, and 14 days. Lengths were recorded for computation of change in length (See Appendix B for expansion measurements). An oven was utilized to maintain the required temperature and a data logging temperature probe was used to monitor the temperature throughout the test duration. Two test runs were made with six coarse aggregate sources in each run. The coarse aggregate sample from source A020012 was chosen as a control sample for both test runs due to its low expansion and similar expansion values reported by New Hampshire DOT in their study.

Petrographic Analysis

At least one mortar bar sample representing each of the sources was evaluated petrographically utilizing the polarized-light microscope. A polarized-light microscope is a compound transmitted-light microscope to which components have been added to enable the determination of the optical properties of translucent substances. Polarizing filters and special analyzers allow for the identification of mineral species and other physical properties of rock specimens. All minerals exhibit certain optical properties that can aid in identification.

Individual samples were prepared utilizing petrographic thin sectioning techniques. The thin sectioning process used is described in Appendix A.

Several samples from those sources that tested as potentially reactive (expansion of 0.10 % or greater at 14 days) using the T303-00 testing procedure were examined. The petrographic examinations were conducted to identify the reacting aggregates within the concrete, ASR gel and the micro-structural distress caused by ASR. Samples were viewed under 40X and 100X, however, in some instances magnification up to 400X was used.



Standards utilized as a guide in the petrographic examinations included ASTM C295-98, Standard Guide for Petrographic Examination of Aggregates for Concrete; ASTM C856-95, Standard Practice for Petrographic Examination of Hardened Concrete and ASTM C294-98, Standard Descriptive Nomenclature for Constituents of Concrete Aggregates.

Photomicrographs of samples were taken utilizing a Kodak MDS-290 Microscopy Documentation System consisting of a Kodak DC-290 digital camera, specialized phototube and Kodak MDS-290 software plug-in for Adobe Photoshop version 7.0.

Figure 2 Petrographic Microscope (notice Kodak DC-290 Digital camera mounted on phototube).

It was suspected that visual evidence of ASR activity might not be distributed uniformly throughout the mortar bars. In an attempt to provide greater opportunities to detect ASR activity, multiple thin sections were prepared from various portions of the bars. For samples that showed expansions greater than 0.1%, three thin sections from various parts of the mortar bars were prepared and evaluated.

RESULTS

Mortar Bar Testing

Of the eleven different coarse aggregates sources tested, five were found to have expansions equal to or greater than 0.10% and two had expansions equal to or greater than 0.08% but less than 0.1%. Of the five samples that had expansions equal to or greater than 0.1%, three were quarry stone sources and two were bank run sources. The two that had expansions equal to or greater than 0.08% but less than 0.1% were both bank run sources. Results from AASHTO T303-00 testing are included in Appendix B.

Petrographic Analysis

A total of eleven aggregate sources were evaluated using the petrographic microscope. Of these eleven sources, six samples had exhibited T303-00 expansions less than 0.10%. The other five samples exhibited expansions greater than 0.10% with values ranging from 0.1013% to 0.2060%. Thin sections of the samples were observed under plane light and polarized light (Cross Polars). The micro-cracks stood out better under cross polars and as such, photomicrographs were made under cross polarized light. Photomicrographs of suspected ASR in each of the samples are presented in Appendix C. Most photomicrographs were taken through the microscope under 100- power although some were taken at 40-power.

Based on observations made under the petrographic microscope, possible signs of ASR were identified in seven of the eleven samples (A010594, A020011, A020012, A020013, A020014, A020019 and A020020). Of the seven samples that showed petrographic evidence of possible ASR development, three had exhibited expansion values less than 0.10%. These three samples (A010594, granite; A020012; amphibolite and A020019, a gravel composed primarily of granite) showed only minor occurrences of darkened paste and micro-cracking. These samples did not exhibit mineral assemblages or structures that would be conducive for the formation of ASR. Sample A020018, with a reported expansion of 0.1087%, showed no evidence of ASR. The results of analysis are presented in Table 1.

Table 1 Summary of Sample Properties. Expansions greater than 0.10% are highlighted.

SOURCE ID	TYE OF AGGREGATE	PETROGRAPHIC ASR FEATURES	AASHTO test method T303-00 14 DAY EXPANSION %	ROCK TYPE
ASR A010594	Stone	Minor darkened paste. Slight micro-cracking.	0.0673	Granite
ASR A010595	Stone	None	0.0530	Granodiorite
ASR A020001	Stone	None	0.0287	Dolomite
ASR A020002	Gravel	None	0.0843	Carbonate/Siliceous Mix
ASR A020011	Stone	Darkened paste. Micro-cracking.	0.1013	Granodiorite
ASR A020012	Stone	Minor darkened paste. Minor micro-cracking.	0.0777	Amphibolite
ASR A020013	Stone	Darkened paste. Micro-cracking.	0.1283	Biotite Gneiss
ASR A020014	Gravel	Darkened paste. Micro-cracking.	0.2060	Metamorphic/Granitic Mix
ASR A020018	Stone	None	0.1087	Dolomitic Quartzite
ASR A020019	Gravel	Minor darkened paste and minor micro-cracking.	0.0897	Granite Mix
ASR A020020	Gravel	Darkened paste. Micro-cracking.	0.1970	Metamorphic Mix

Generally, ASR gel filled cracks were observed within cement paste, either between aggregate particles and air voids or aggregate-aggregate particles. The ASR observed appeared to be associated with micro-crystalline quartz, strained quartz, schist/phyllite, and some amphibolites. Many of the samples contained darkened paste around the rim of aggregate particles and air voids.

It was observed that very few micro-cracks travel further than one aggregate/aggregate or aggregate/void pair. Micro-cracking extending across significant portions of the sample was not noted. It appeared that there was no preference for ASR development near the edges of the mortar bar samples. Actual cracking of an aggregate particle was observed in only one instance. There did not appear to be a noticeable preference for ASR development between micro crystalline quartz and macro crystalline quartz.

As part of this study, numerous studies conducted by other State DOTs, concrete producer organizations, FHWA, universities and foreign transportation administrations were reviewed. One study, International Center for Aggregates Research, *Research Report ICAR - 301-1f*, compared results from C-1260 (accelerated mortar bar test) testing to results obtained from C-1293 (concrete prism test) testing. In their discussion the authors indicated that petrographic analysis of slowly reactive aggregates with 14-day expansions between 0.10% and 0.20% failed to detect reactive materials in these

aggregates. Other researchers, notably in Canada and Norway, have also indicated that detection of ASR in slow/late reacting aggregates was difficult.

CONCLUSIONS

- Based on mortar bar testing of eleven sources, five were found to have expansions equal to or greater than 0.1% and two had expansions equal to or greater than 0.08% but less than 0.1%. Appendix D presents aggregate source locations showing AASHTO T303-00 test results depicted on a generalized bedrock geologic map of Vermont.
- Based on petrographic observations seven of the eleven aggregate sources evaluated exhibit what would be considered moderate susceptibility for the development of ASR.
- Sample A020014 and A020020 exhibited the greatest abundance of micro-cracks and ASR gel development.
- The development of ASR gel and micro-cracks appeared to be evenly distributed throughout the samples (there seemed to be no “edge effect” for the development of micro-cracking).
- Aggregates in Vermont tend to be of the slow/late expanding type and as such, it was not surprising to see only moderate ASR development in the mortar bar samples. It is suspected that more obvious ASR manifestations will be encountered during the next part of our study as structures containing potentially reactive aggregates will have had a longer period of time to react with the alkali in the cement. Researchers have found that some slow/late reactive aggregates may take up to 20 years to manifest it’s self.

RECOMMENDATIONS

Based on the results of this study, the following recommendations are suggested:

1. Consider testing fine aggregate in future ASR studies.
2. Re-test the aggregates that have exceeded the suggested threshold for potential reactivity using the actual cement and pozzolan proportions to look for decreased expansion.
3. Investigate existing structures built with the potentially reactive coarse aggregate that have been in service for 10 or more years.
4. Recommend changes if needed to our current preventative ASR high performance concrete proportioning and or specifications.
5. Consider conducting ASTM C 1293, Alkali-Silica Reaction in Concrete Prisms testing on those aggregate sources that exhibited T303-00 test results greater than 0.08% and/or showed evidence of ASR development based on petrographic analysis.

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APPENDIX A

**THIN SECTION
SAMPLE PREPARATION**

APPENDIX A THIN SECTION SAMPLE PREPARATION

The preparation of thin sections made from mortar bars is discussed below. Photographs are included showing each step.

It has been suggested that the influence of sample preparation on the results of this study may be an issue. It was thought that by using hydrous rather than anhydrous thin section preparation techniques, the detection of ASR gel and micro-cracks produced by the gel would be difficult.

In a recent paper *Effect of Sample Preparation on the Chemical Composition and Morphology of Alkali-Silica Reaction Products* (Hanson et. al. 2003), the authors concluded that although the use of water in preparing thin sections for examination of alkali-silica reaction product alters the morphology and chemical composition of the phases of interest, if the results of a study are intended solely to confirm the presence of alkali-silica reaction product, then hydrous preparation is acceptable. Specific chemical testing of gel was not part of this study and as such the hydrous method of sample preparation was deemed appropriate and therefore this method of preparation was used.

STEP 1

The first step in preparing the thin section samples were to cut $\frac{3}{4}$ " blocks from the mortar bars. This was accomplished utilizing a diamond trim saw lubricated with propylene glycol. For the first six sample sources, cubes were cut at random portions of the bars. Later, it was determined that it would be advantageous to cut cubes for thin sections from areas of mortar bars that showed precipitate or other possible evidence of ASR. Therefore, the remaining five sample sources were cut from areas of the bar that showed an abundance of white precipitate.



Figure 1 Mortar bar showing $\frac{3}{4}$ " cube cut from bar. Cubes were cut utilizing a Raytech 10" Trim Saw cooled with RV propylene glycol antifreeze coolant.

STEP 2

After being cut, each $\frac{3}{4}$ " cube was washed then dried overnight in a 112°C oven. After drying, the blocks were impregnated on one side with a two-part epoxy resin that was

thinned with acetone. Impregnation was performed to help bind the sample together and protect it from damage during the grinding/polishing operations.



Figure 2 Mortar bar cubes and two-part epoxy used to bind sample to slide .



Figure 3 Mortar bar cube showing epoxy coated surface.

STEP 3

Samples were then air-dried overnight and lapped with three levels of diamond disks using a specimen polisher until the sample surface was perfectly flat and smooth.



Figure 4 Grinder/Polisher used to prepare sample for mounting to slide. Samples were polished by holding the cube to the wheel using progressively finer grit disks while carefully applying water to cool the sample and to wash away waste cuttings.

STEP 4

After each cube was ground to a sufficiently flat surface, they were allowed to dry overnight. After drying, the flat and smooth sides of the cubes were epoxied to a glass slide using the two-part epoxy (uncut with thinners), clamped and allowed to cure for a minimum of three days.



Figure 5 Clamp used to hold slide securely to sample while curing.



Figure 6 View of underside of epoxied sample.



Figure 7 View of top sample of epoxied sample.

STEP 5

Samples were then cut and ground to approximately 30-microns in thickness using a thin section machine with a diamond saw and grinding wheel.



Figure 8 Thin section saw/grinder used to prepare sample. This equipment allows the sample to be ground down to 30 microns or less.

STEP 6

Final polishing of the thin section was accomplished by hand using water and #600 grit silicon carbide on a thick piece of glass.



Figure 9 Photograph showing hand lapping equipment.

STEP 7

Once the thin section was polished to 30 microns in thickness, a cover slip was placed on the thin section using Crossmon's Mounting Medium, which has a refractive index of 1.54.



Figure 10 Completed thin section slide. This slide contains a sample that is 30 microns in thickness. This allows the sample to be analyzed using the petrographic microscope.

