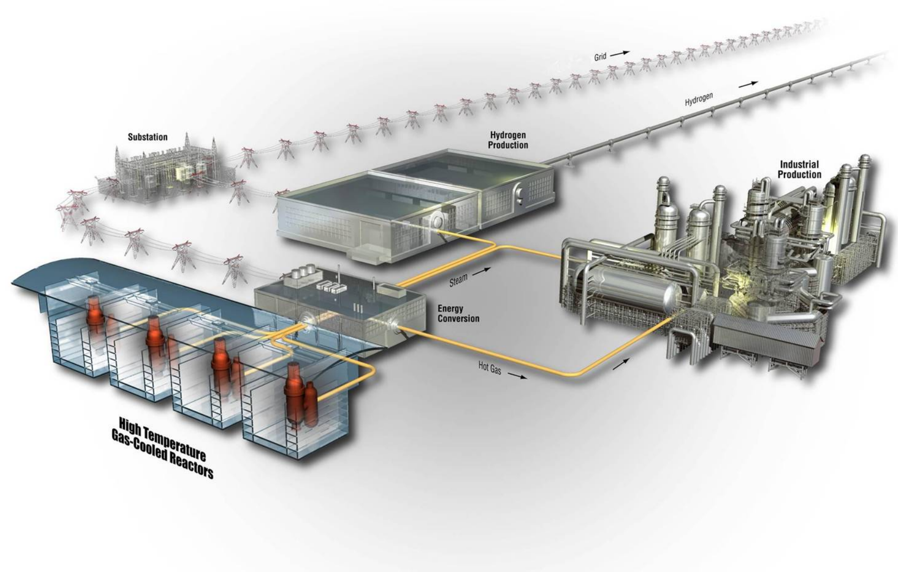
INL/EXT-10-19588
Revision 1

AGC-2 Graphite Preirradiation Data Package

David Swank
Joseph Lord
David Rohrbaugh
William Windes

October 2012



The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

Idaho National Laboratory

INL/EXT-10-19588
Revision 1

AGC-2 Graphite Preirradiation Data Package

David Swank, Joseph Lord, David Rohrbaugh, William Windes

October, 2012

Idaho National Laboratory
Next Generation Nuclear Plant Project
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

This page is intentionally left blank

Very High Temperature Reactor Program

AGC-2 Graphite Preirradiation Data Package

INL/EXT-10-19588
Revision 1

October **2012**

Approved by:

David Swank Author	9/18/12 Date
William Windes VHTR TDO Graphite R&D Lead	10/2/12 Date
Travis Mitchell VHTR TDO Project Manager	10/9/12 Date
David Jensen VHTR TDO Quality Assurance	9/12/12 Date

This page is intentionally left blank

SUMMARY

The Next Generation Nuclear Plant Project Graphite Research and Development program is currently establishing the safe operating envelope of graphite core components for a very high temperature reactor design. The program is generating quantitative data necessary for predicting the behavior and operating performance of the new nuclear graphite grades. To determine the in-service behavior of the graphite for pebble bed and prismatic designs, the Advanced Graphite Creep (AGC) experiment is underway. This experiment is examining the properties and behavior of nuclear grade graphite over a large spectrum of temperatures, neutron fluencies, and compressive loads. Each experiment consists of over 400 graphite specimens that are characterized prior to irradiation and following irradiation. Six experiments are planned with the first, AGC-1, currently being irradiated in the Advanced Test Reactor and preirradiation characterization of the second, AGC-2, completed. This data package establishes the readiness of 512 specimens for assembly into the AGC-2 capsule.

This page is intentionally left blank

CONTENTS

This page is intentionally left blank

AGC-2 Graphite Preirradiation Data Package

1. INTRODUCTION

The Next Generation Nuclear Plant (NGNP) will be a high temperature gas-cooled reactor (HTGR) with a large graphite core. Graphite has been effectively used as both structural and moderator material in research reactors as well as commercial HTGRs. While the general characteristics necessary for producing nuclear grade graphite are understood, historical nuclear grades no longer exist. New grades must therefore be produced, characterized, and irradiated in order to demonstrate that current grades of graphite exhibit acceptable irradiated and nonirradiated properties, upon which the thermomechanical design of the structural graphite in the NGNP is based.

The nuclear graphite type H-451, used previously in the United States for HTGR graphite components, is no longer available. New graphite types have been developed and are considered suitable candidates for the new NGNP reactor design. To support the design and licensing of NGNP core components within a commercial reactor, a complete properties database must be developed for these current grades of graphite. Quantitative data are required for the physical, mechanical (including radiation-induced creep), and oxidation properties of each graphite type.

To determine the in-service behavior of the graphite for both pebble bed and prismatic reactor designs, the Advanced Graphite Creep (AGC) experiment is underway. This experiment is examining the properties and behavior of nuclear grade graphite over a large spectrum of temperatures, irradiation fluencies, and compressive loads. Each experiment consists of over 500 graphite specimens that are characterized before and after irradiation. Six experiments are planned with the first, AGC-1, currently being irradiated in the Advanced Test Reactor (ATR) and preirradiation characterization of the second, AGC-2, completed. This data package establishes the readiness of 512 specimens for assembly into the AGC-2 capsule buy documenting the completion of the preirradiation characterization and establishing that the laser engraved identity of each specimen is legible and the specimen is contained in a correctly labeled container.

2. PREIRRADIATION PROPERTY CHARACTERIZATION

The objective of the AGC-2 experiment is to determine the material property changes induced in nuclear grade graphite during exposure to a high temperature neutron environment. The approach is to perform extensive preirradiation characterization testing on each sample before exposing the graphite samples to various neutron doses. After irradiation, the same characterization tests will be performed on each irradiated sample to ascertain the quantitative changes to the material properties of the graphite.

The AGC-2 specimens have been characterized per PLN-3267 “AGC-2 Characterization Plan.” This plan describes the thermal, physical, and mechanical measurement techniques and methods that were used to characterize the different graphite types being tested in the AGC-2 experiment and is intended to meet the requirements of Management Control Procedure (MCP) MCP-1380, “Research and Development Test Control,” and NQA-1 Test Control. Described within the plan are the instruments, fixtures, and methods used for preirradiation material property measurements of bulk density, thermal diffusivity, coefficient of thermal expansion, elastic modulus, and electrical resistivity.

Major grades of the nuclear-grade graphite types to be tested in AGC-2 are NBG-17, NBG-18, PCEA, IG-430, H-451, 2114, and IG-110. Minor grades of graphite include NBG-25, PCIB, PPEA, NBG-10, BAN, HLM, PGX, S2020, HOPG, and A3 matrix. All major grades have been characterized fully per PLN-3267 and the minor grades have only had dimensional, density and thermal diffusivity measurements performed on them. The two primary specimen types in the AGC experiments are creep samples and piggyback samples. “Creep” specimens from major grade graphite types are shown in INL Drawing 600786-21, Rev. 1, and will be subjected to a mechanical load during irradiation to induce irradiation creep within the specimens. “Piggyback” specimens from both major and minor grade graphite types are shown in INL Drawing 600786-1, Rev. 1. They are not subjected to a mechanical load and are subjected only to neutron irradiation at high operating temperatures to assess the effects of a reactor environment on the specific graphite grade.

All specimens are 12.7 mm in diameter, with the creep specimens being 25.4 mm long and the piggyback specimens being 6 mm long. Details of how specimens were cut from the graphite blocks are contained in INL Drawing 600787, Rev. 2, "ATR Advanced Graphite Capsule (AGC-2) Experiment Graphite Specimen Cut-Out Diagrams."

The data resulting from the preirradiation characterization are plotted in Figures A-1 through A-66 in Appendix A. Interpretation and detailed analysis of the data will follow in an AGC-2 data analysis report. Statistical evaluation will be performed using an inner quartile range analysis to identify levels of uncertainty and outliers in the data. The measured properties and characteristics of different graphite types will be compared along with the effect of grain orientation. As part of the publication of this report, the data and report will be independently reviewed by Oak Ridge National Lab.

3. IDENTIFICATION VERIFICATION

To establish the condition and identification of the AGC-2 specimens a "Source/Receiving Inspection Instruction" was completed by an INL certified inspector after all characterization measurements were complete. Each specimen was photographed four times around the circumference to record its physical condition. Each specimen's laser engraved identification was verified to match the bar-coded label on the specimen container. The complete "Source/Receiving Inspection Instruction" is contained in Appendix B.

Appendix A

AGC-2 Preirradiation Data

Appendix A—AGC-2 Preirradiation Data

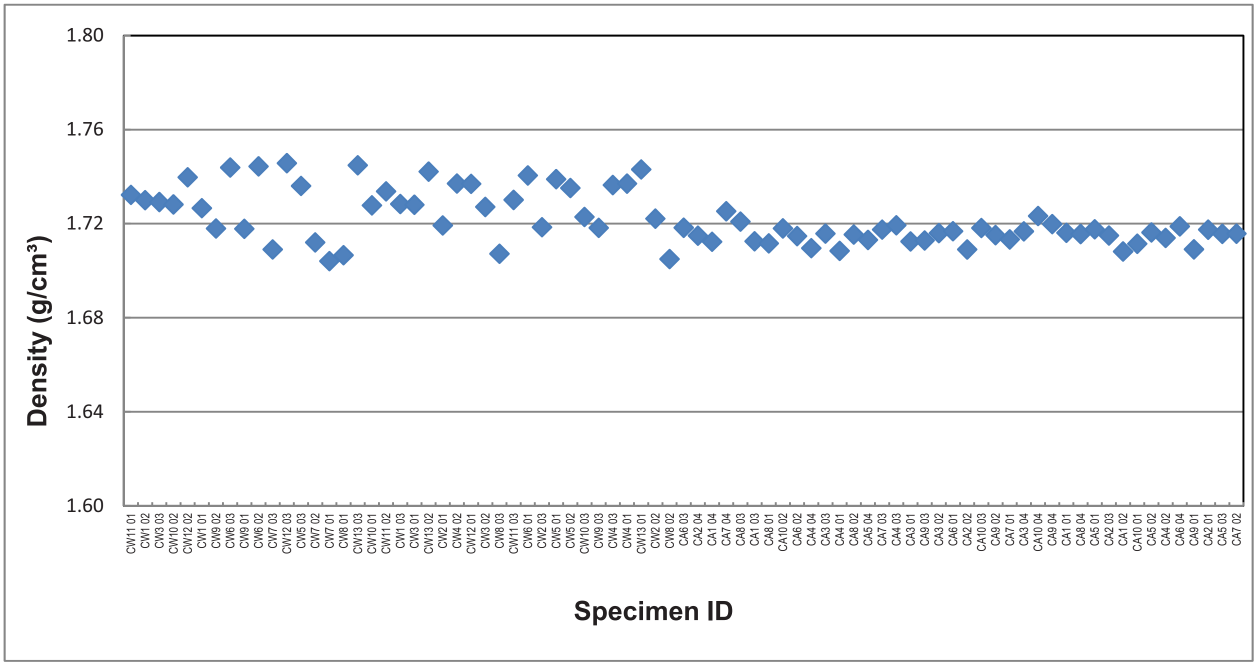


Figure A-1. Density for H-451.

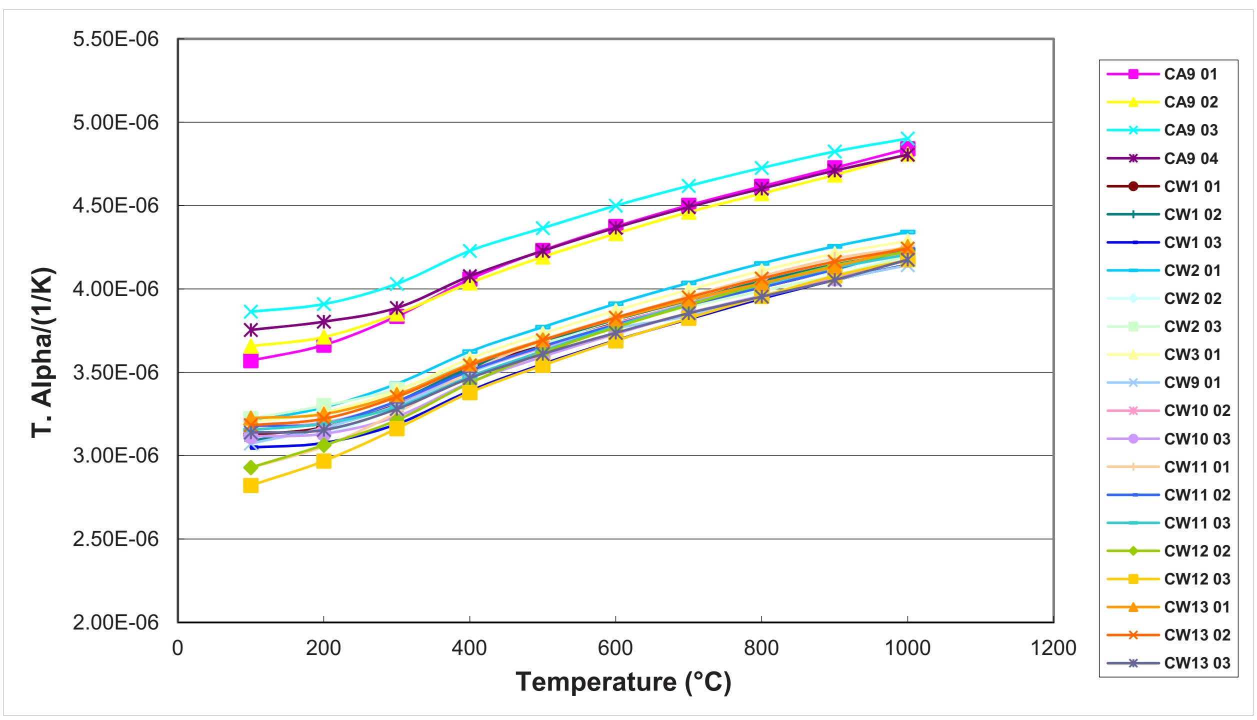


Figure A-2. Coefficient of thermal expansion for H-451.

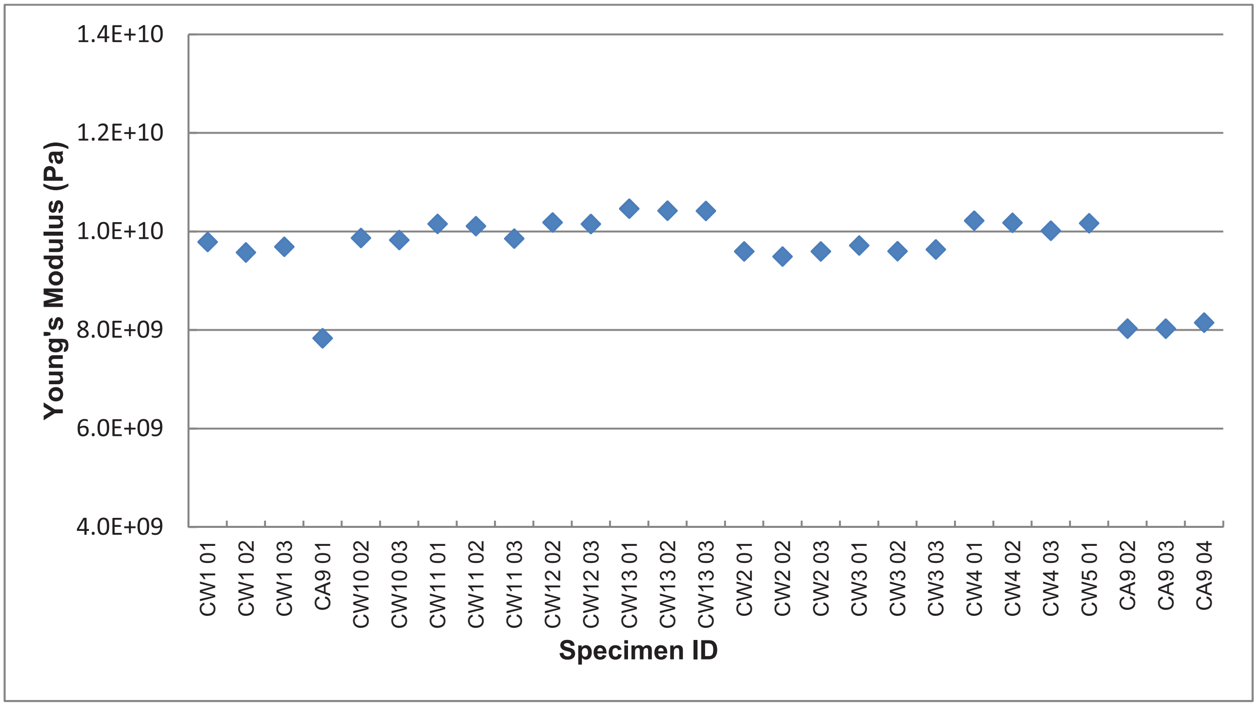


Figure A-3. Young's Modulus by sonic resonance for H-451.