APPENDIX B

AASHTO T303-00 TESTING RESULTS

APPENDIX B

AASHTO T303-00 Test Results

Samples Mixed 6-12-02, End of test 6-28-02
ASR A0200012

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C	Percent %	Percent length average
0	0.0047	0	0.0175	0	0.0183	0	0.0000
3	0.0061	0.014	0.0187	0.012	0.019	0.007	0.0110
5	0.0069	0.022	0.0194	0.019	0.0199	0.016	0.0190
7	0.0081	0.034	0.0207	0.032	0.0212	0.029	0.0317
10	0.0102	0.055	0.022	0.045	0.0225	0.042	0.0473
13	0.0119	0.072	0.0243	0.068	0.0249	0.066	0.0687
14	0.0125	0.078	0.0245	0.07	0.0255	0.072	0.0733

ASR A020018

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C	Percent %	Percent length average
0	0.0083		0.0173		0.0183	0	0.0000
3	0.0103	0.02	0.0194	0.021	0.0206	0.023	0.0213
5	0.0123	0.04	0.0212	0.039	0.0225	0.042	0.0403
7	0.0135	0.052	0.0224	0.051	0.0239	0.056	0.0530
10	0.0161	0.078	0.0261	0.088	0.026	0.077	0.0810
13	0.01836	0.1006	0.0271	0.098	0.028	0.097	0.0985
14	0.0189	0.106	0.0289	0.116	0.0287	0.104	0.1087

ASR A010595

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C	Percent %	Percent length average
0	0.0238		0.0195		0.0143	0	0.0000
3	0.0252	0.014	0.0206	0.011	0.0157	0.014	0.0130
5	0.0255	0.017	0.0224	0.051	0.0161	0.018	0.0287
7	0.0246	0.008	0.023	0.057	0.0163	0.02	0.0283
10	0.0267	0.029	0.0241	0.068	0.0172	0.029	0.0420
13	0.0269	0.031	0.0238	0.065	0.0189	0.046	0.0473
14	0.0275	0.037	0.0243	0.07	0.0195	0.052	0.0530

Samples Mixed 6-12-02, End of test 6-28-02

ASR A020002

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C	Percent %	Percent length average
0	0.0049		0.0315		0.0043	0	0.0000
3	0.0071	0.022	0.0343	0.028	0.0066	0.023	0.0243
5	0.0082	0.033	0.0356	0.041	0.0075	0.032	0.0353
7	0.009	0.041	0.0361	0.046	0.0081	0.038	0.0417
10	0.0113	0.064	0.0381	0.066	0.0101	0.058	0.0627
13	0.0129	0.08	0.0386	0.071	0.0117	0.074	0.0750
14	0.0134	0.085	0.0402	0.087	0.0124	0.081	0.0843

ASR A020019

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C	Percent %	Percent length average
0	0.0161		0.0024		0.0002	0	0.0000
3	0.0176	0.015	0.0038	0.014	0.0021	0.019	0.0160
5	0.0186	0.025	0.0044	0.02	0.0024	0.022	0.0223
7	0.0197	0.036	0.0057	0.033	0.0035	0.033	0.0340
10	0.0224	0.063	0.0073	0.049	0.0068	0.066	0.0593
13	0.0248	0.087	0.0104	0.08	0.0088	0.086	0.0843
14	0.0259	0.098	0.0106	0.082	0.0091	0.089	0.0897

ASR A020001

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C	Percent %	Percent length average
0	0.0095		0.0006		-0.0017	0	0.0000
3	0.0107	0.012	0.0017	0.011	-0.0006	0.011	0.0113
5	0.0112	0.017	0.0027	0.021	-0.0004	0.013	0.0170
7	0.0111	0.016	0.0026	0.02	-0.0002	0.015	0.0170
10	0.0118	0.023	0.0026	0.02	0.0004	0.021	0.0213
13	0.0123	0.028	0.0038	0.032	0.0006	0.023	0.0277
14	0.0121	0.026	0.004	0.034	0.0009	0.026	0.0287

Samples Mixed7-10-02, End of test 7-26-02

ASR A020012

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C	Percent %	Percent length average
0	-0.0056	0	0.0053	0	-0.0143	0	0.0000
3	-0.0043	0.013	0.0062	0.009	-0.0138	0.005	0.0090
5	-0.0036	0.02	0.0069	0.016	-0.0126	0.017	0.0177
7	-0.0023	0.033	0.0082	0.029	-0.011	0.033	0.0317
10	-0.0003	0.053	0.011	0.057	-0.0086	0.057	0.0557
13	0.0016	0.072	0.0124	0.071	-0.0073	0.07	0.0710
14	0.0017	0.073	0.0134	0.081	-0.0064	0.079	0.0777

ASR A020013

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C	Percent %	Percent length average
0	0.0091		0.005		-0.0061	0	0.0000
3	0.0146	0.055	0.0154	0.104	-0.0004	0.057	0.0720
5	0.0205	0.114	0.0132	0.082	0.0013	0.074	0.0900
7	0.0174	0.083	0.0143	0.093	0.0025	0.086	0.0873
10	0.0198	0.107	0.0166	0.116	0.0047	0.108	0.1103
13	0.0211	0.12	0.0177	0.127	0.0062	0.123	0.1233
14	0.0216	0.125	0.0184	0.134	0.0065	0.126	0.1283

ASR A020011

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C	Percent %	Percent length average
0	0.0089		-0.0047		0.0052	0	0.0000
3	0.0061	-0.028	-0.004	0.007	0.0067	0.015	-0.0020
5	0.0083	-0.006	-0.002	0.027	0.0087	0.035	0.0187
7	0.0106	0.017	0.0001	0.048	0.0109	0.057	0.0407
10	0.0134	0.045	0.0031	0.078	0.0142	0.09	0.0710
13	0.0156	0.067	0.0057	0.104	0.0063	0.011	0.0607
14	0.0164	0.075	0.0063	0.11	0.0171	0.119	0.1013

Samples Mixed 7-10-02, End of test 7-26-02

ASR A010594

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C	Percent %	Percent length average
0	0.0001		0.0131		-0.0003	0	0.0000
3	-0.0026	-0.027	0.0186	0.055	0.0051	0.054	0.0273
5	-0.0008	-0.009	0.0159	0.028	0.0022	0.025	0.0147
7	-0.0003	-0.004	0.0171	0.04	0.0035	0.038	0.0247
10	0.0017	0.016	0.0227	0.096	0.0054	0.057	0.0563
13	0.0039	0.038	0.0206	0.075	0.0074	0.077	0.0633
14	0.004	0.039	0.0215	0.084	0.0076	0.079	0.0673

ASR A020020

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C *	Percent %	Percent length average
0	0.0028		0.0155		N/A	N/A	0.0000
3	0.0066	0.038	0.0188	0.033	N/A	N/A	0.0355
5	0.0069	0.041	0.0231	0.076	N/A	N/A	0.0585
7	0.0098	0.07	0.0265	0.11	N/A	N/A	0.0900
10	0.0164	0.136	0.0313	0.158	N/A	N/A	0.1470
13	0.0198	0.17	0.0358	0.203	N/A	N/A	0.1865
14	0.0209	0.181	0.0368	0.213	N/A	N/A	0.1970

* Note: Bar C broke while being demolded

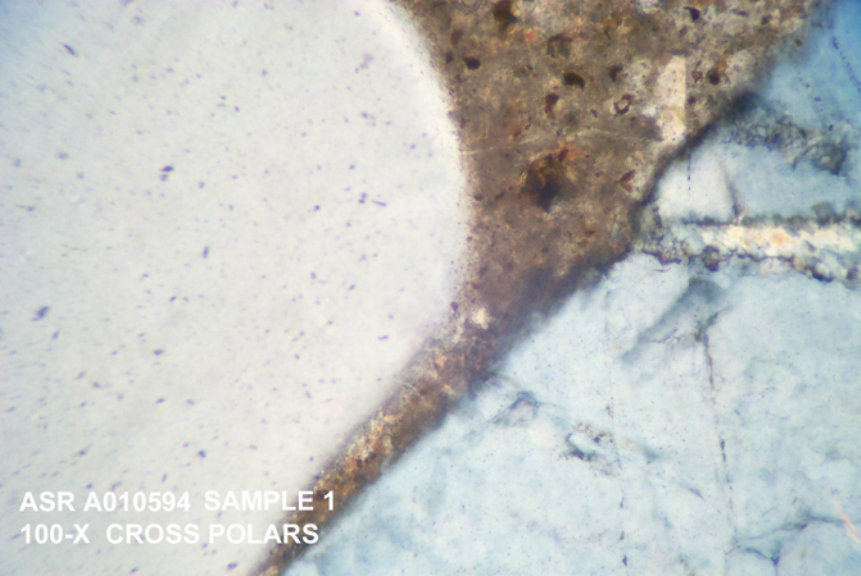
ASR A020014

Day measured	Expansion bar A	Percent %	bar B	Percent %	bar C	Percent %	Percent length average
0	-0.0094		0.0104		0.0072	0	0.0000
3	-0.0035	0.059	0.014	0.036	0.0073	0.001	0.0320
5	0.0049	0.143	0.0128	0.024	0.0102	0.03	0.0657
7	-0.0019	0.075	0.0206	0.102	0.0131	0.059	0.0787
10	0.0045	0.139	0.0241	0.137	0.0203	0.131	0.1357
13	0.0095	0.189	0.0262	0.158	0.0255	0.183	0.1767
14	0.0149	0.243	0.028	0.176	0.0271	0.199	0.2060

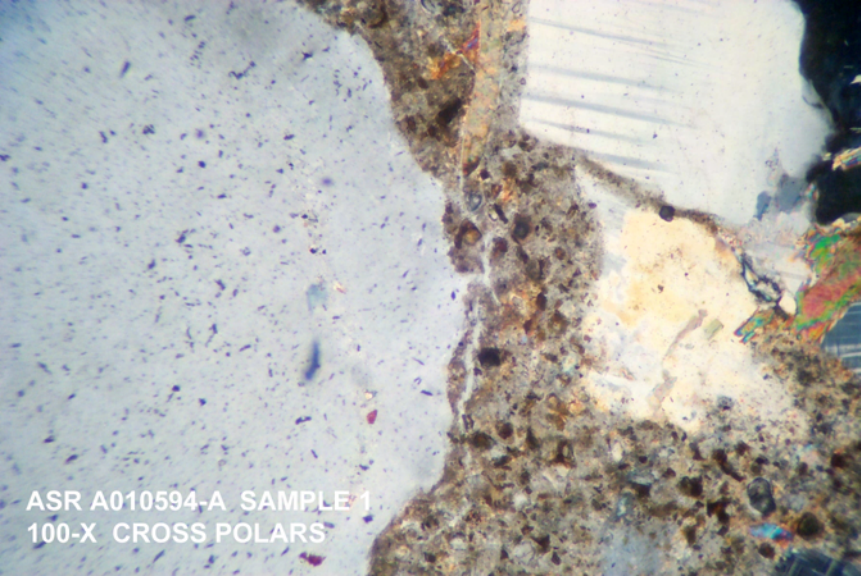
APPENDIX C

PHOTOMICROGRAPHS

SAMPLE ASR A010594

A micrograph showing a cross-section of a material under cross-polarized light. The image is divided into three main regions. On the left is a large, bright white area with scattered small, dark blue-purple spots. In the center is a dark brown, textured band. On the right is a light blue, crystalline region with a network of dark lines and a prominent horizontal crack. The overall appearance is that of a composite or layered material with different phases.

ASR A010594 SAMPLE 1
100-X CROSS POLARS

A micrograph showing a cross-section of a material under cross-polarized light. The image is divided into several distinct regions. On the left, there is a large, light-colored area with a fine, granular texture and scattered small, dark, needle-shaped clefts. To the right of this area is a darker, more heterogeneous region with a complex, porous appearance and various colors including brown, tan, and yellow. Further to the right, there is a white, rectangular area with horizontal striations, possibly representing a different material or a specific layer. The overall appearance suggests a composite or layered material structure.

ASR A010594-A SAMPLE 1
100-X CROSS POLARS

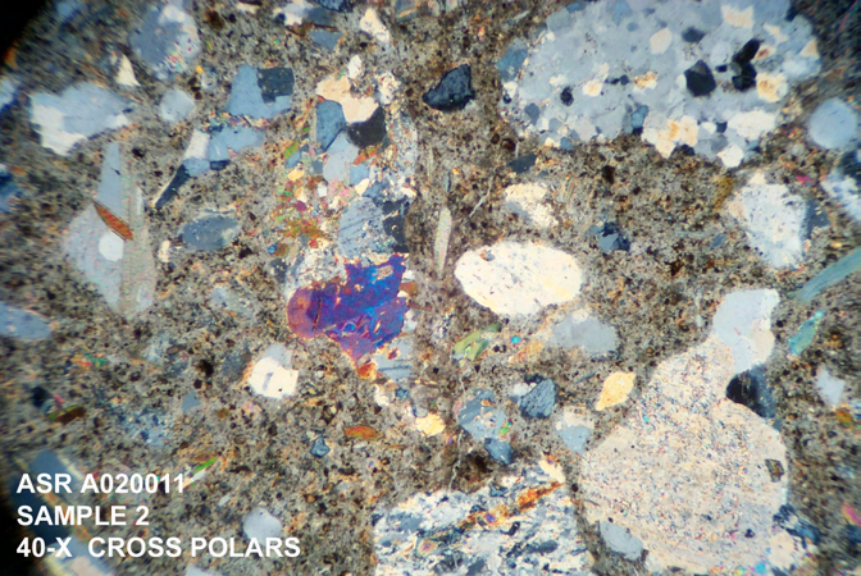
SAMPLE ASR A020011



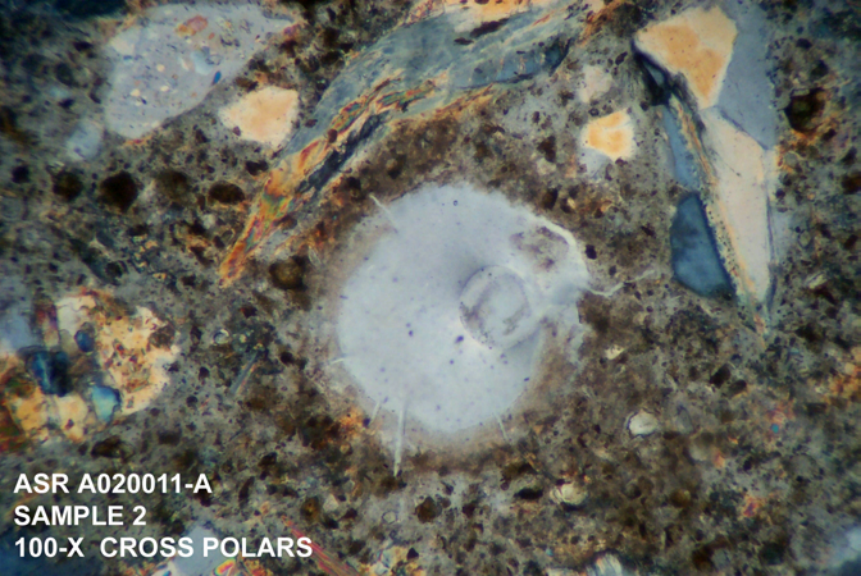
ASR A020011
SAMPLE 1
100-X CROSS POLARS

A micrograph showing a complex mineral texture under cross-polarized light. The image displays a dense field of small, irregularly shaped mineral grains. The grains exhibit a variety of colors, including shades of blue, green, yellow, and brown, which are characteristic of different mineral species or orientations. The overall appearance is highly textured and heterogeneous. In the bottom-left corner, there is white text providing sample identification and imaging conditions.

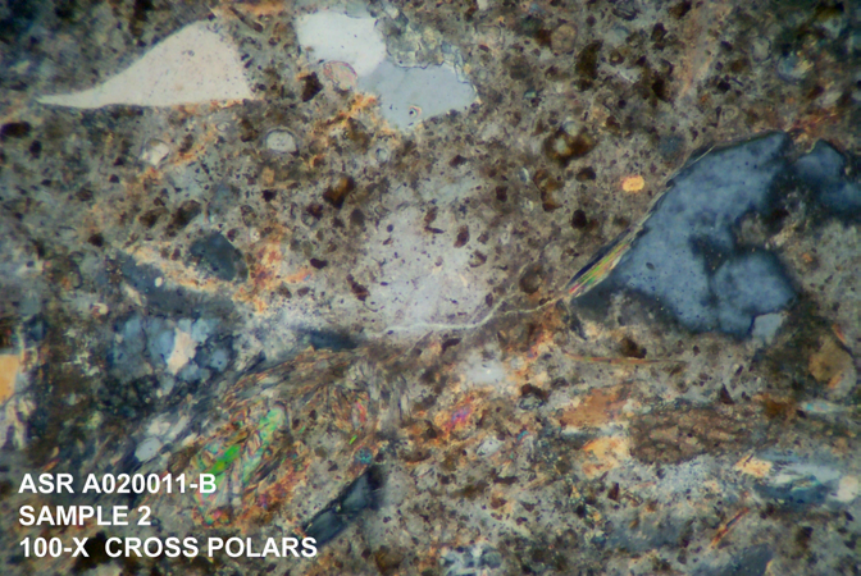
ASR A020011-A
SAMPLE 1
100-X CROSS POLARS



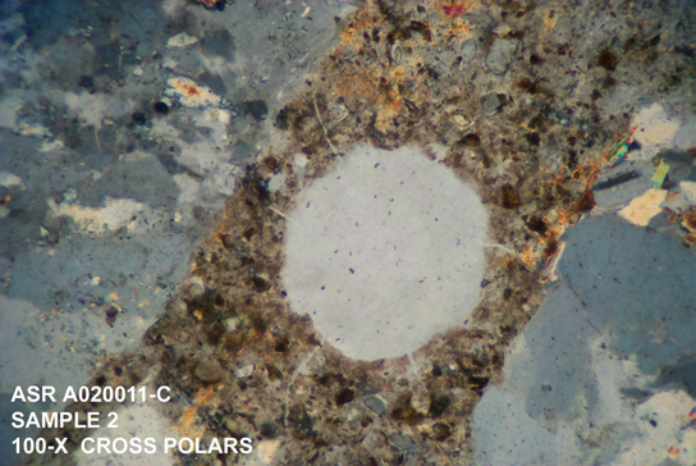
ASR A020011
SAMPLE 2
40-X CROSS POLARARS



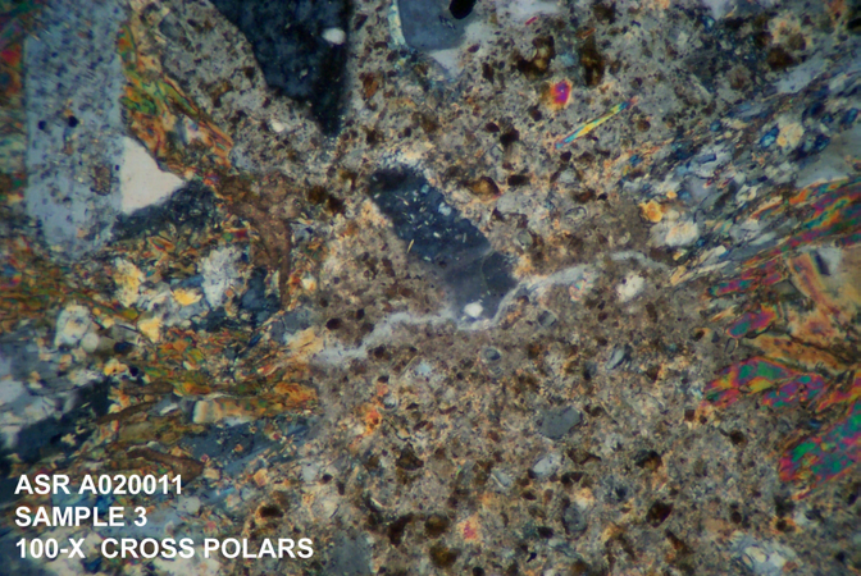
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SAMPLE 2
100-X CROSS POLARS



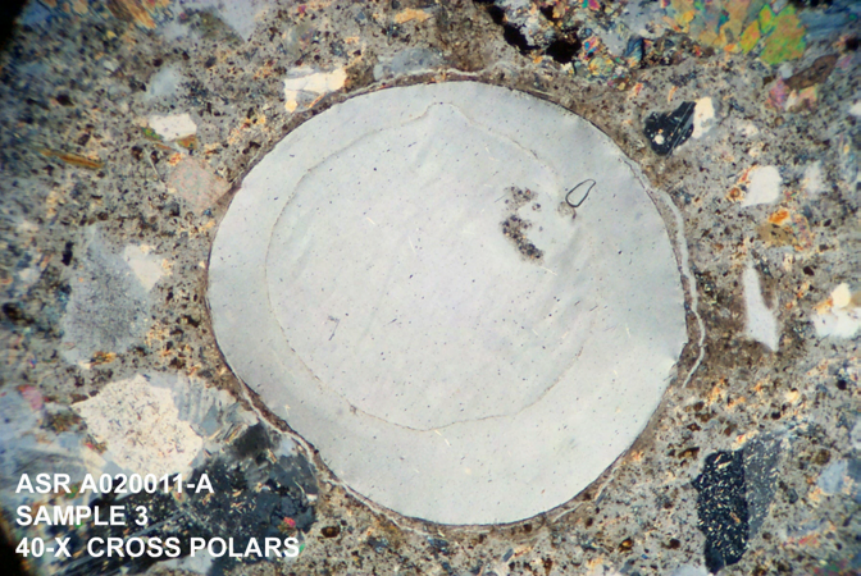
ASR A020011-B
SAMPLE 2
100-X CROSS POLARS