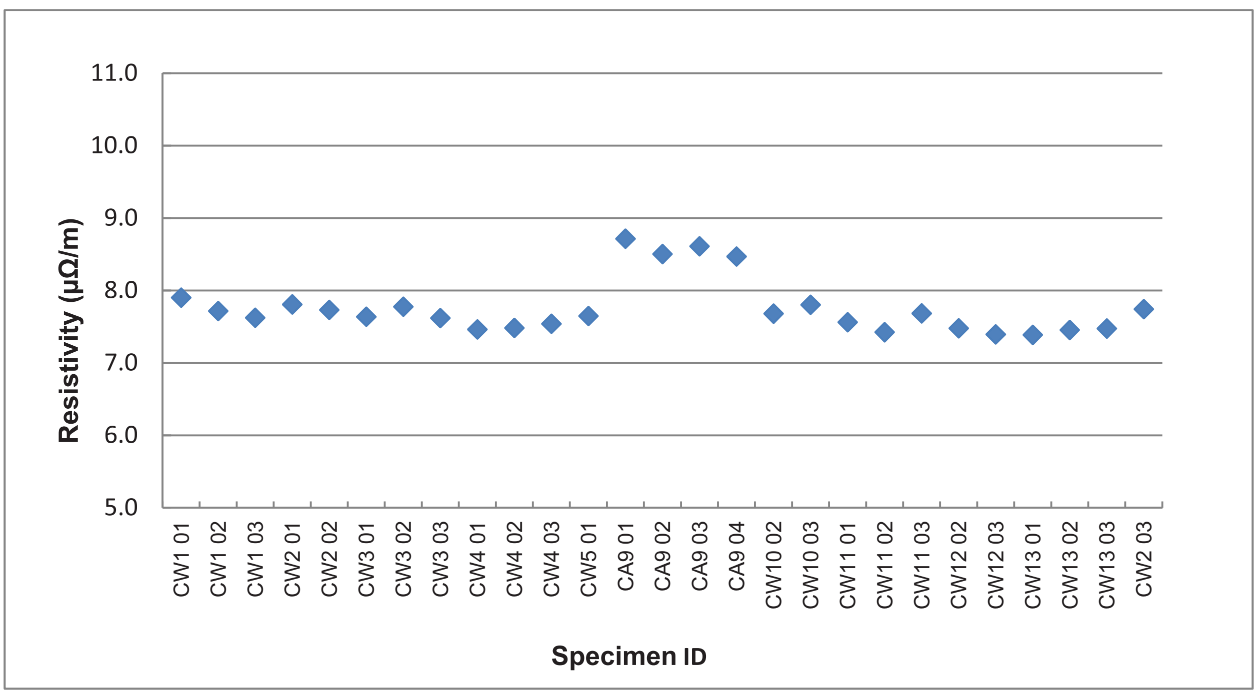


Figure A-4. Resistivity for H-451.

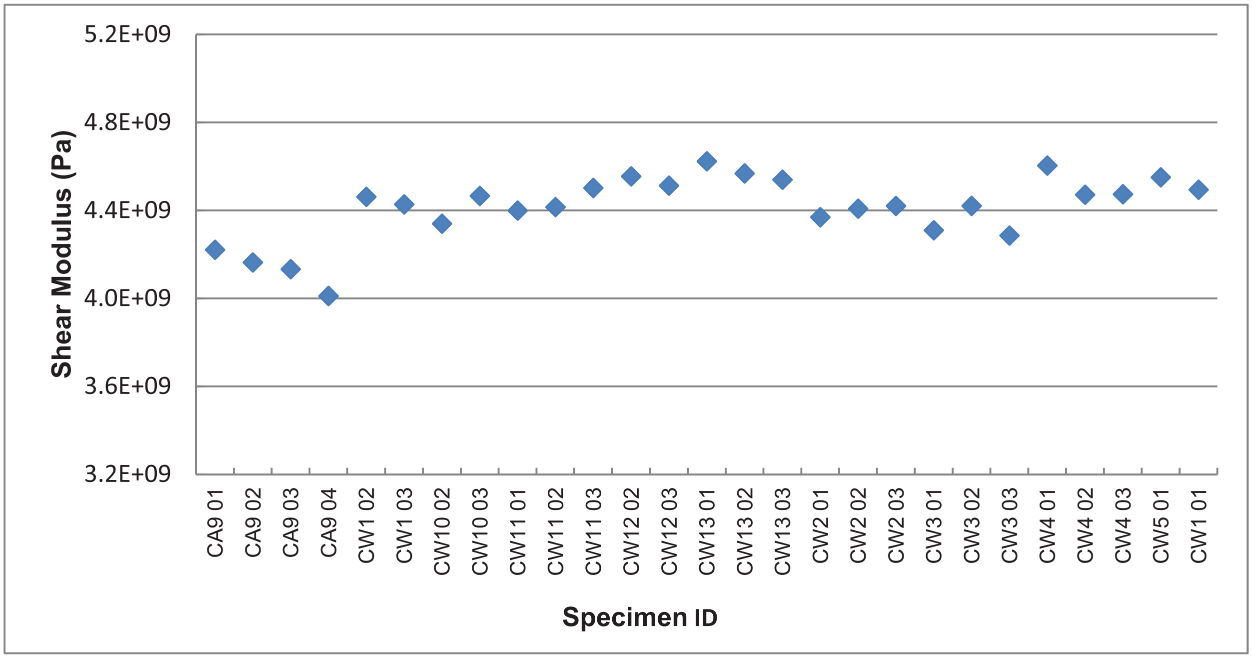


Figure A-5. Shear Modulus by sonic velocity for H-451.

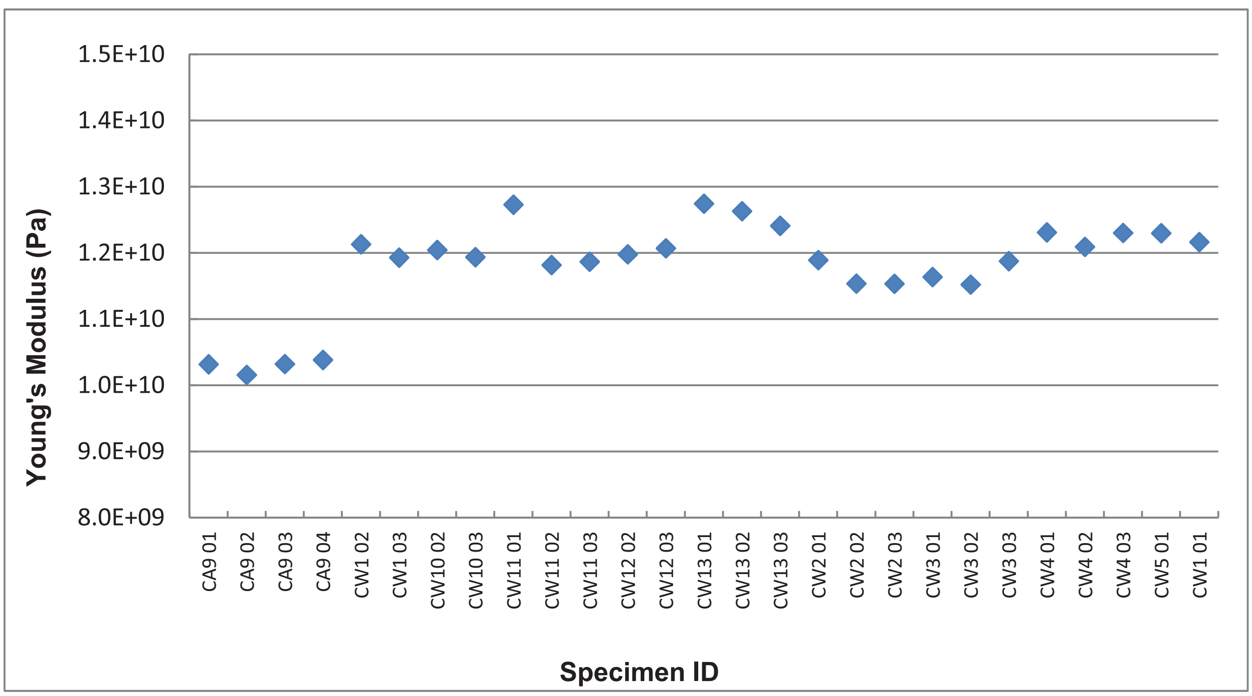


Figure A-6. Young’s Modulus by sonic velocity for H-451.

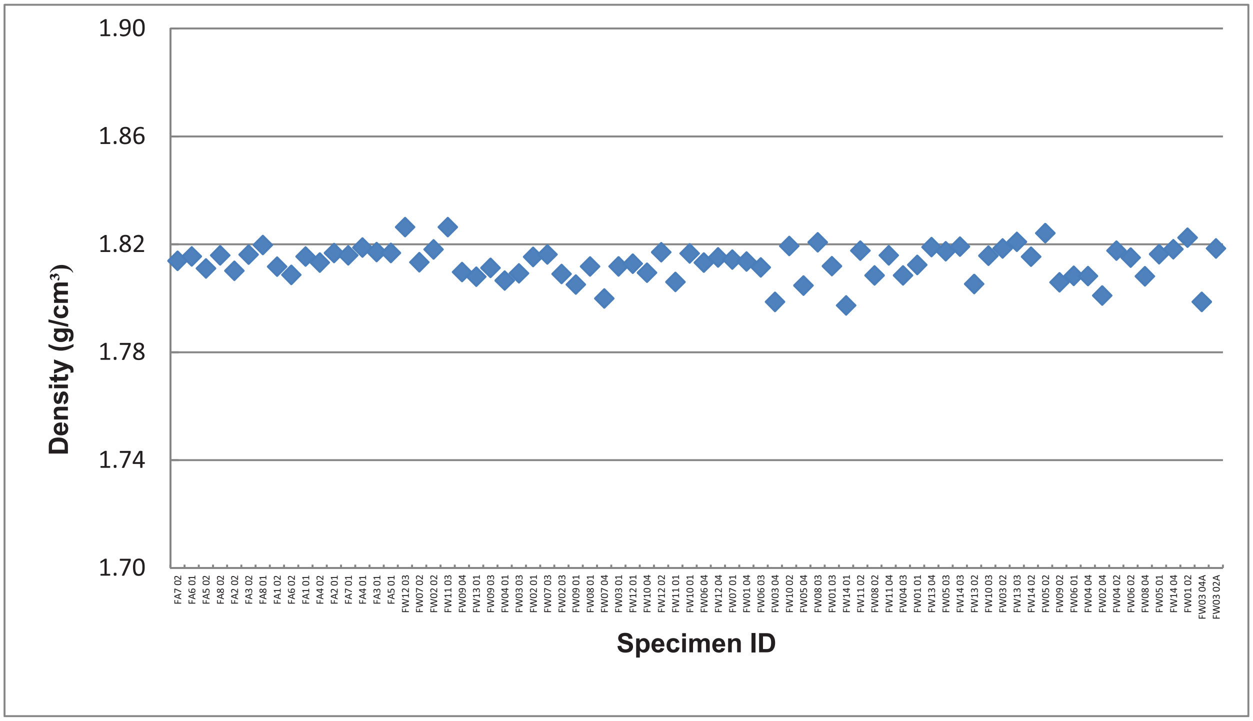


Figure A-7. Density for IG-430.

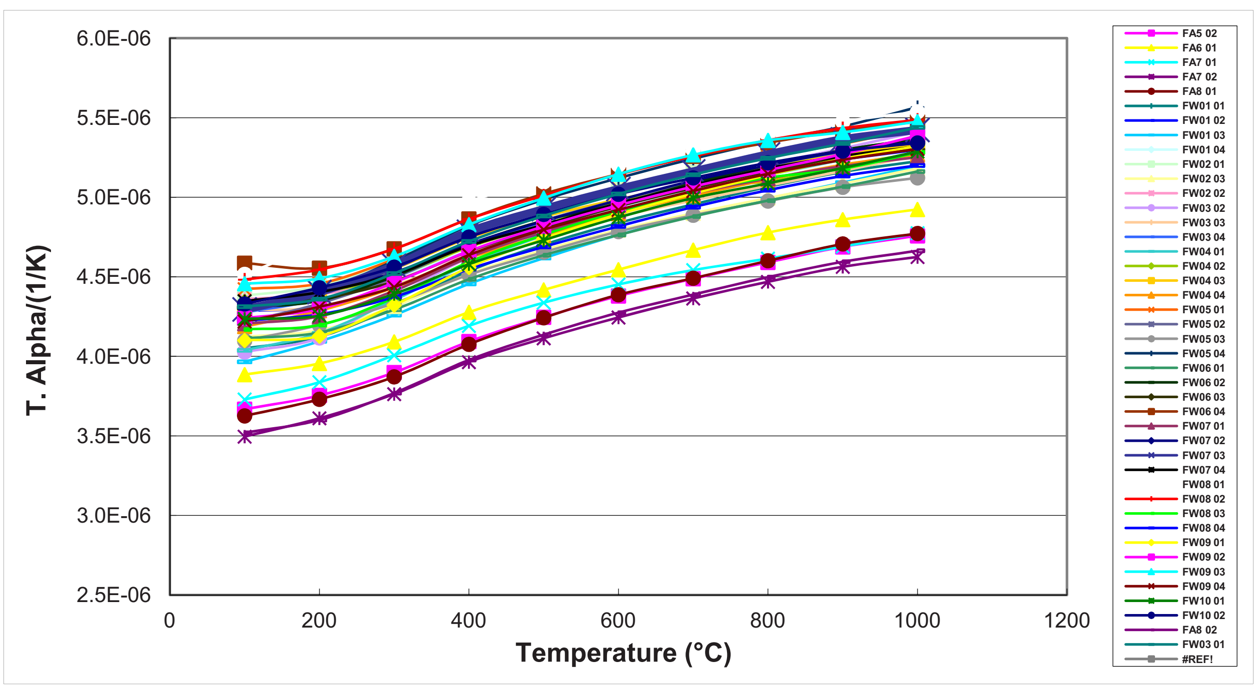


Figure A-8. Coefficient of thermal expansion for IG-430.

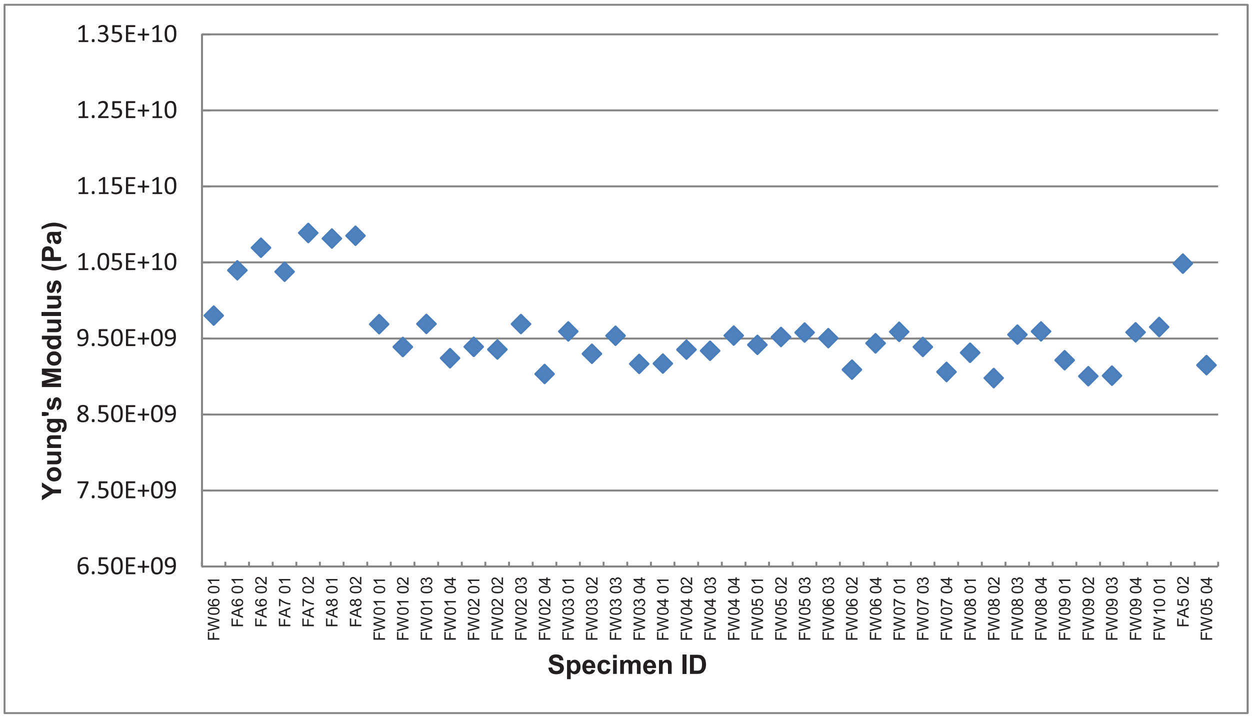


Figure A-9. Young's Modulus by sonic resonance for IG-430.

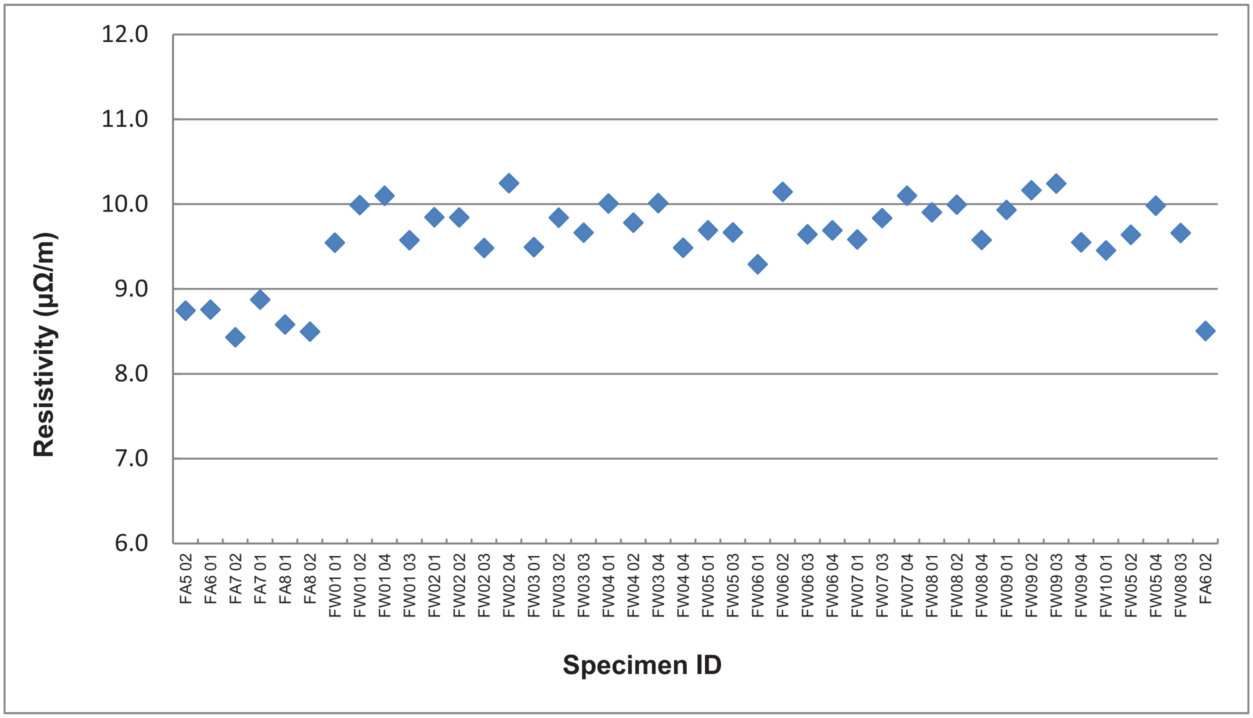


Figure A-10. Resistivity for IG-430.

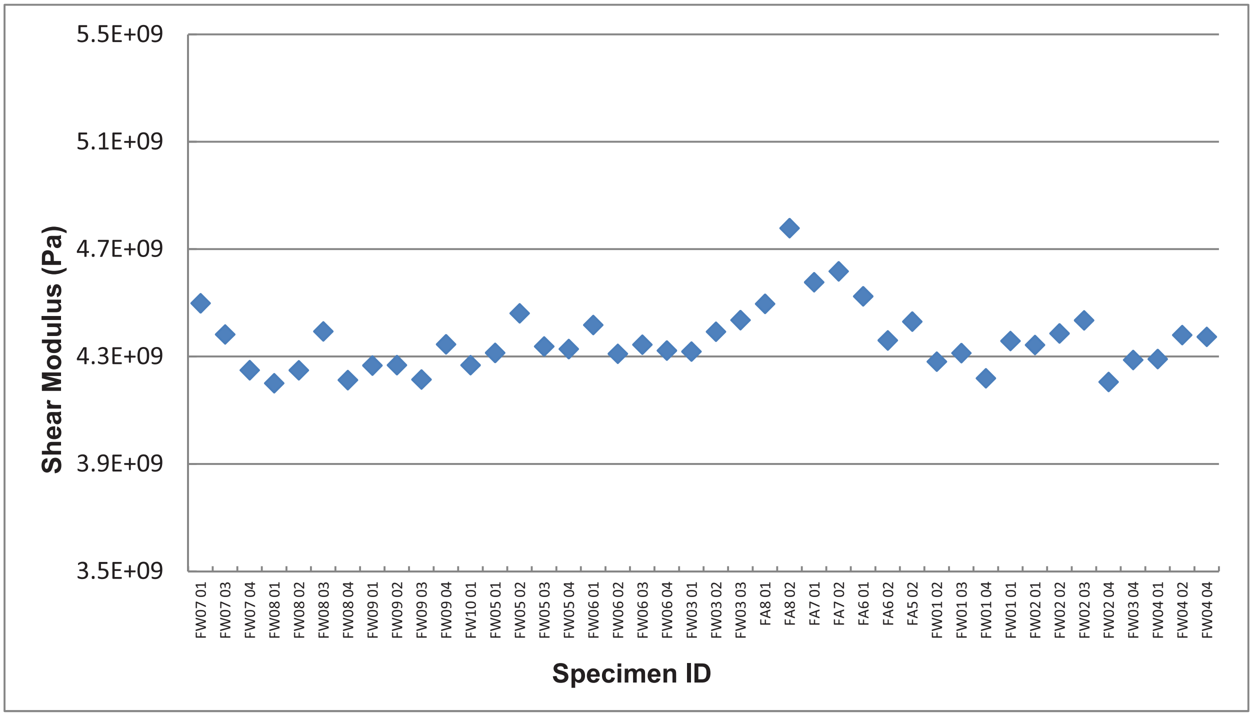


Figure A-11. Shear Modulus by sonic velocity for IG-430.

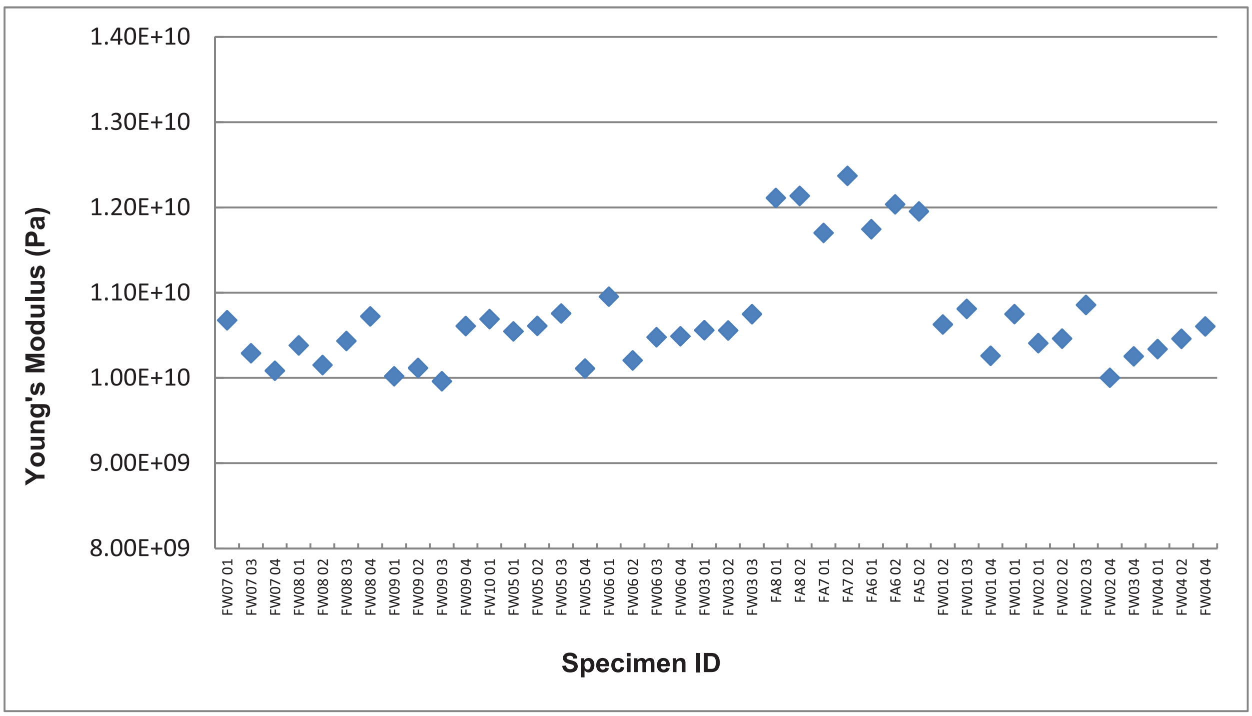


Figure A-12. Young’s Modulus by sonic velocity for IG-430.

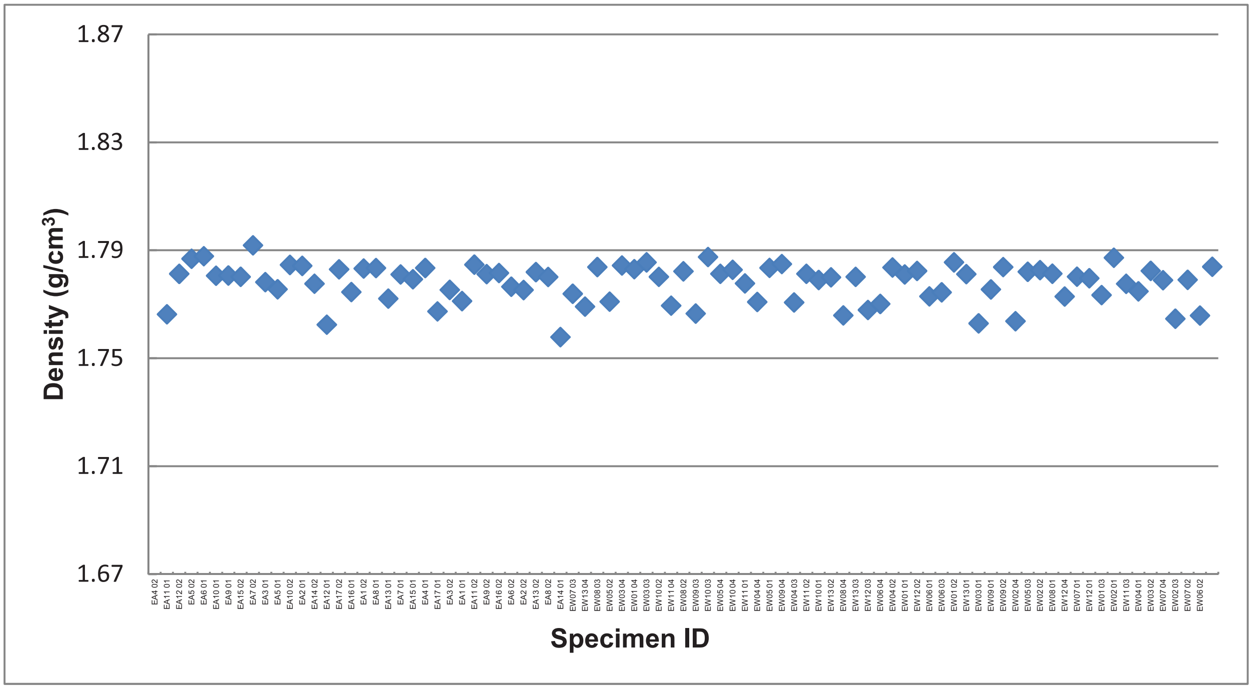


Figure A-13. Density for IG-110.

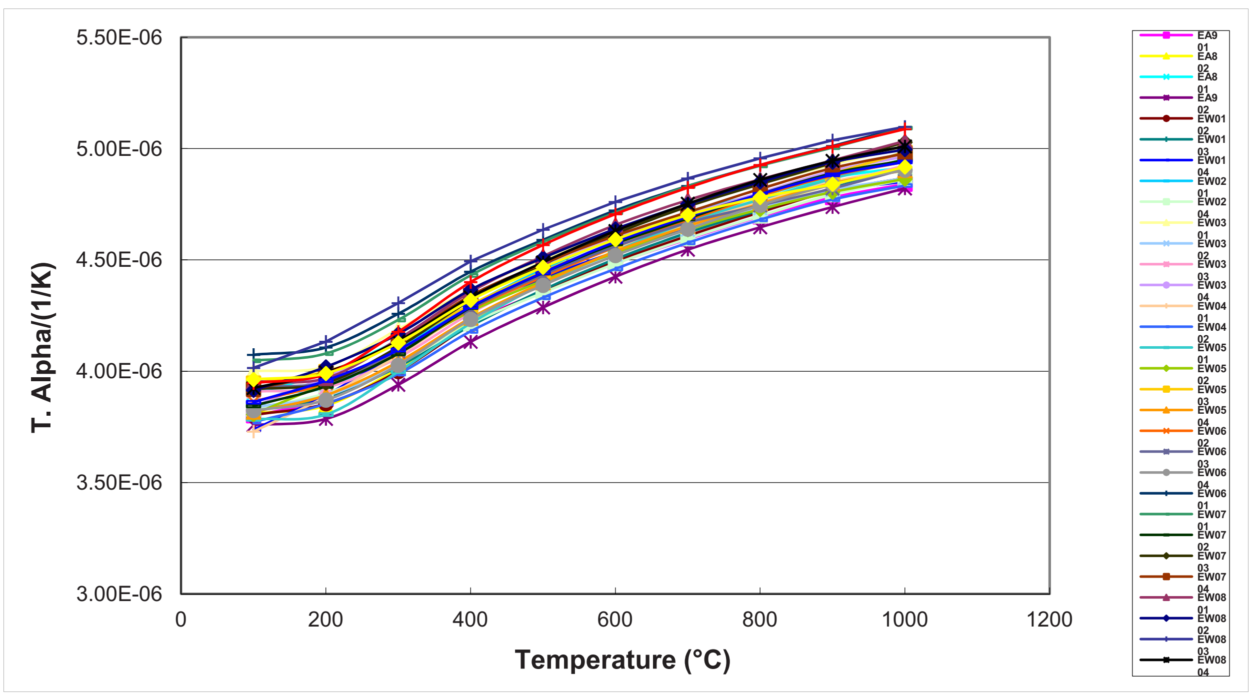


Figure A-14. Coefficient of thermal expansion for IG-110.