ASR A020011-C
SAMPLE 2
100-X CROSS POLARS

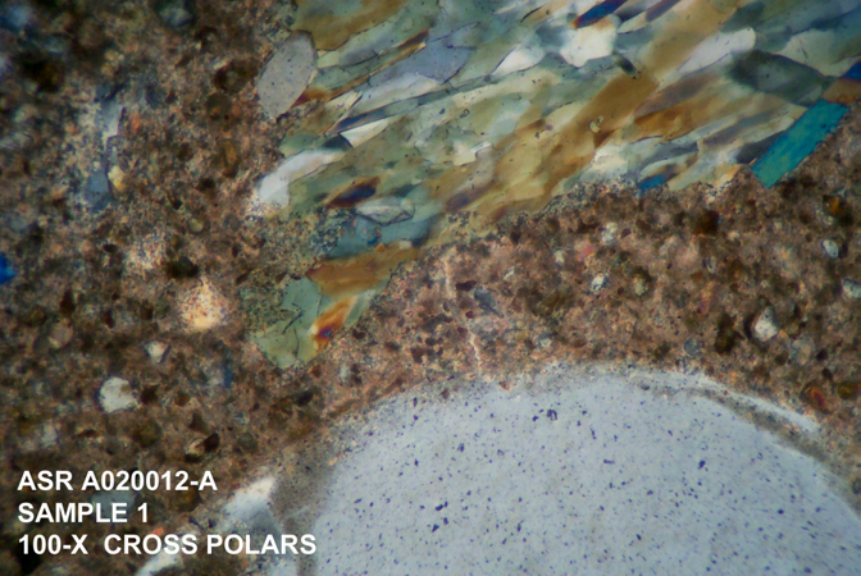


ASR A020011
SAMPLE 3
100-X CROSS POLARS

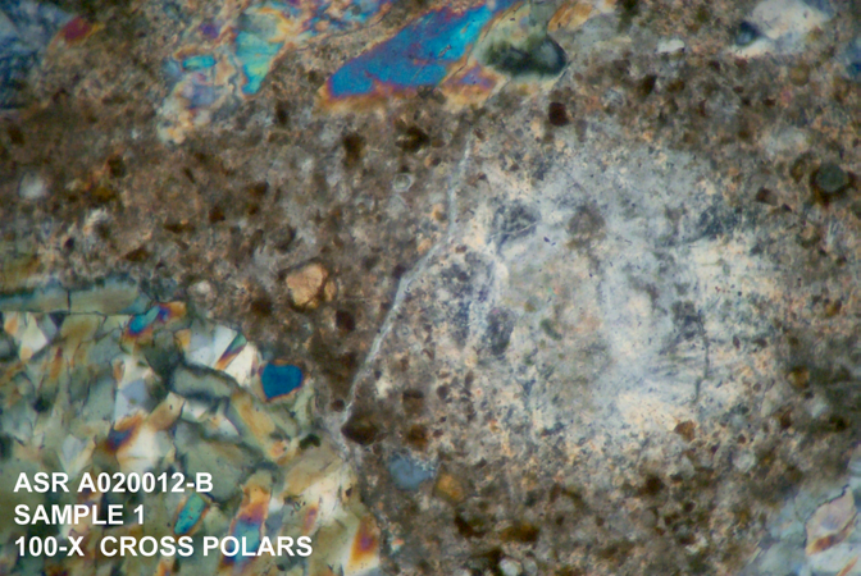


ASR A020011-A
SAMPLE 3
40-X CROSS POLARS

SAMPLE ASR A020012

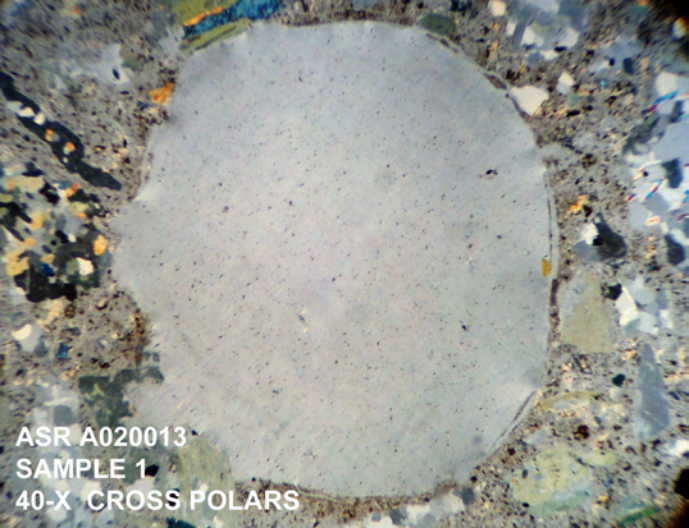


ASR A020012-A
SAMPLE 1
100-X CROSS POLARS

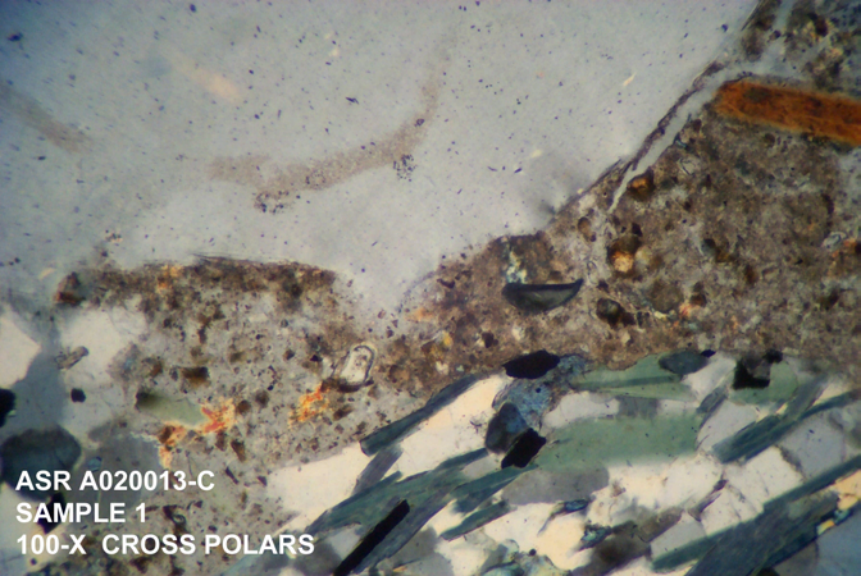


ASR A020012-B
SAMPLE 1
100-X CROSS POLARS

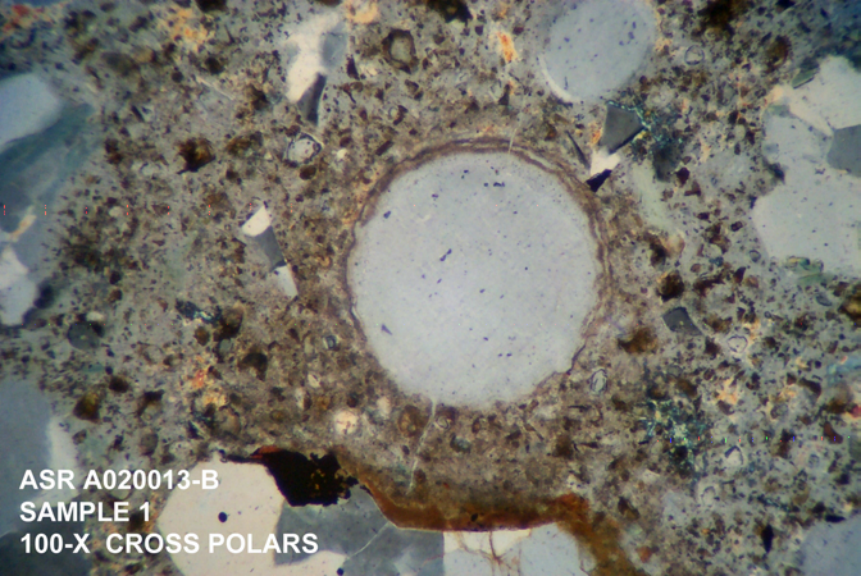
SAMPLE ASR A020013



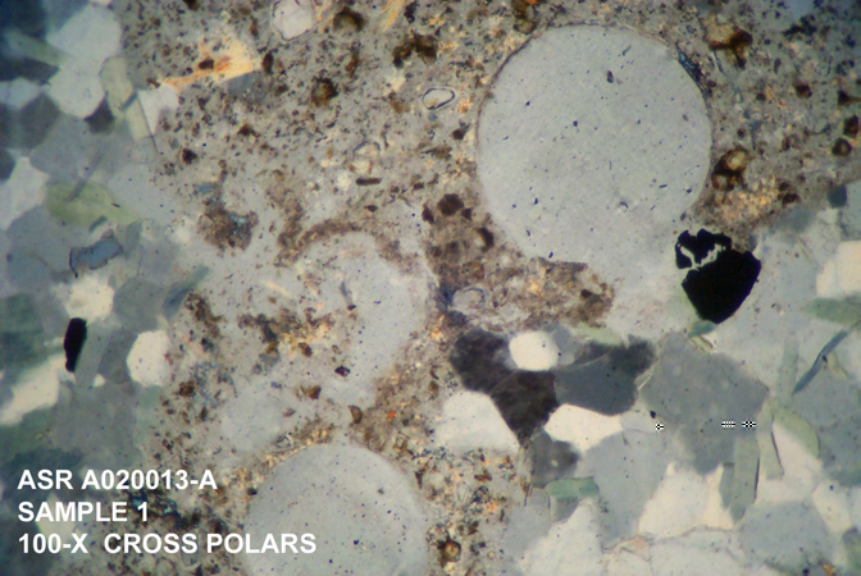
ASR A020013
SAMPLE 1
40-X CROSS POLARS



ASR A020013-C
SAMPLE 1
100-X CROSS POLARS



ASR A020013-B
SAMPLE 1
100-X CROSS POLARS



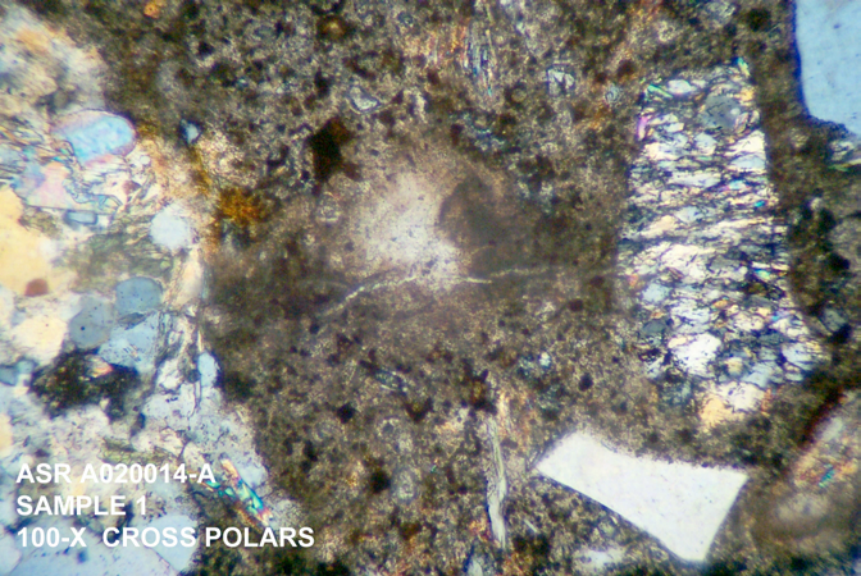
ASR A020013-A
SAMPLE 1
100-X CROSS POLARS



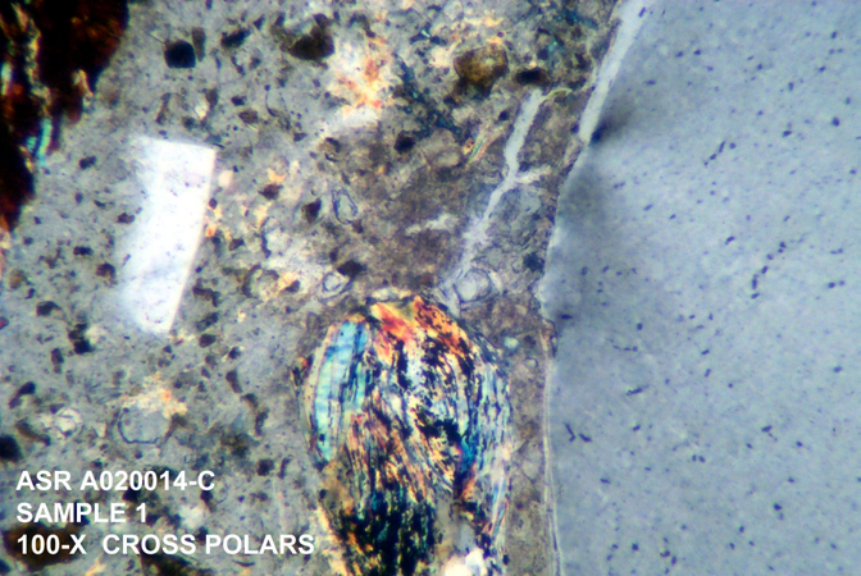
ASR A020013-D
SAMPLE 1
100-X CROSS POLARS

This micrograph shows a cross-section of a material under cross-polarized light. A prominent vertical crack runs through the center of the image. To the right, there is a diagonal fracture surface showing a complex, layered structure with various colors including brown, yellow, and blue. The surrounding material has a fine, granular texture with scattered dark spots.

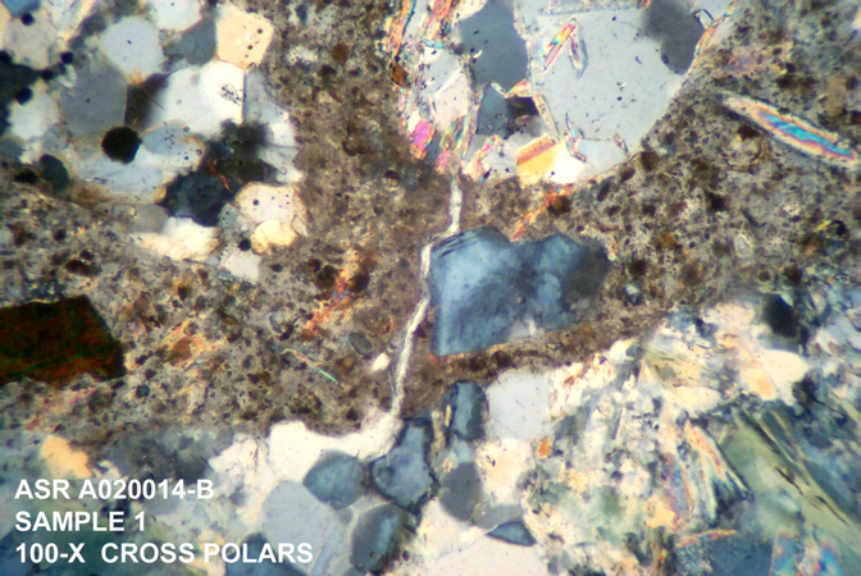
SAMPLE ASR A020014



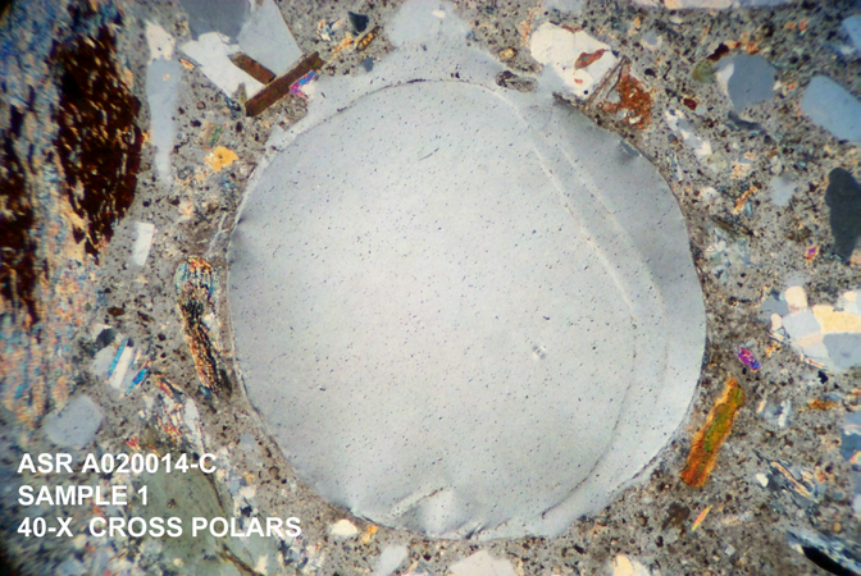
ASR A020014-A
SAMPLE 1
100-X CROSS POLARS



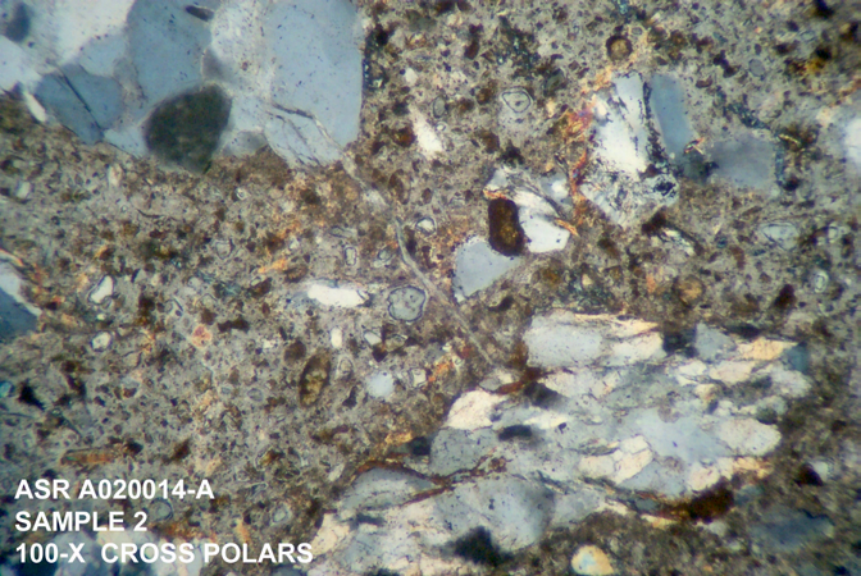
ASR A020014-C
SAMPLE 1
100-X CROSS POLARS



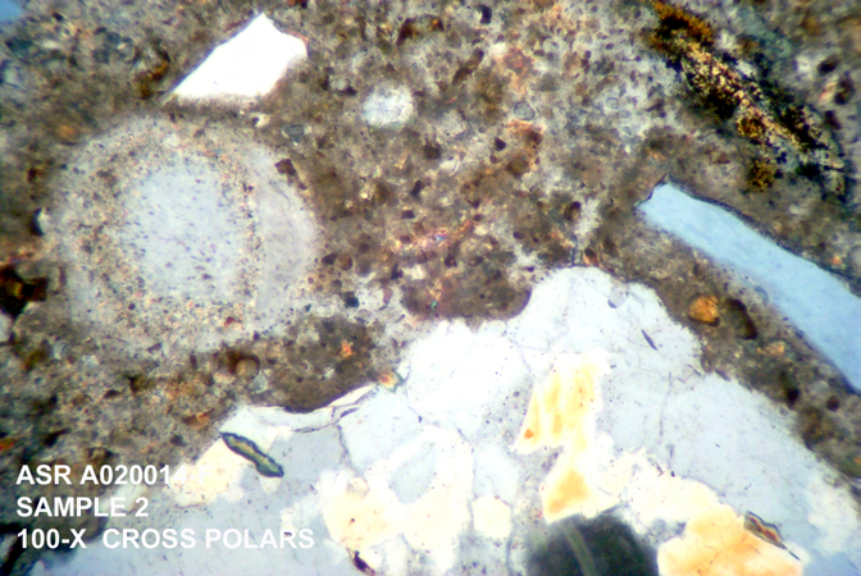
ASR A020014-B
SAMPLE 1
100-X CROSS POLARS



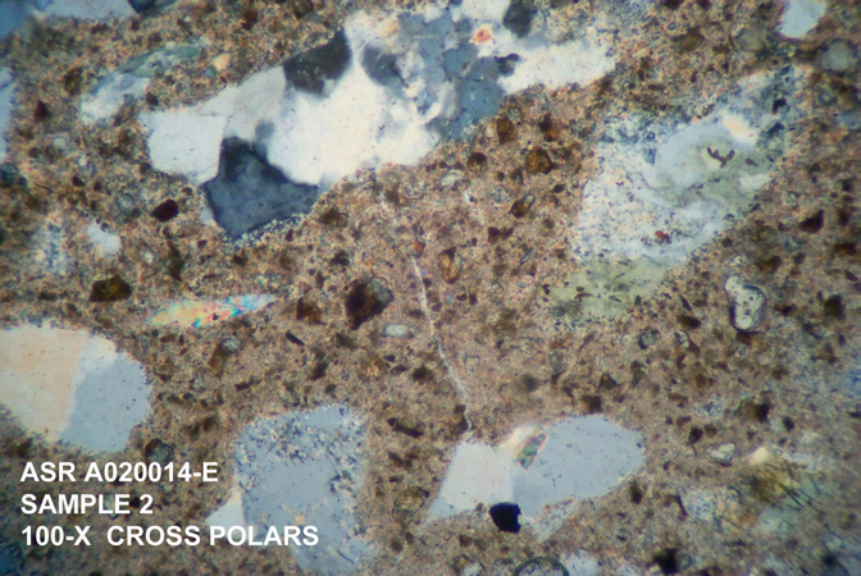
ASR A020014-C
SAMPLE 1
40-X CROSS POLARS



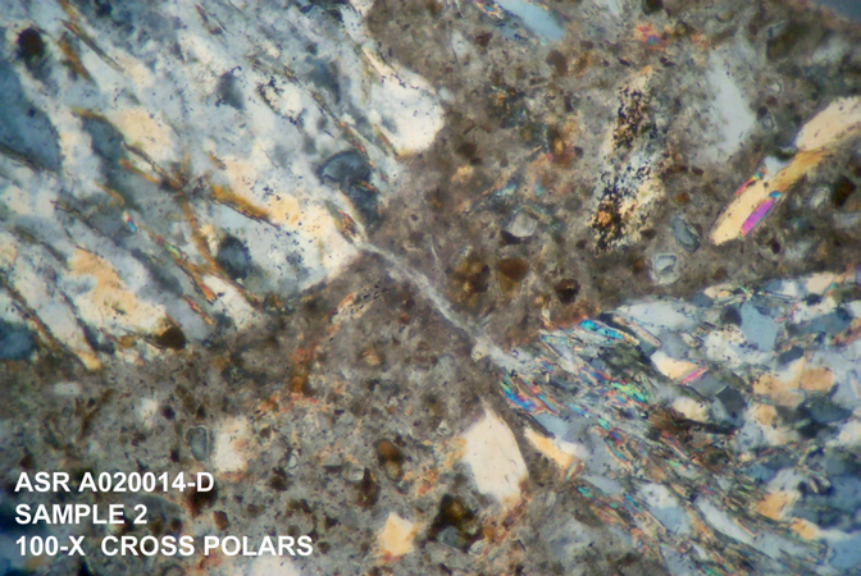
ASR A020014-A
SAMPLE 2
100-X CROSS POLARS



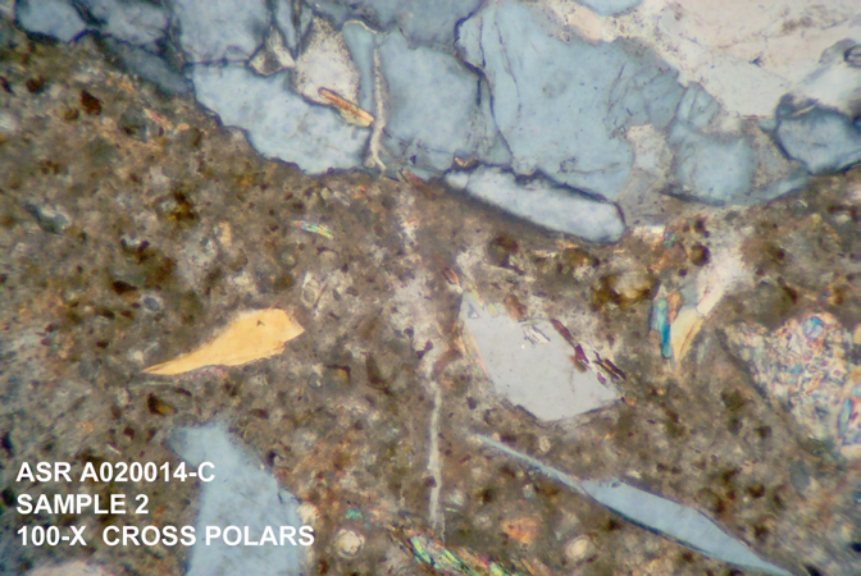
ASR A020014
SAMPLE 2
100-X CROSS POLARS



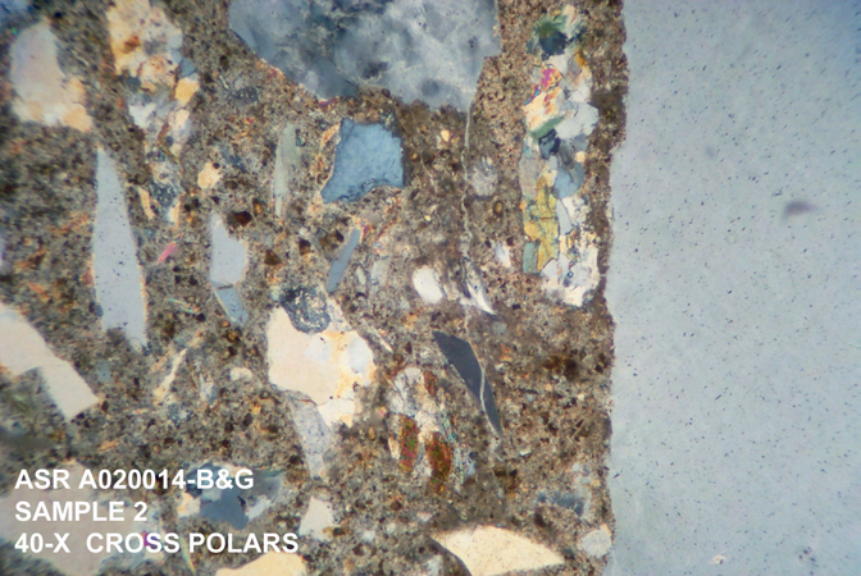
ASR A020014-E
SAMPLE 2
100-X CROSS POLARS



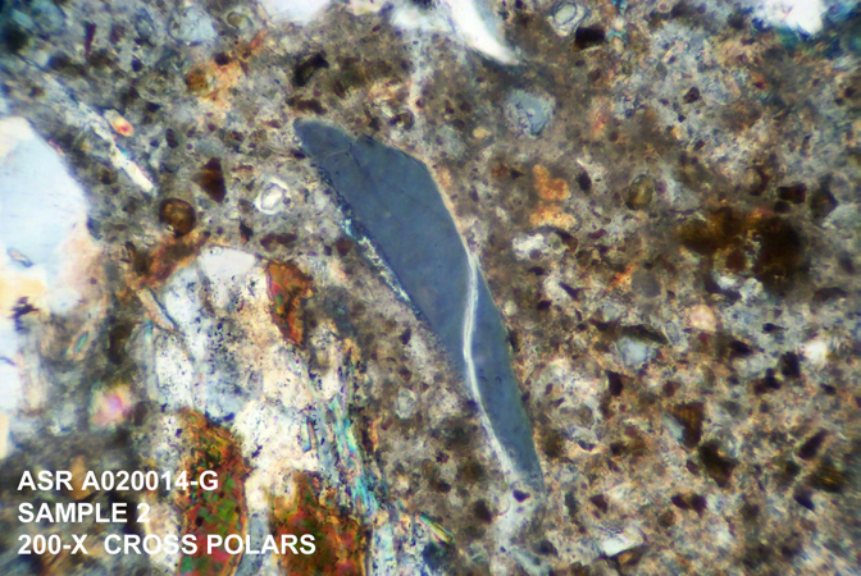
ASR A020014-D
SAMPLE 2
100-X CROSS POLARS



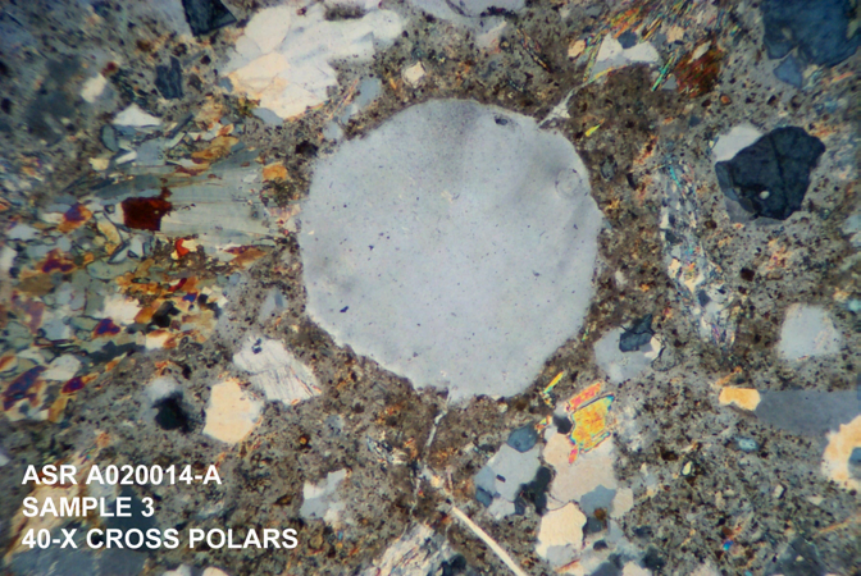
ASR A020014-C
SAMPLE 2
100-X CROSS POLARS