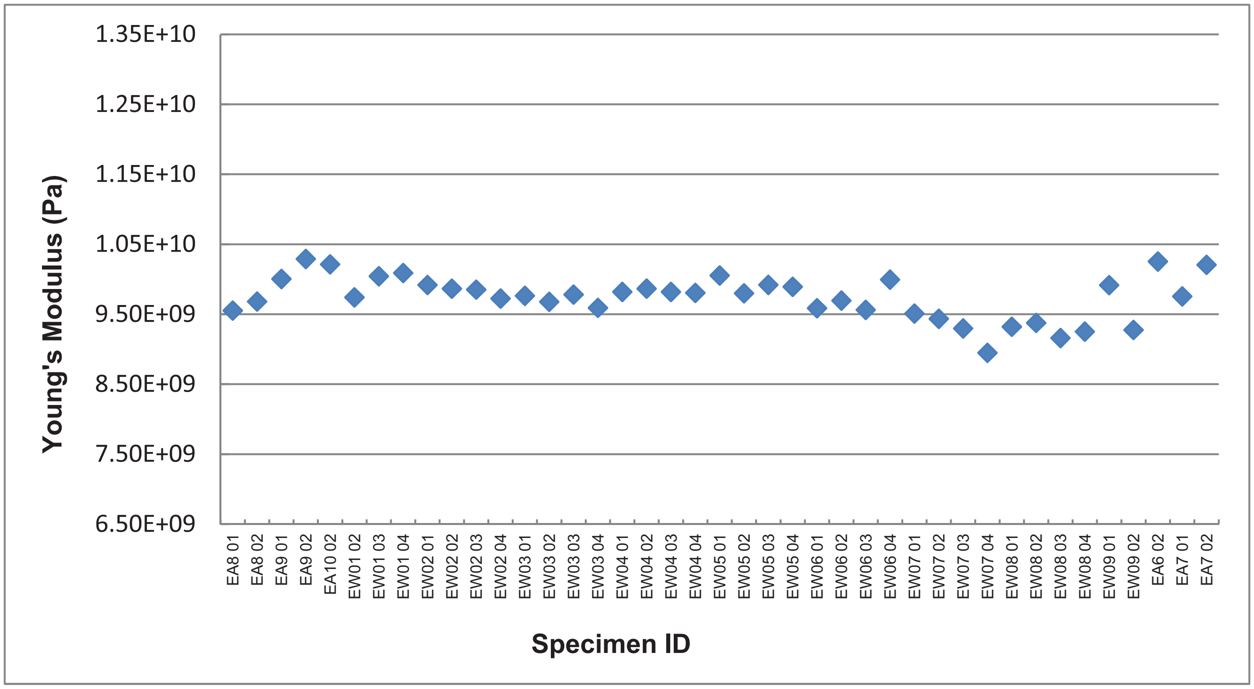


Figure A-15. Young's Modulus by sonic resonance for IG-110.

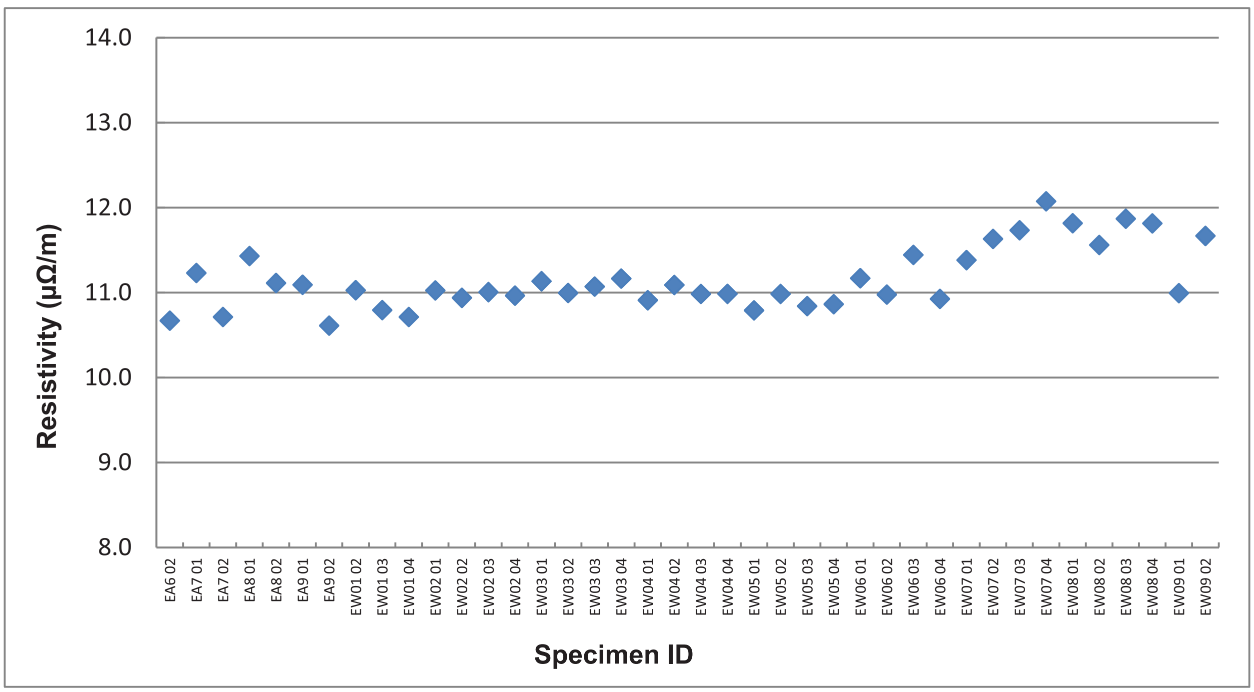


Figure A-16. Resistivity for IG-110.

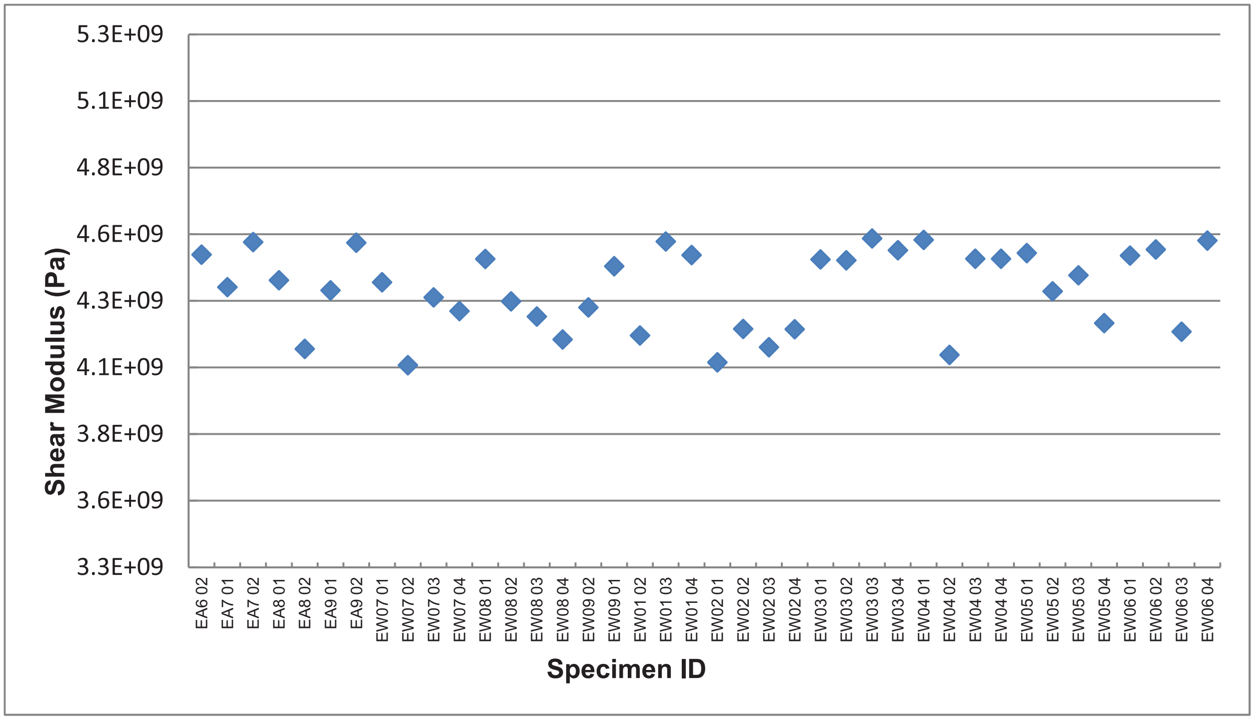


Figure A-17. Shear Modulus by sonic velocity for IG-110.

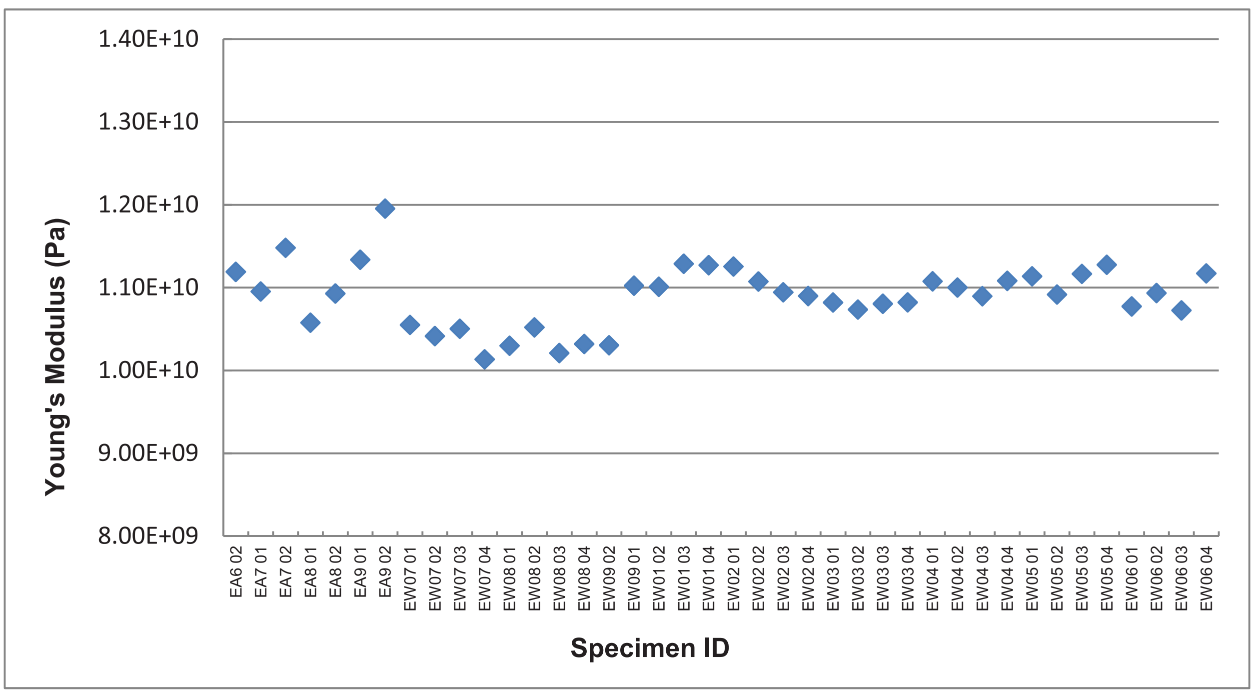


Figure A-18. Young's Modulus by sonic velocity for IG-110.

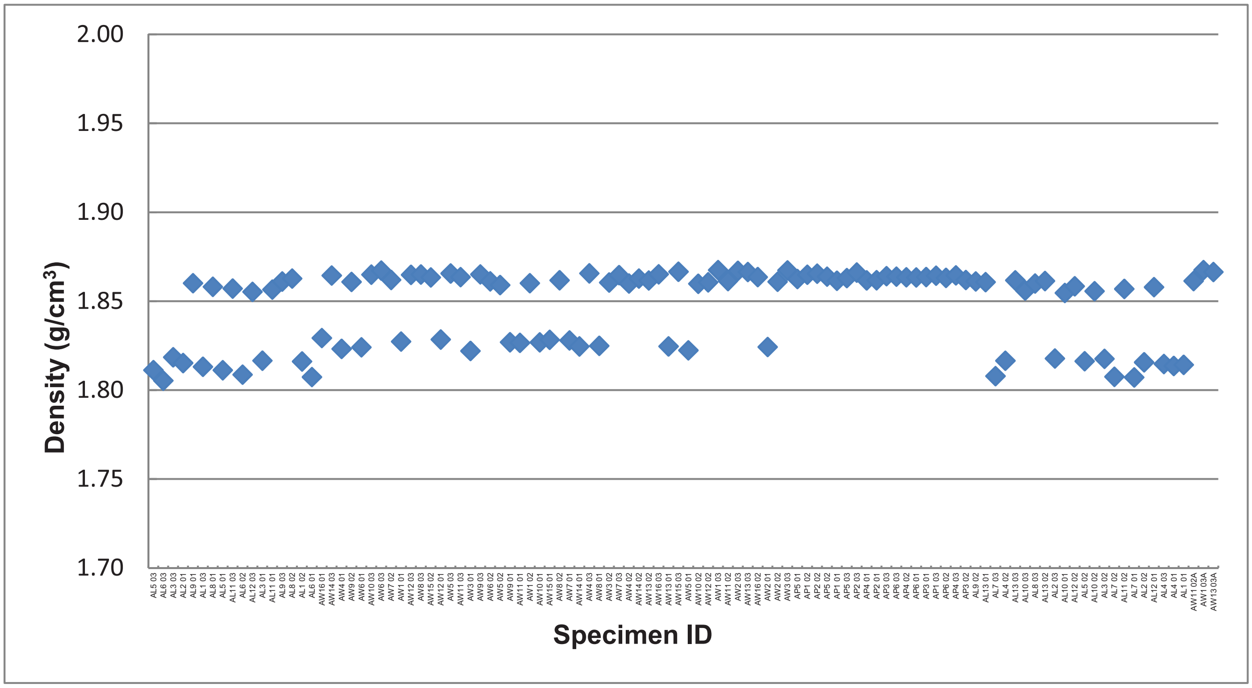


Figure A-19. Density for NBG-17.

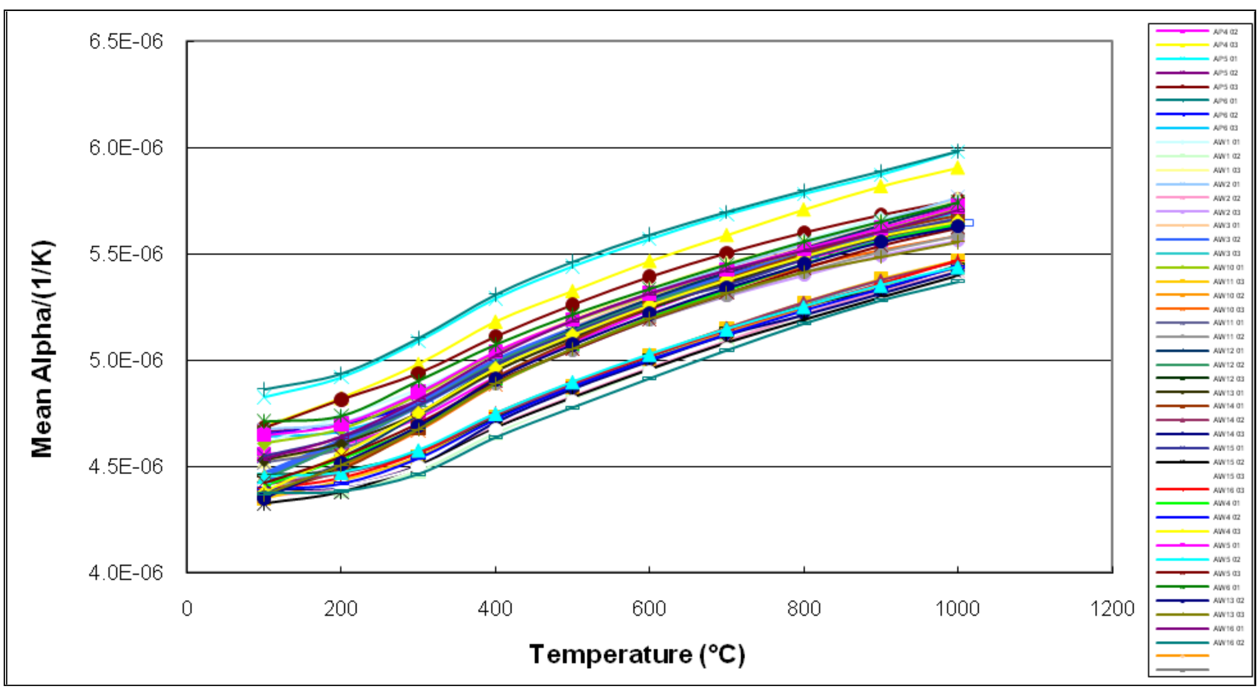


Figure A-20. Coefficient of thermal expansion for NBG-17.