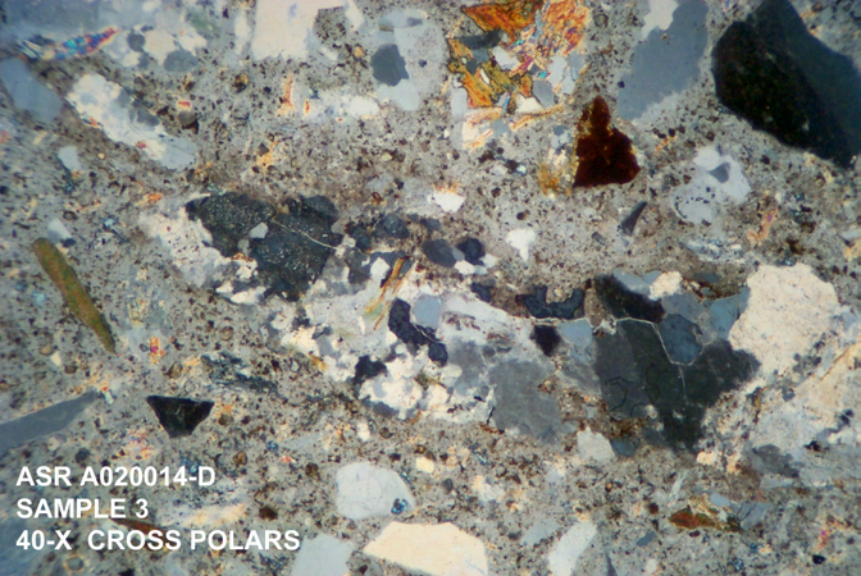
ASR A020014-B&G
SAMPLE 2
40-X CROSS POLARS



ASR A020014-G
SAMPLE 2
200-X CROSS POLARS



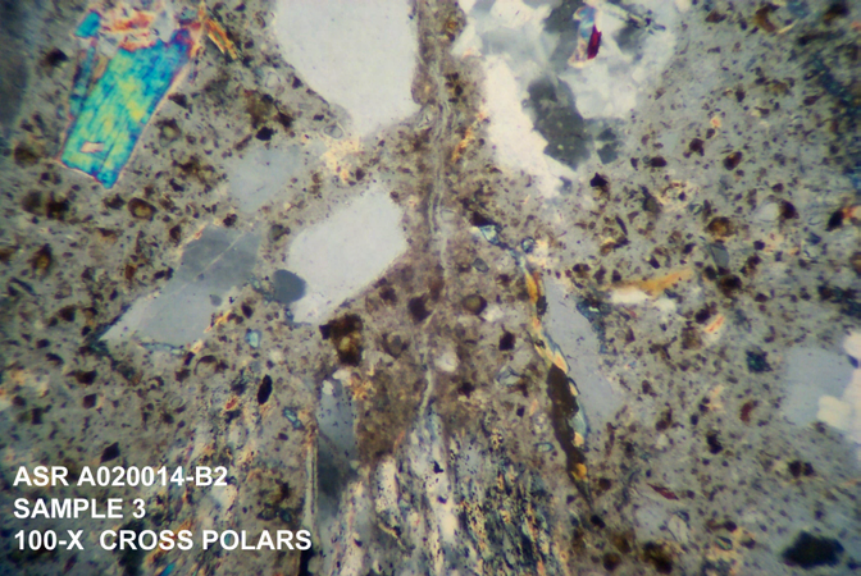
ASR A020014-A
SAMPLE 3
40-X CROSS POLARS



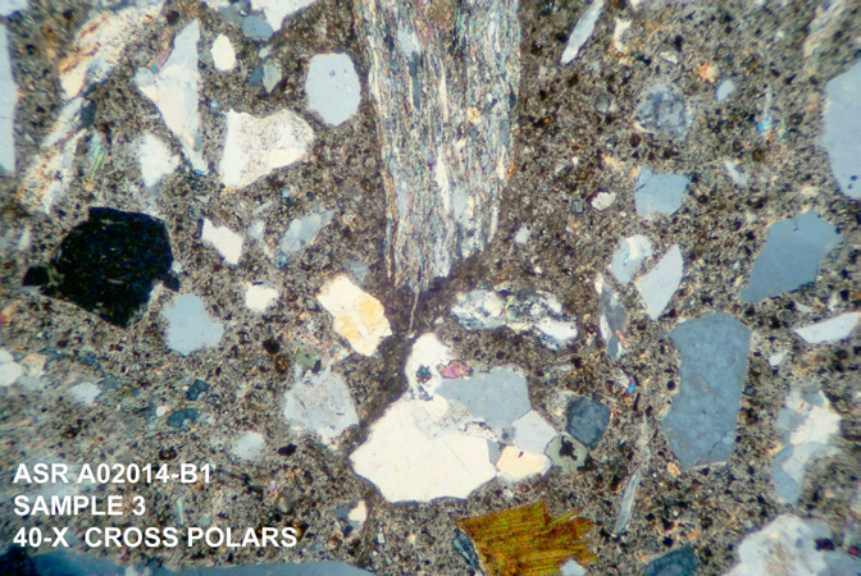
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SAMPLE 3
40-X CROSS POLARS



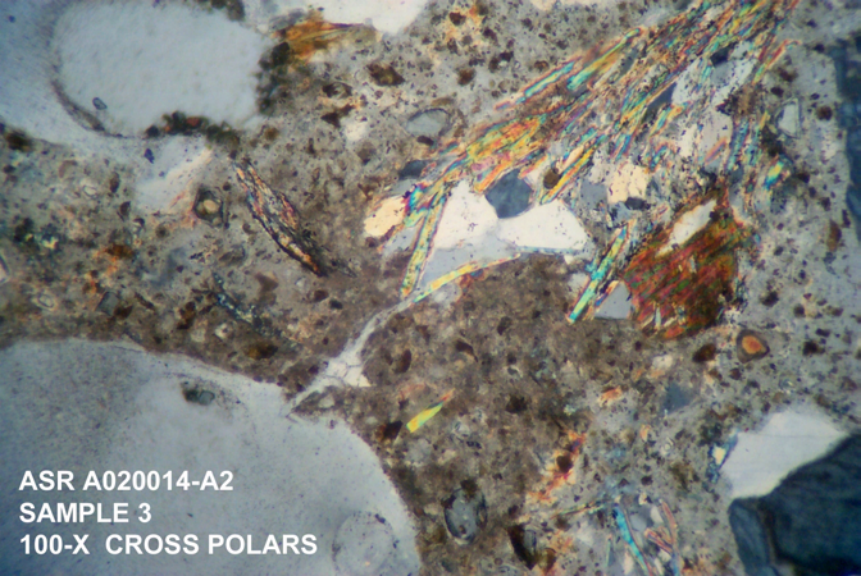
ASR A020014-C
SAMPLE 3
100-X CROSS POLARS



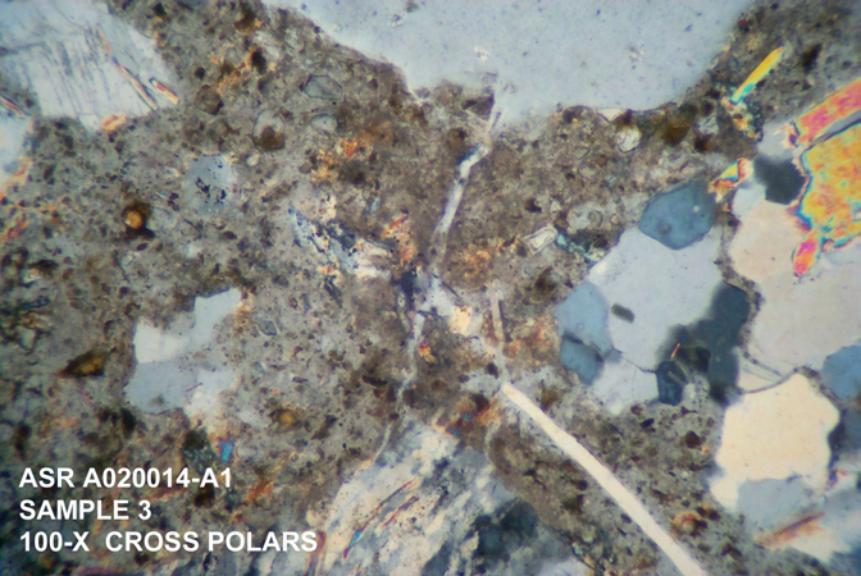
ASR A020014-B2
SAMPLE 3
100-X CROSS POLARS



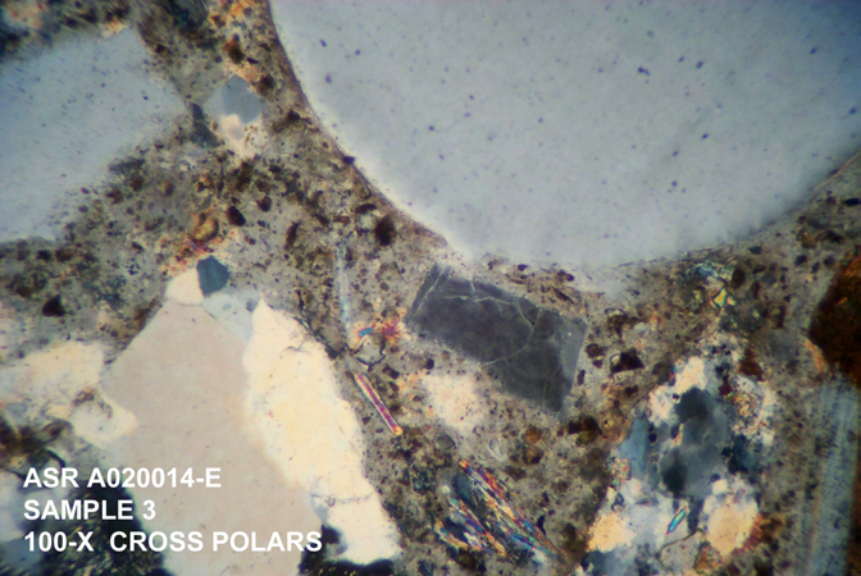
ASR A02014-B1
SAMPLE 3
40-X CROSS POLARS



ASR A020014-A2
SAMPLE 3
100-X CROSS POLARS

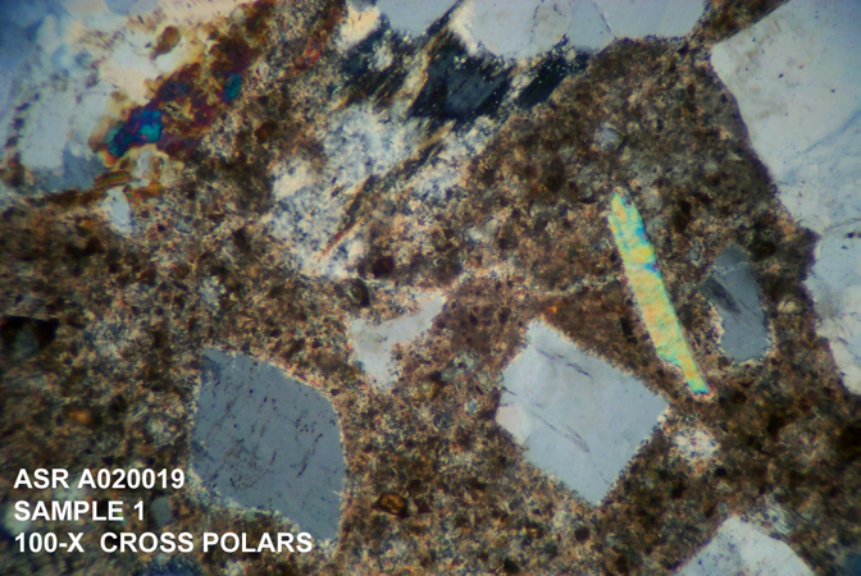


ASR A020014-A1
SAMPLE 3
100-X CROSS POLARS

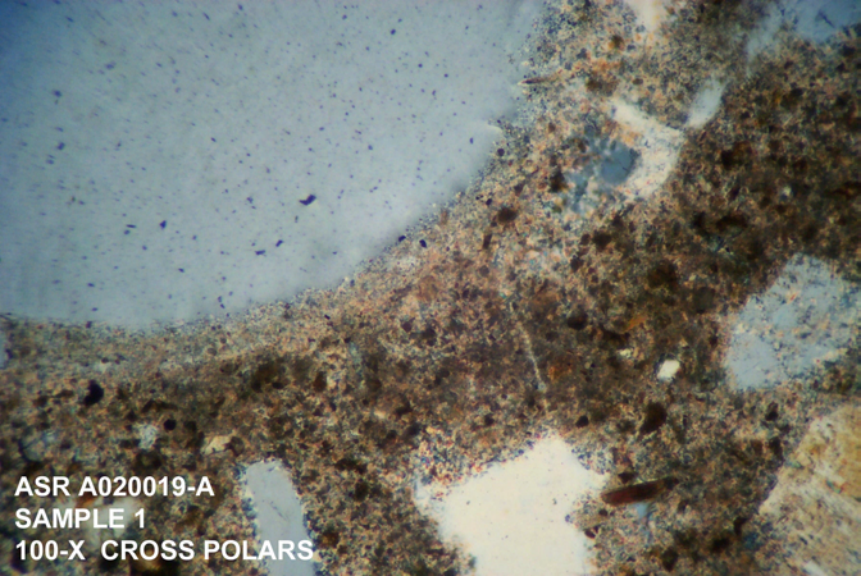


ASR A020014-E
SAMPLE 3
100-X CROSS POLARS

SAMPLE ASR A020019

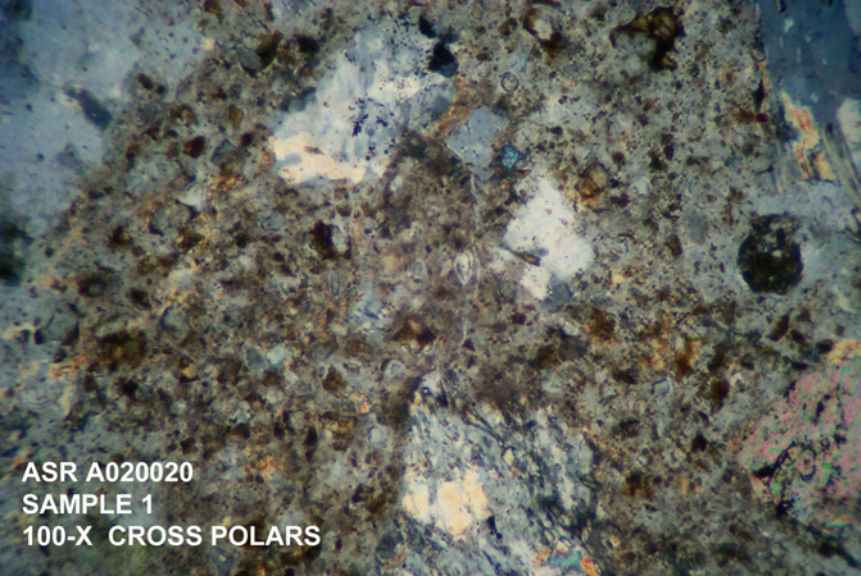


ASR A020019
SAMPLE 1
100-X CROSS POLARS



ASR A020019-A
SAMPLE 1
100-X CROSS POLARS

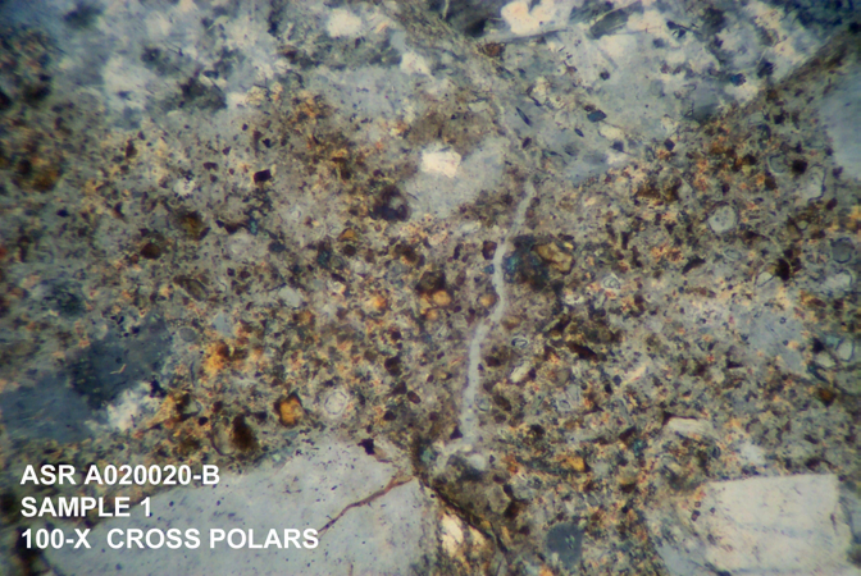
SAMPLE ASR A020020



ASR A020020
SAMPLE 1
100-X CROSS POLARS

A micrograph showing a mineral sample under cross-polarized light. The central feature is a large, roughly circular, light-colored (pale blue/white) area with a granular texture, possibly representing a specific mineral phase or a reaction zone. This central area is surrounded by a darker, more heterogeneous matrix with various shades of brown, grey, and blue, indicating a complex mineral composition. The overall appearance is that of a thin section of a rock or mineral specimen.

ASR A020020-C
SAMPLE 1
100-X CROSS POLARS

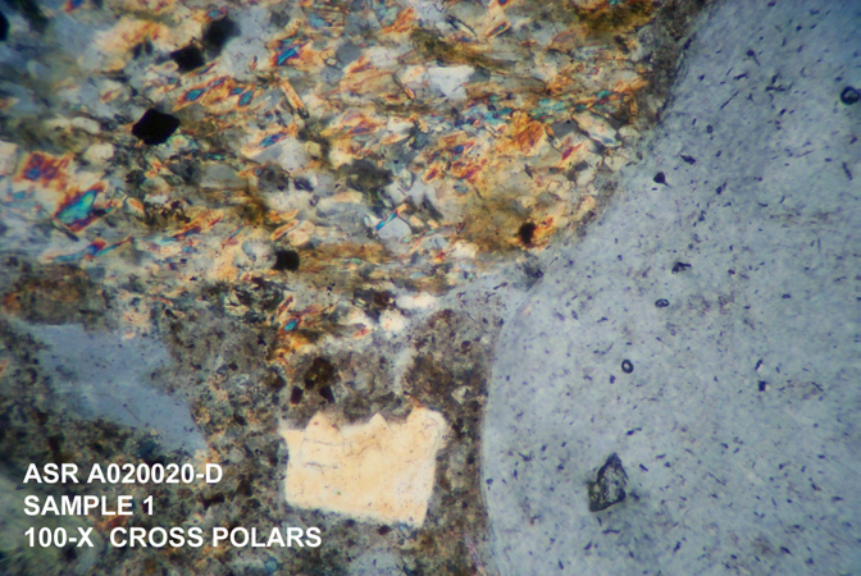


ASR A020020-B
SAMPLE 1
100-X CROSS POLARS

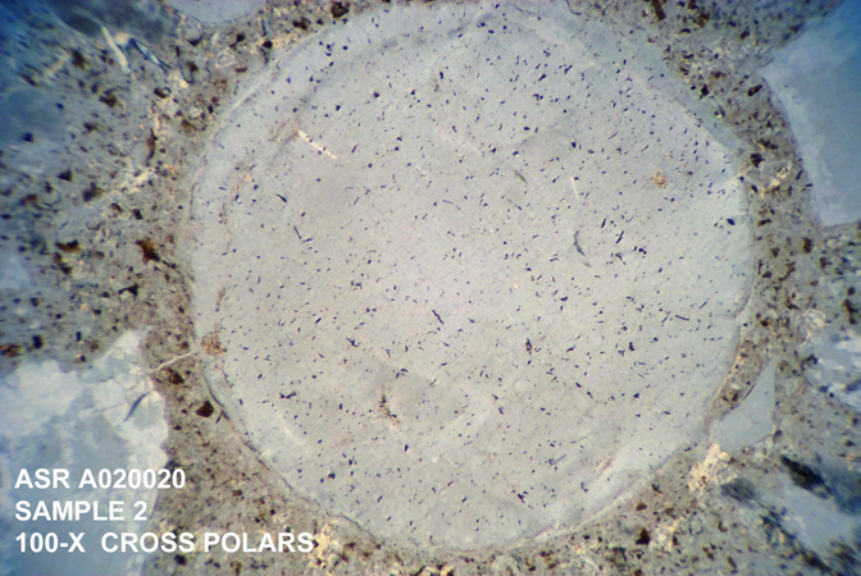


ASR A020020-A
SAMPLE 1
100-X CROSS POLARS

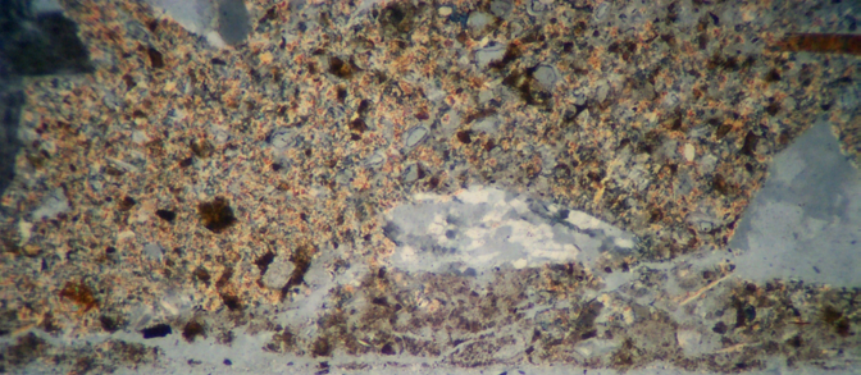
This micrograph shows a complex mineral assemblage under cross-polarized light. The field is dominated by a fine-grained, greyish matrix. Several large, irregularly shaped grains are visible, including a prominent white, somewhat angular grain in the upper center and a large, elongated, reddish-brown grain on the right side. Numerous smaller, dark, circular grains are scattered throughout the matrix. The overall texture is heterogeneous, suggesting a complex geological history.



ASR A020020-D
SAMPLE 1
100-X CROSS POLARS



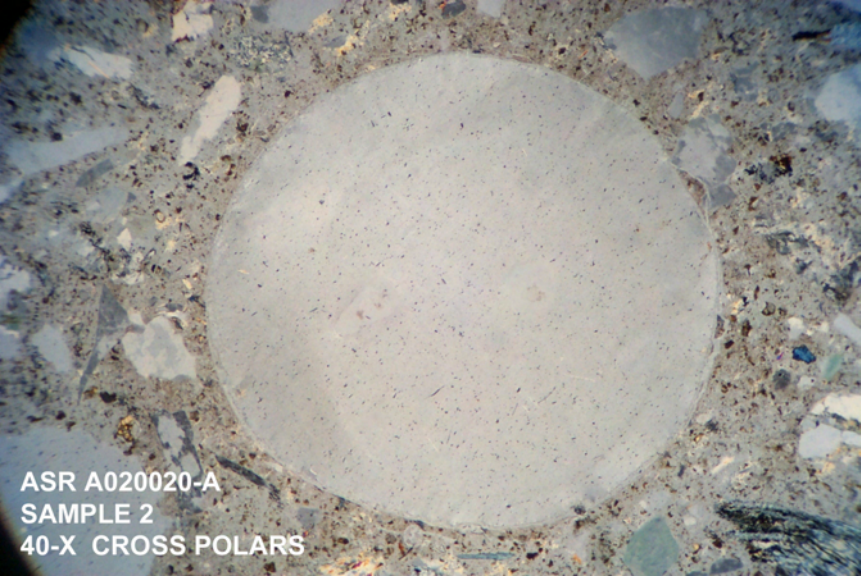
ASR A020020
SAMPLE 2
100-X CROSS POLARS



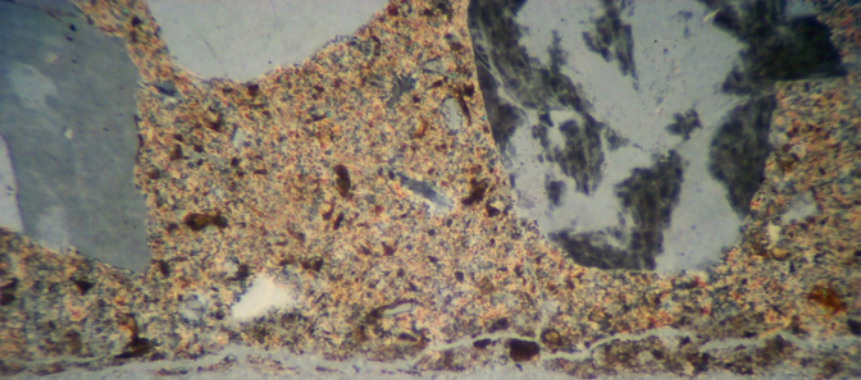
ASR A020020-C
SAMPLE 2
100-X CROSS POLARS



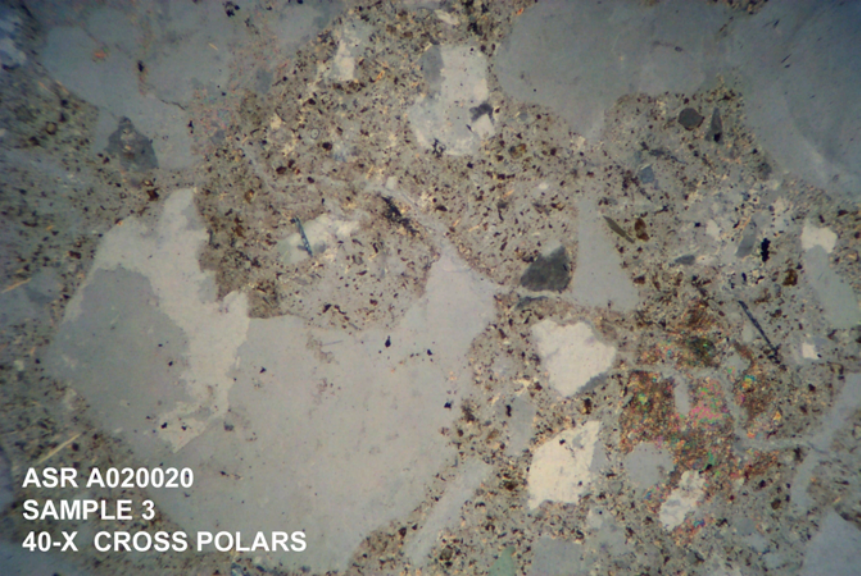
ASR A020020-B
SAMPLE 2
100-X CROSS POLARS

A circular, light-colored sample is centered in the frame, surrounded by a dark, granular matrix. The sample shows a fine, speckled texture. The surrounding matrix contains various mineral grains, some of which are birefringent and show characteristic colors under cross-polarized light, such as blue, green, and yellow. The overall appearance is that of a thin section of a rock or mineral specimen.