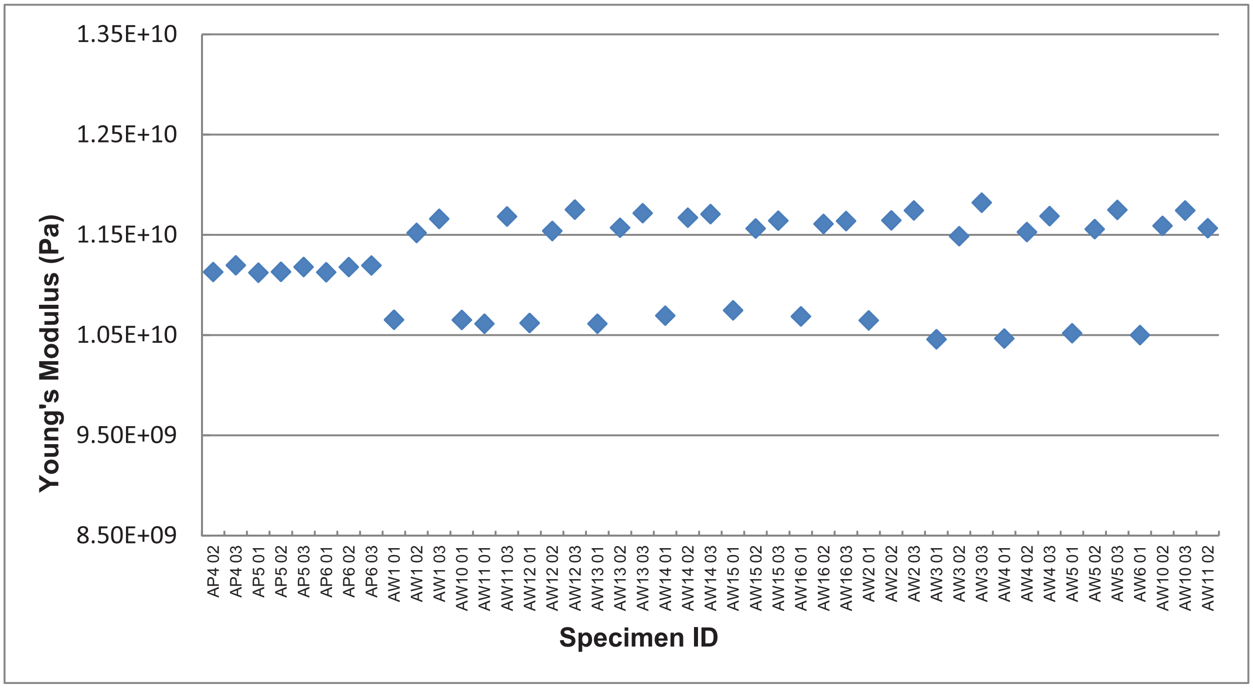


Figure A-21. Young's Modulus by sonic resonance for NBG-17.

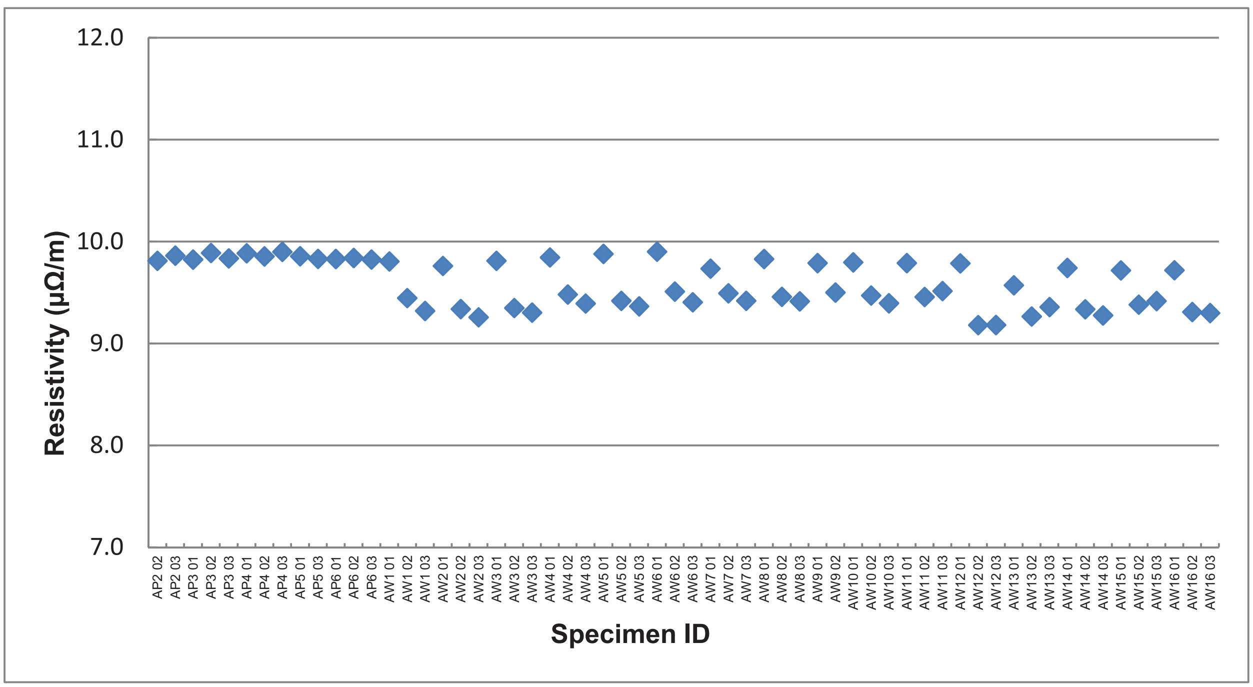


Figure A-22. Resistivity for NBG-17.

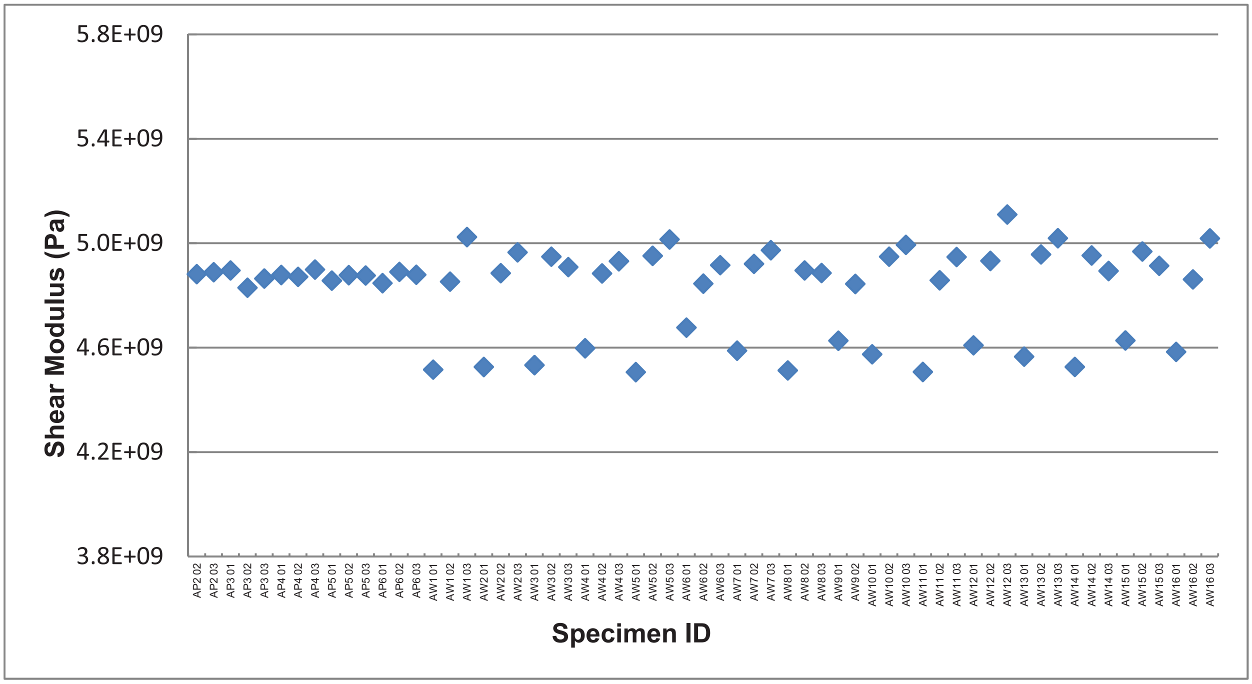


Figure A-23. Shear Modulus by sonic velocity for NBG-17.

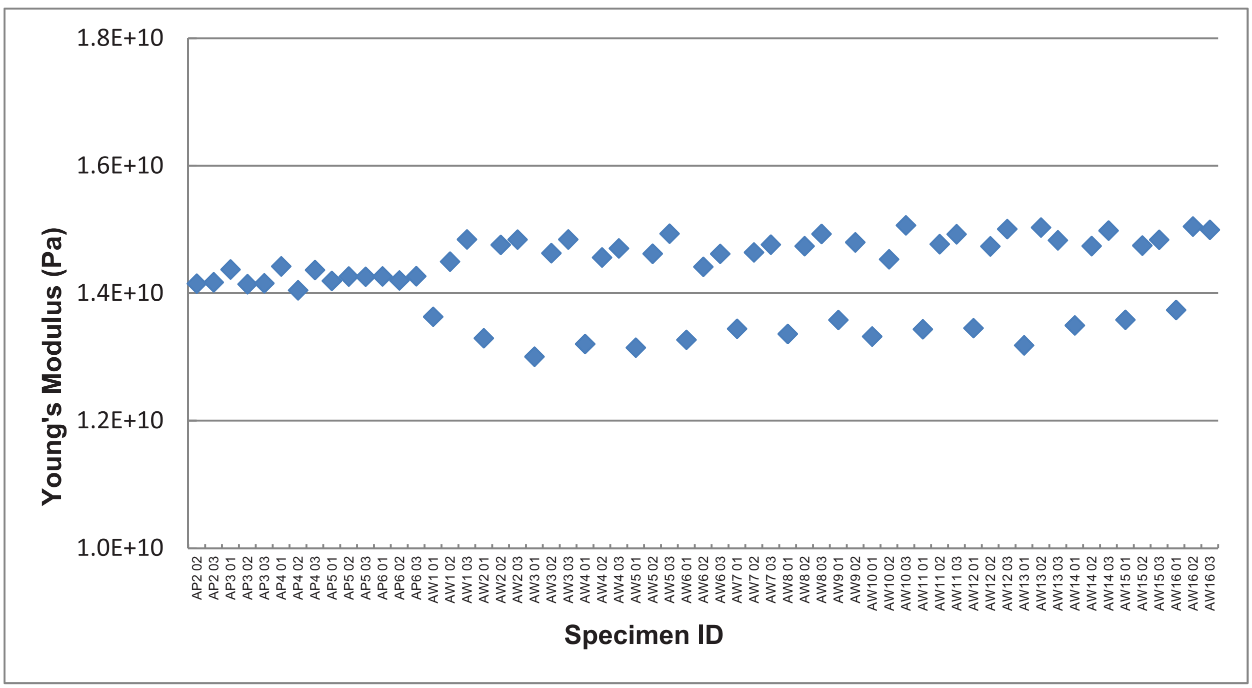


Figure A-24. Young’s Modulus by sonic velocity for NBG-17.

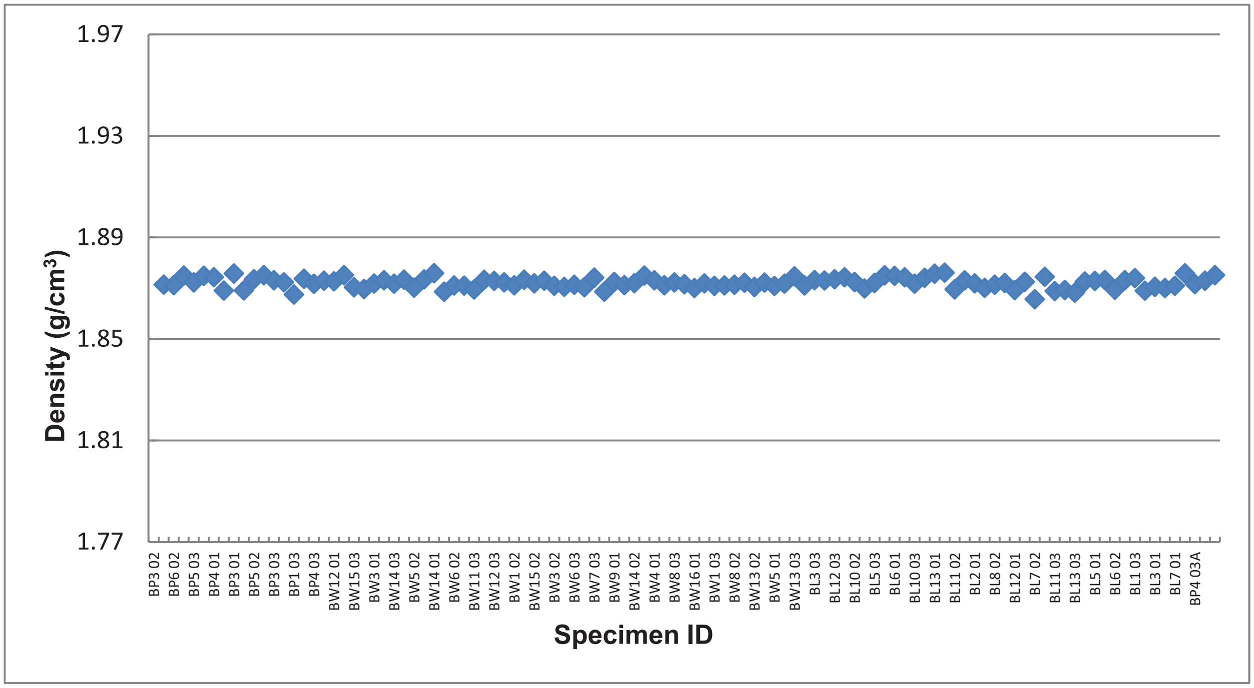


Figure A-25. Density for NBG 18.

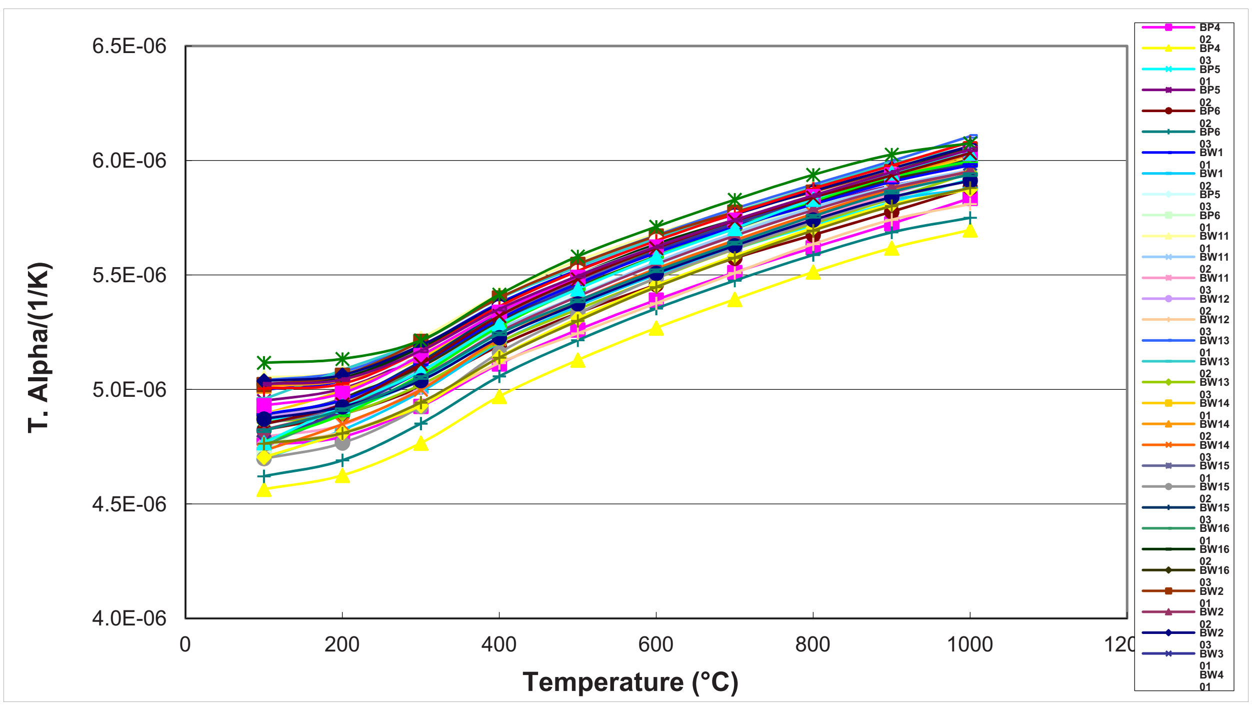


Figure A-26. Coefficient of thermal expansion for NBG-18.

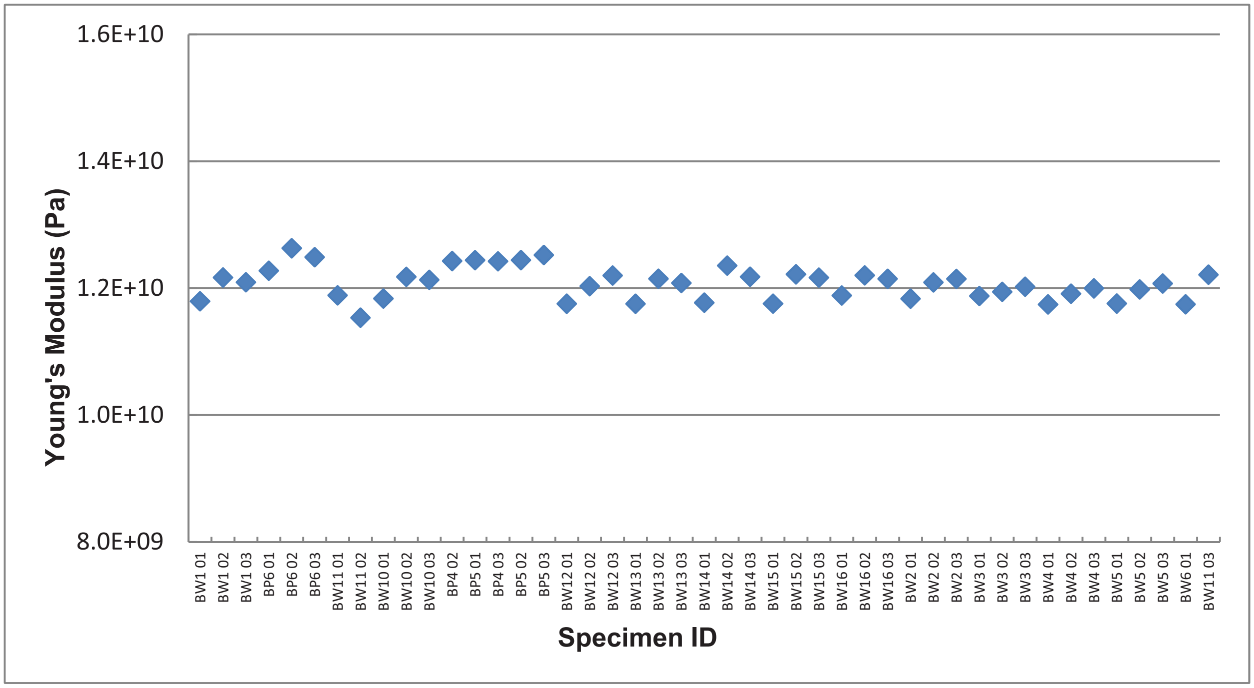


Figure A-27. Young’s Modulus by sonic resonance for NBG-18.

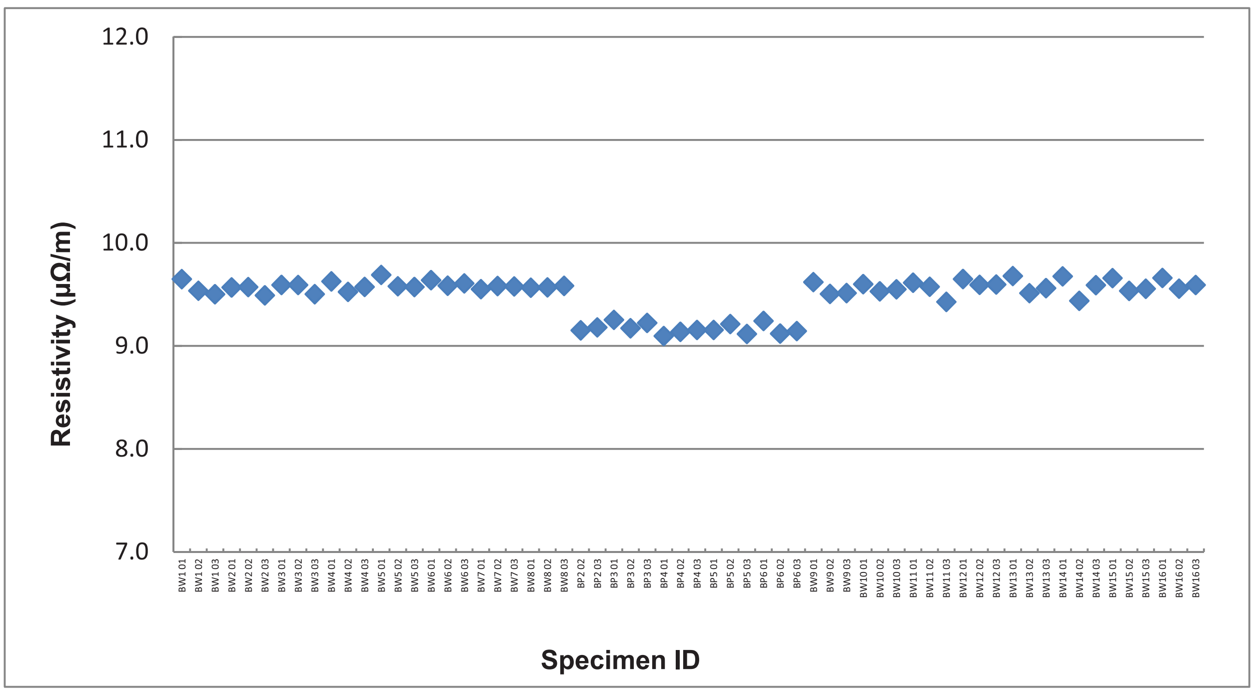


Figure A-28. Resistivity for NBG-18.

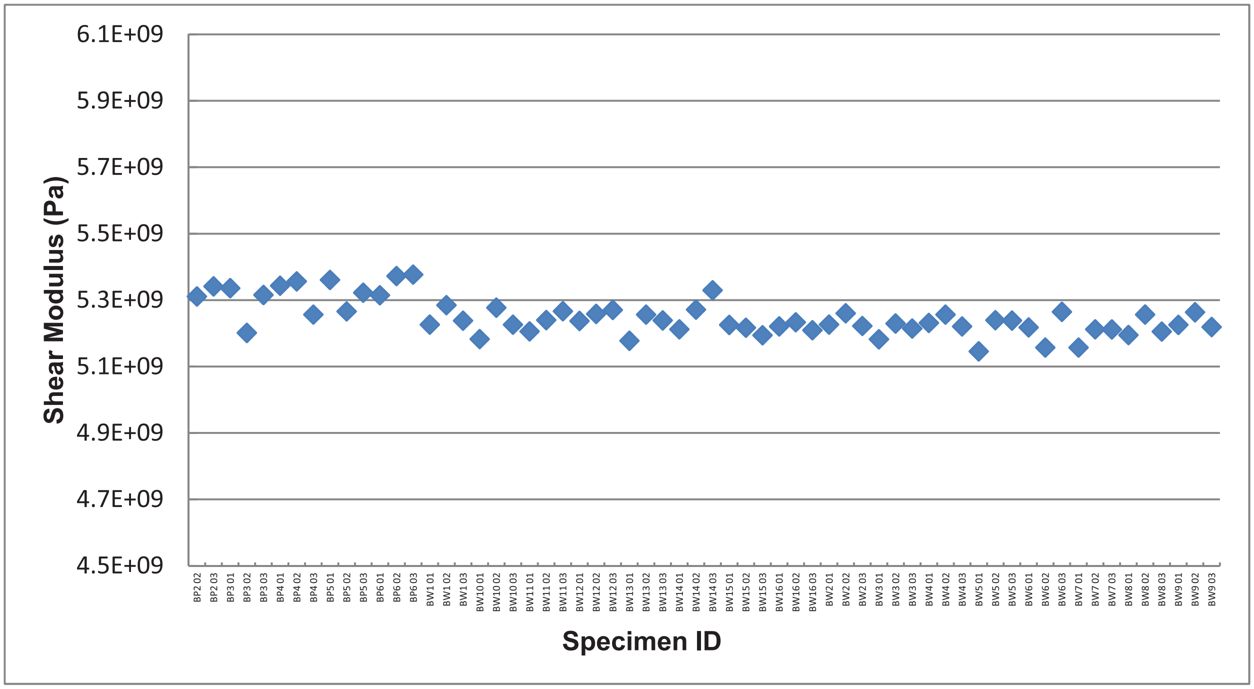


Figure A-29. Shear Modulus by sonic velocity for NBG-18.

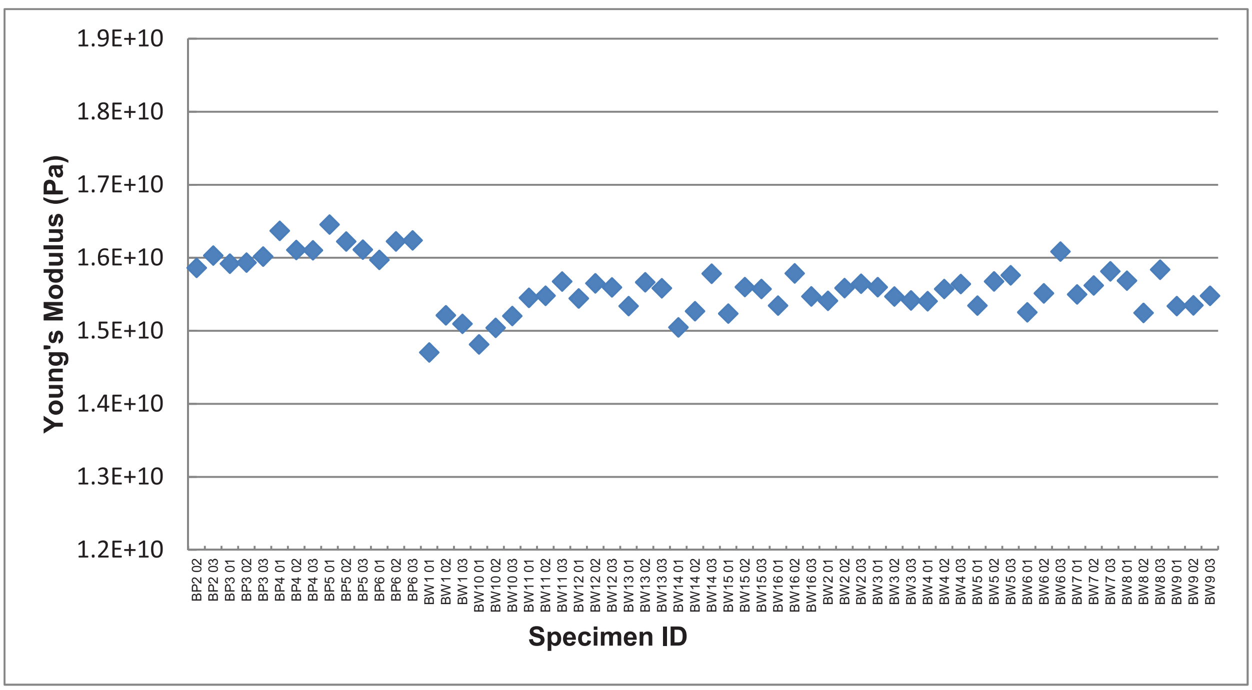


Figure A-30. Young's Modulus by sonic velocity for NBG-18.

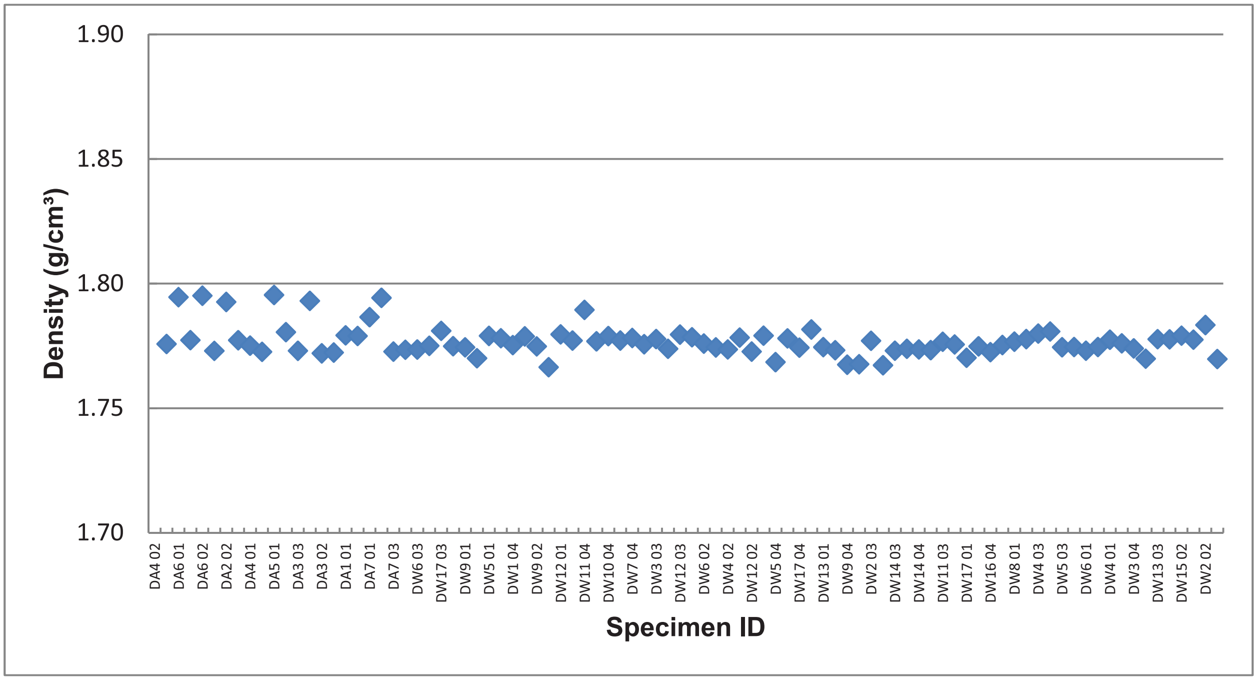


Figure A-31. Density for PCEA.

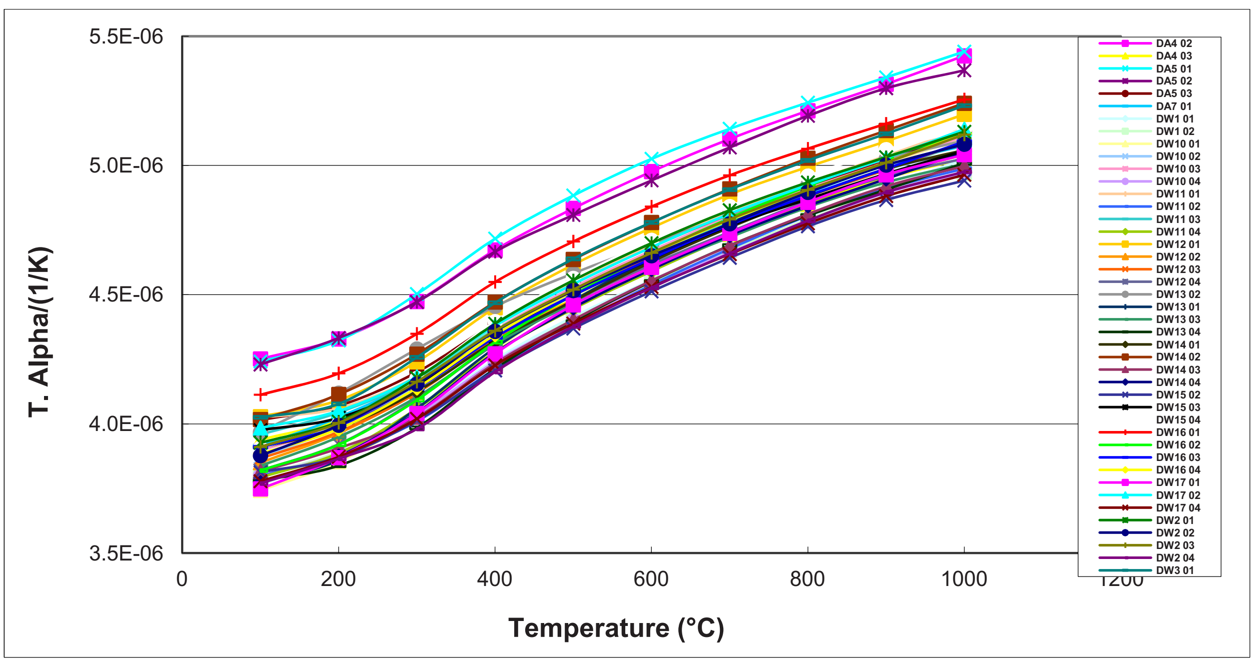


Figure A-32. Coefficient of thermal expansion for PCEA.