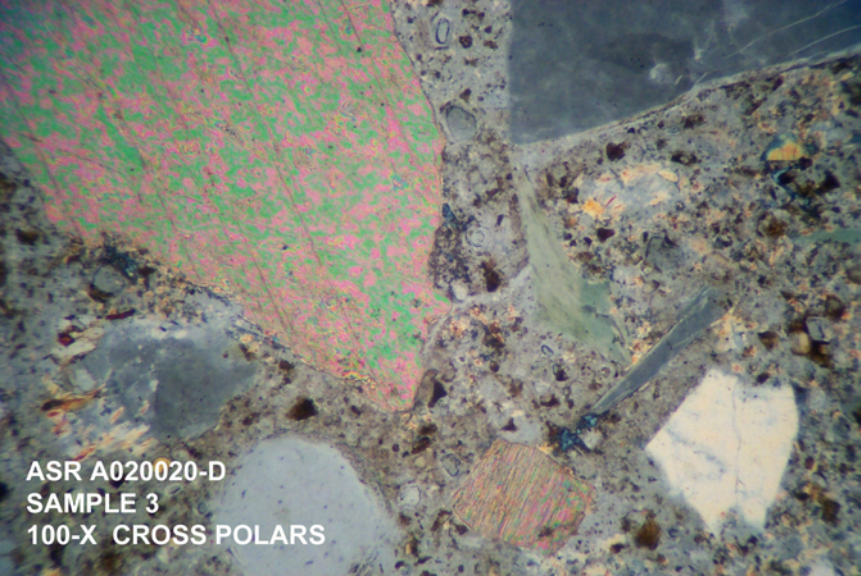
ASR A020020-A
SAMPLE 2
40-X CROSS POLARS



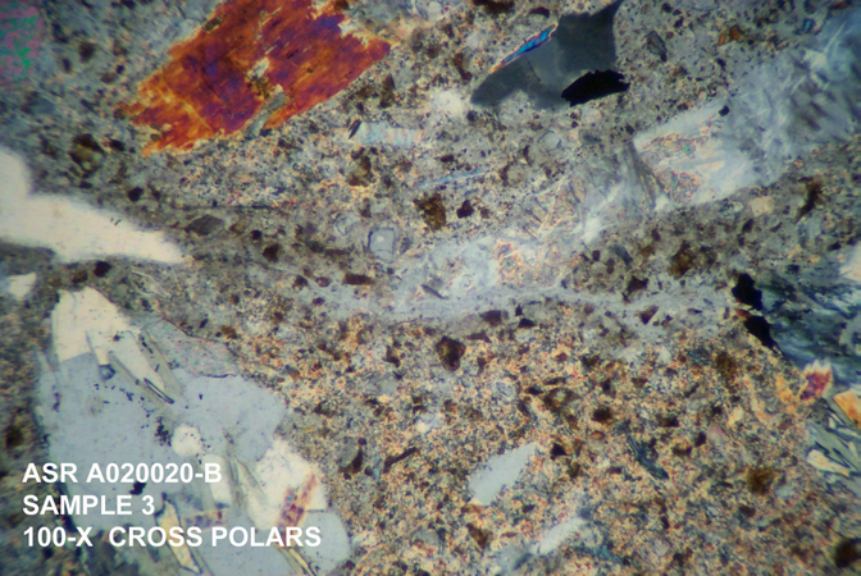
ASR A020020-C2
SAMPLE 2
100-X CROSS POLARS

A micrograph showing a complex mineral texture under cross-polarized light. The image features a light gray matrix with several darker, irregularly shaped regions. These regions contain various mineral grains, some of which are highly birefringent, showing bright, multi-colored interference colors (including red, green, and blue) against a dark background. The overall appearance is that of a heterogeneous rock or mineral sample.

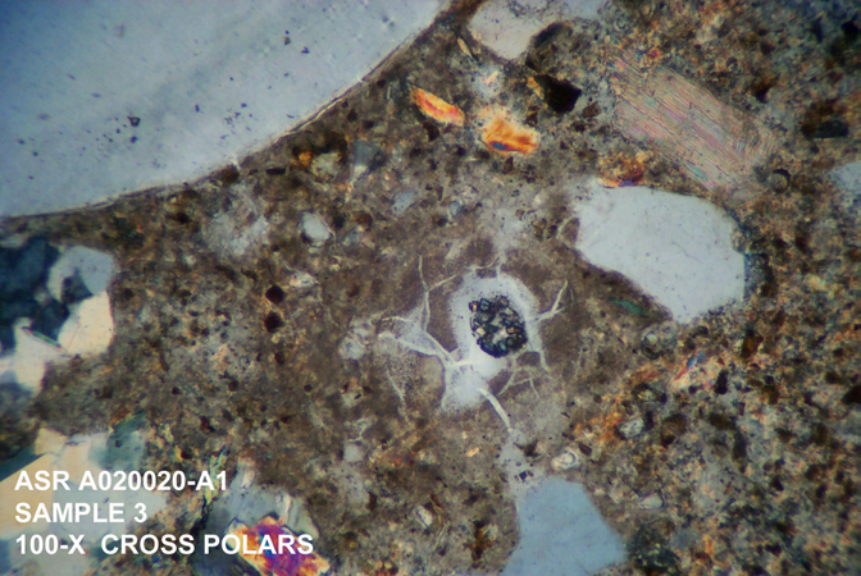
ASR A020020
SAMPLE 3
40-X CROSS POLARS



ASR A020020-D
SAMPLE 3
100-X CROSS POLARS




ASR A020020-B
SAMPLE 3
100-X CROSS POLARS



ASR A020020-A1

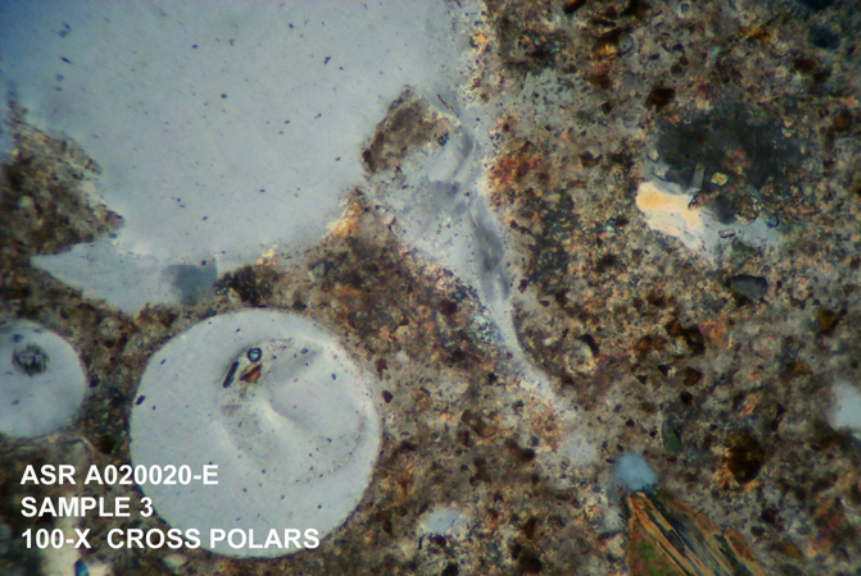
SAMPLE 3

100-X CROSS POLARS



ASR A020020-A
SAMPLE 3
40-X CROSS POLARS

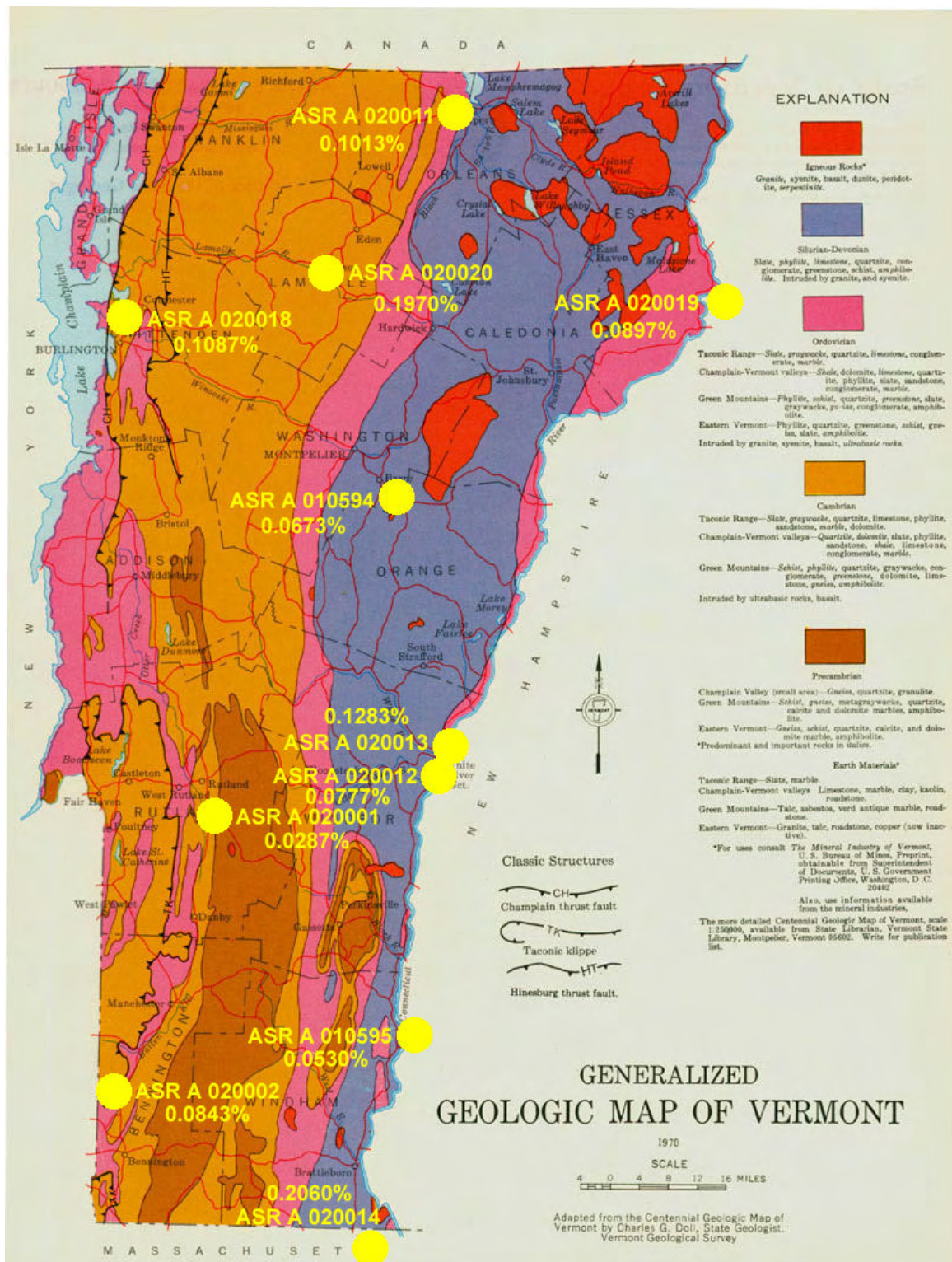
This is a photomicrograph of a mineral sample. The central feature is a large, roughly circular, light-colored grain with a fine, granular texture. This grain is surrounded by a dark, brownish matrix. The matrix contains numerous smaller, angular grains of various colors, including shades of blue, yellow, and white, which are likely different mineral phases or inclusions. The overall appearance is that of a complex, multi-phase mineral aggregate.

A micrograph showing a mineral sample under cross-polarized light. The image displays a complex, multi-colored texture with various shades of brown, tan, and grey, interspersed with bright, circular, and elongated features. These features exhibit characteristic optical properties such as interference colors and extinction patterns, typical of crystalline minerals. The overall appearance is that of a heterogeneous mineral aggregate.

ASR A020020-E
SAMPLE 3
100-X CROSS POLARS

APPENDIX D

MAP SHOWING AGGREGATE SAMPLE SOURCES AND MORTAR BAR EXPANSION VALUES



Generalized bedrock geologic map of Vermont showing aggregate source locations and AASHTO T303-00 Test Results.