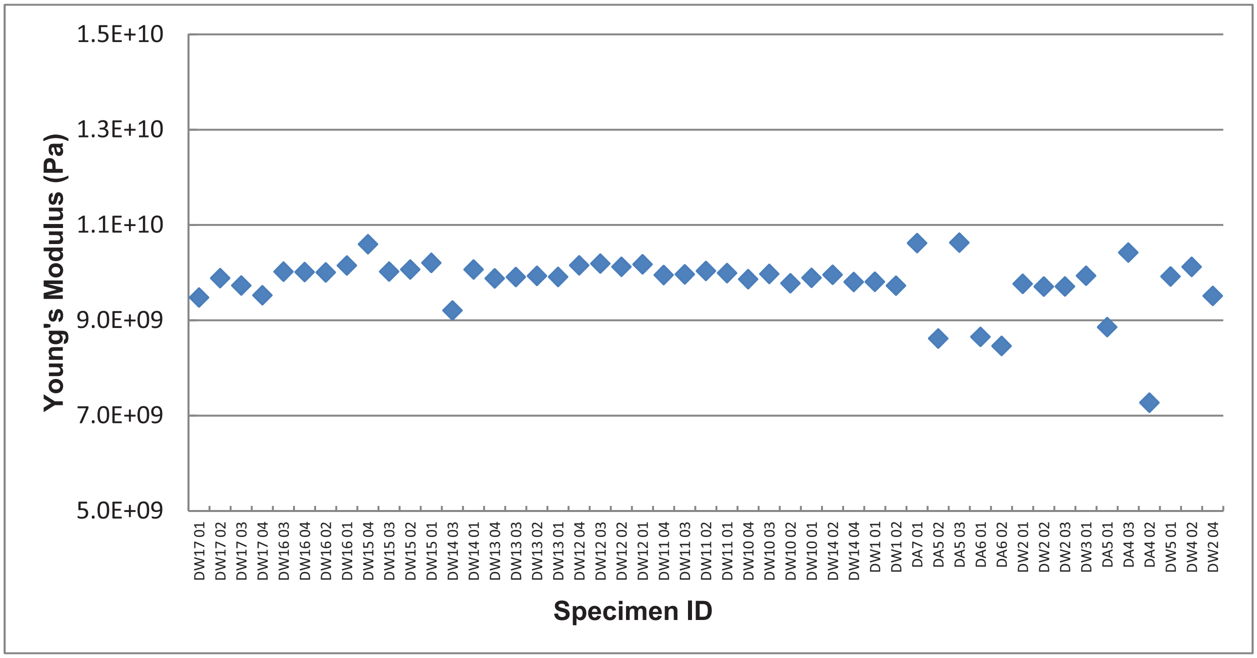


Figure A-33. Young's Modulus by sonic resonance for PCEA.

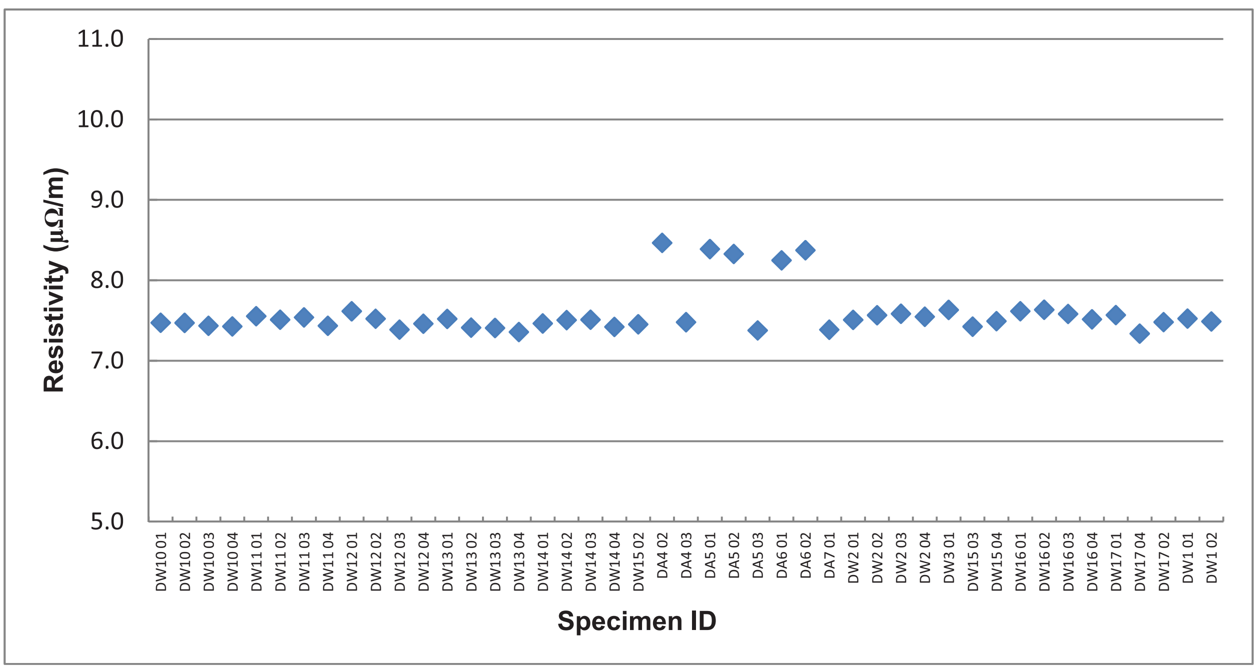


Figure A-34. Resistivity for PCEA.

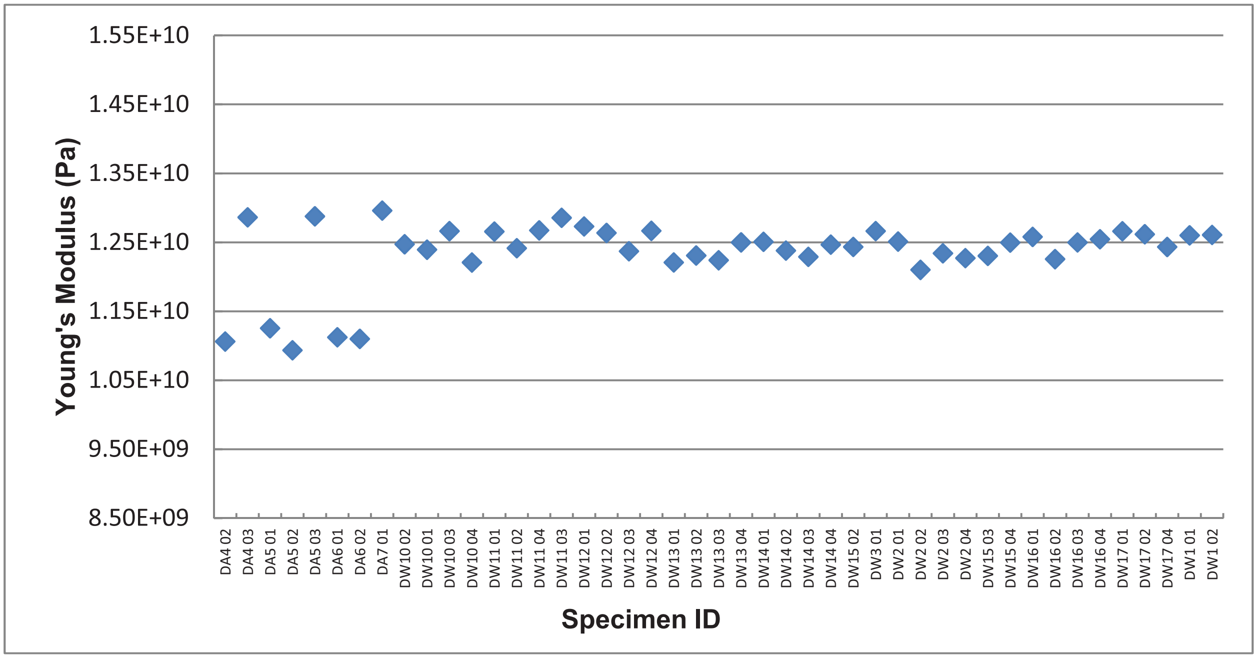


Figure A-35. Young's Modulus by sonic velocity for PCEA.

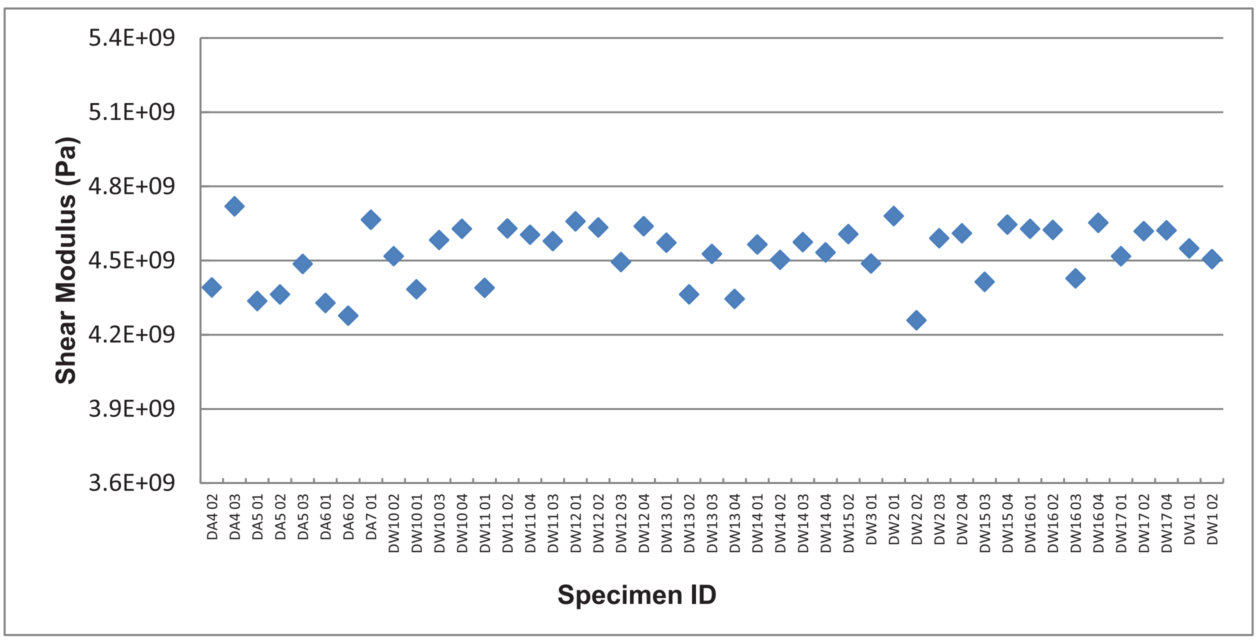


Figure A-36. Shear Modulus by sonic velocity for PCEA.

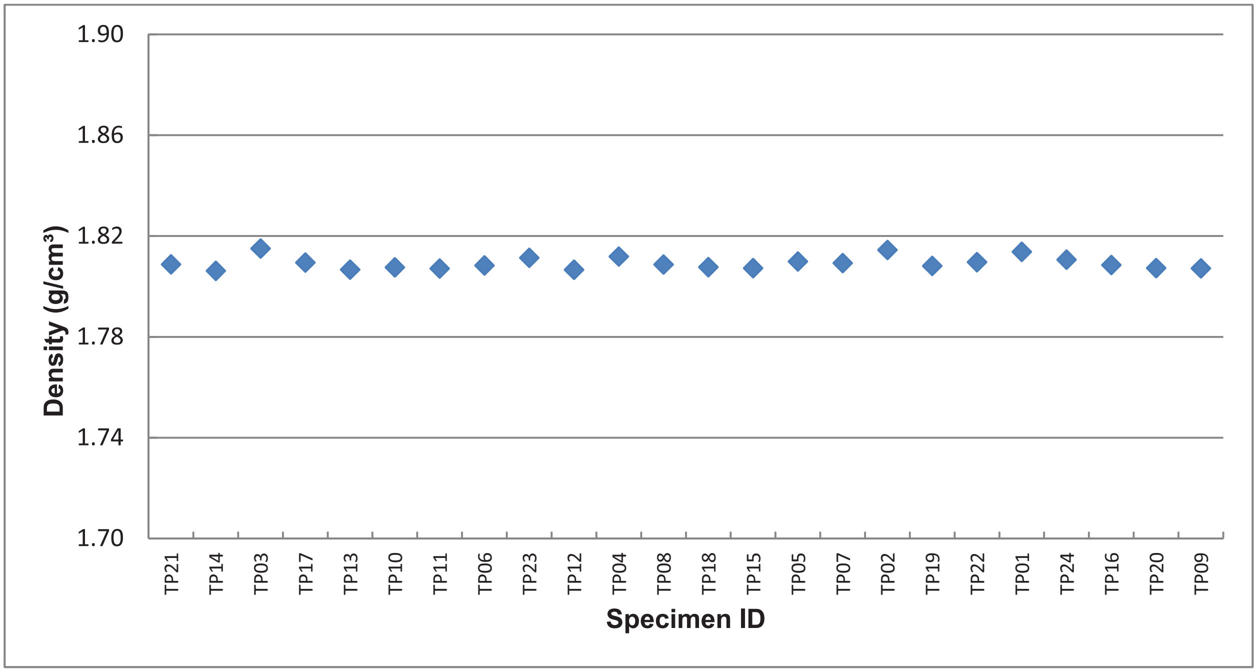


Figure A-37. Density for 2114.

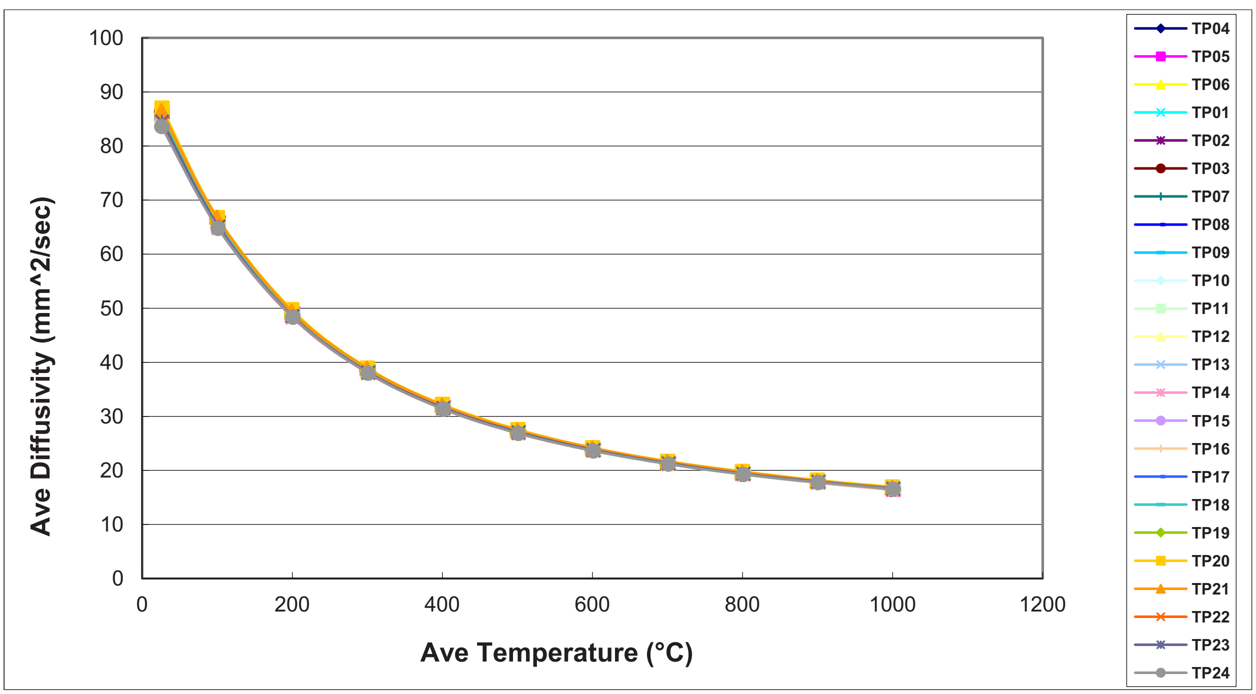


Figure A-38. Thermal diffusivity for 2114.

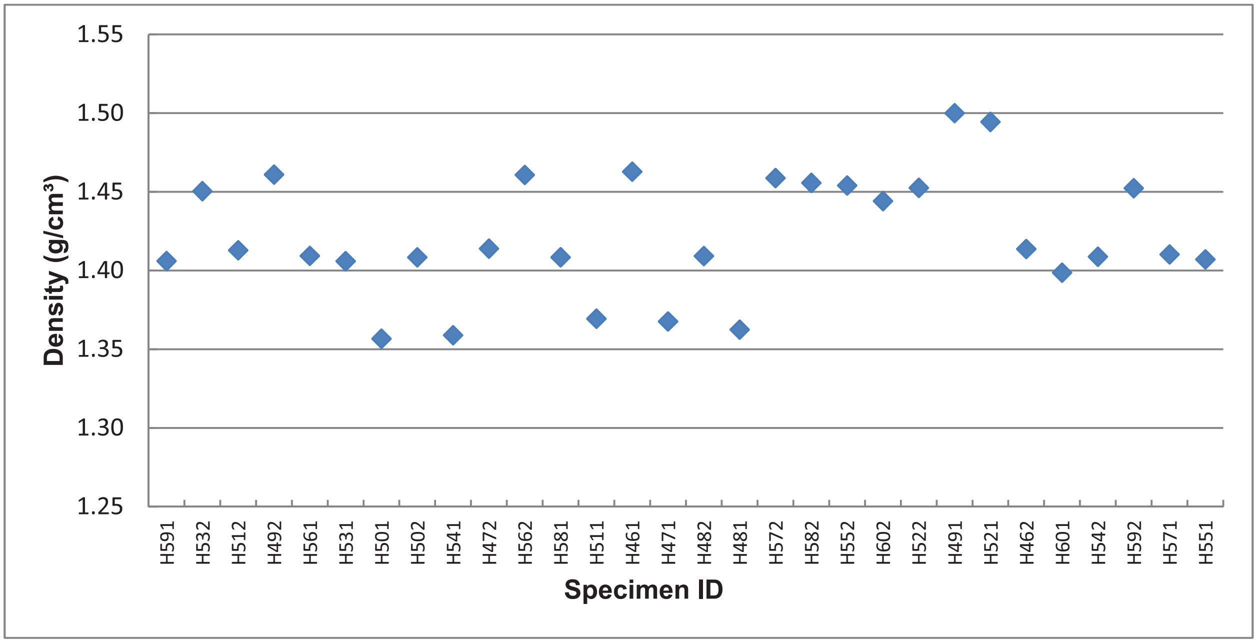


Figure A-39. Density for A3 Matrix.

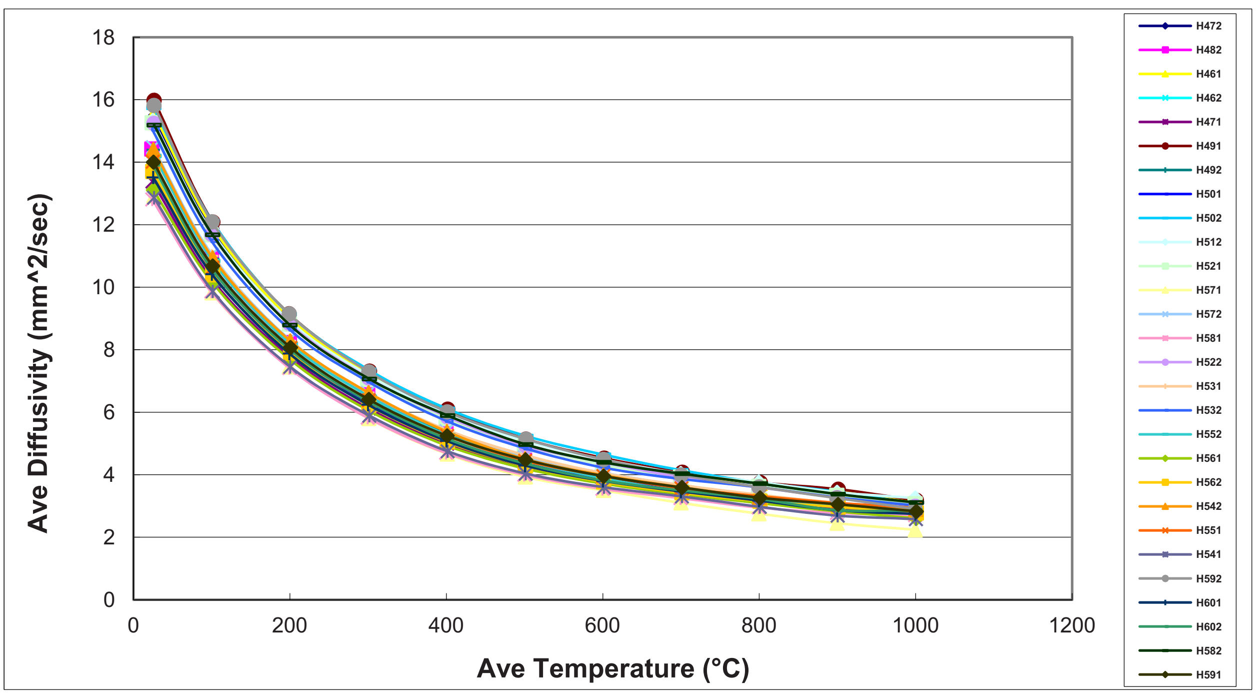


Figure A-40. Thermal diffusivity for A3 Matrix.

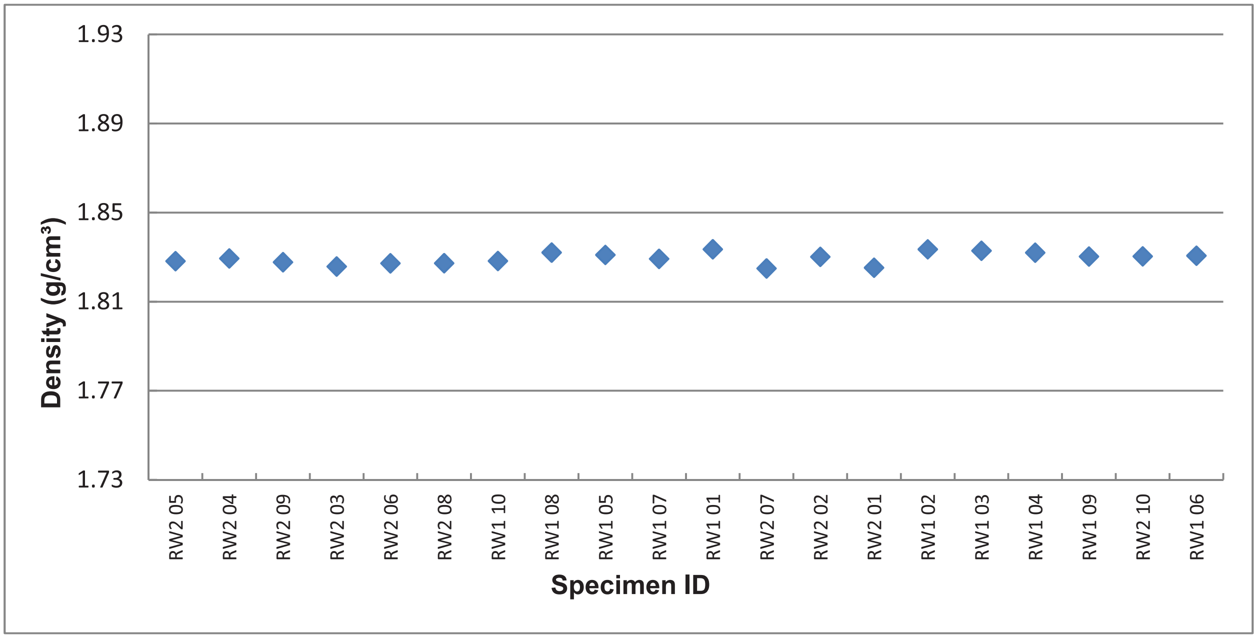


Figure A-41. Density for BAN.

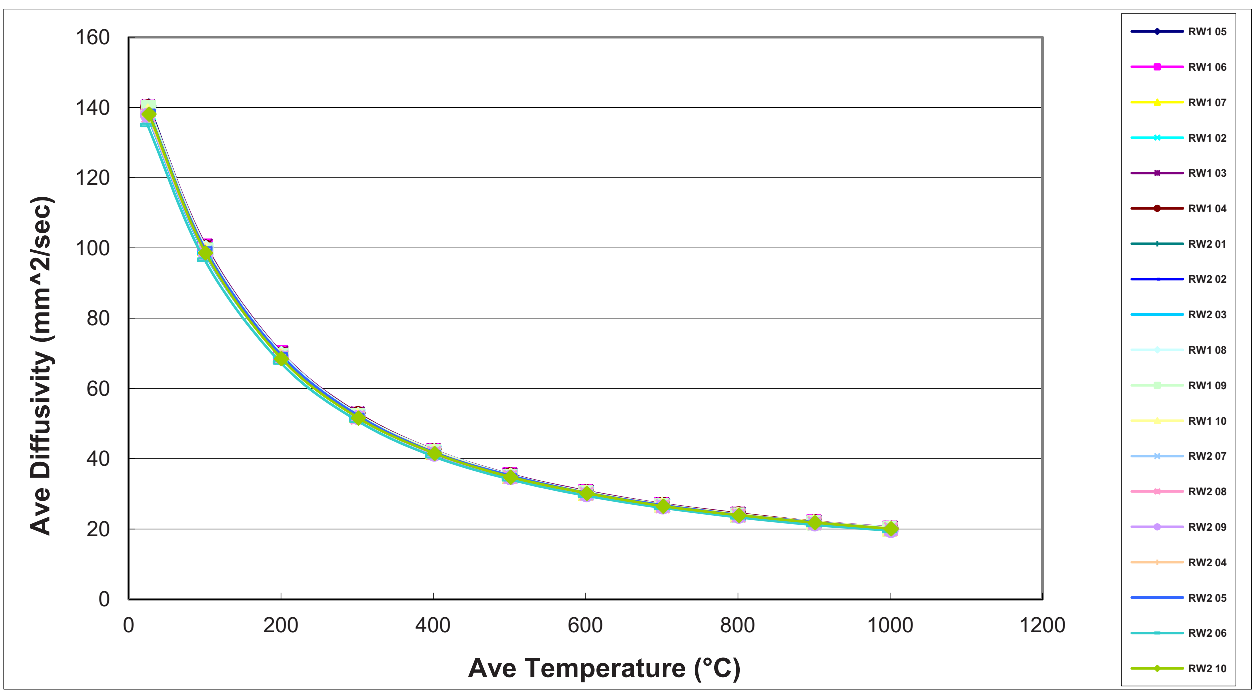


Figure A-42. Thermal for BAN.

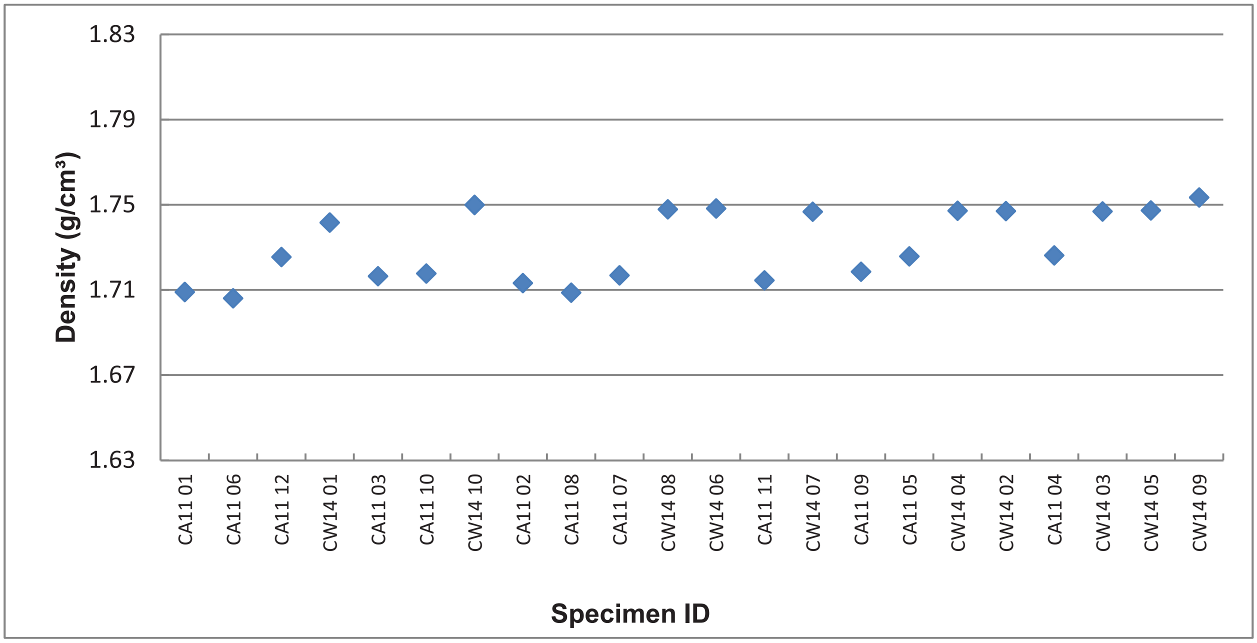


Figure A-43. Density for H-451.

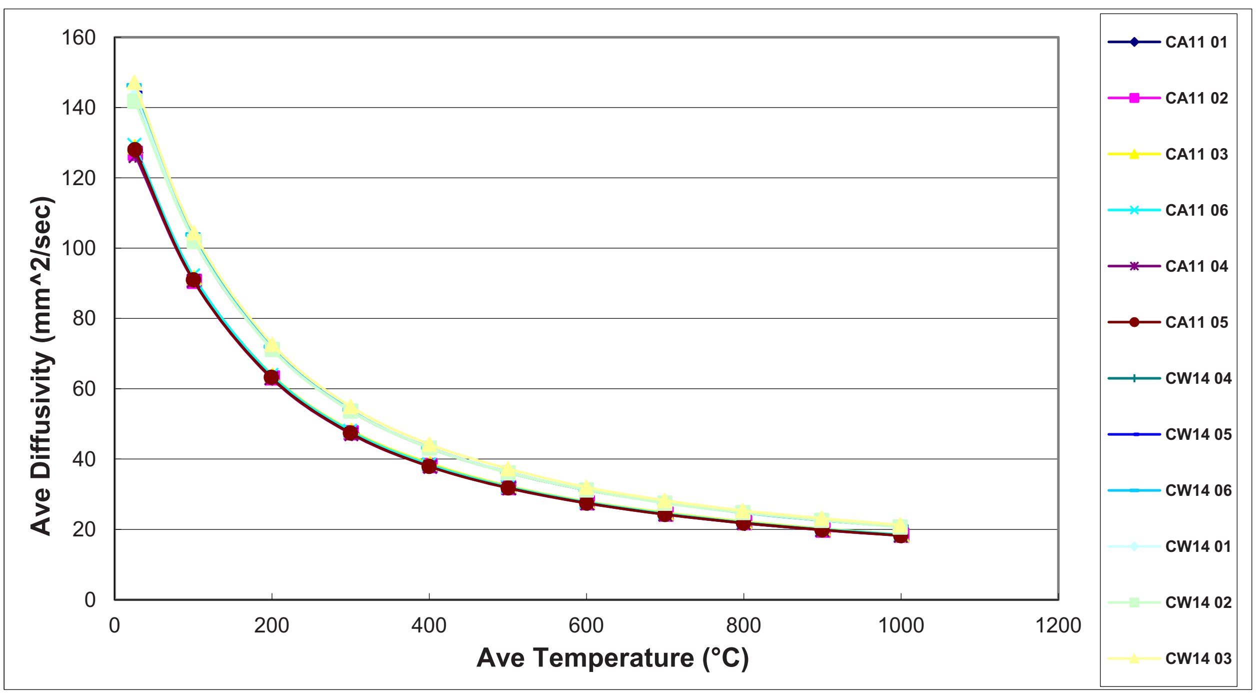


Figure A-44. Thermal diffusivity for H-451.

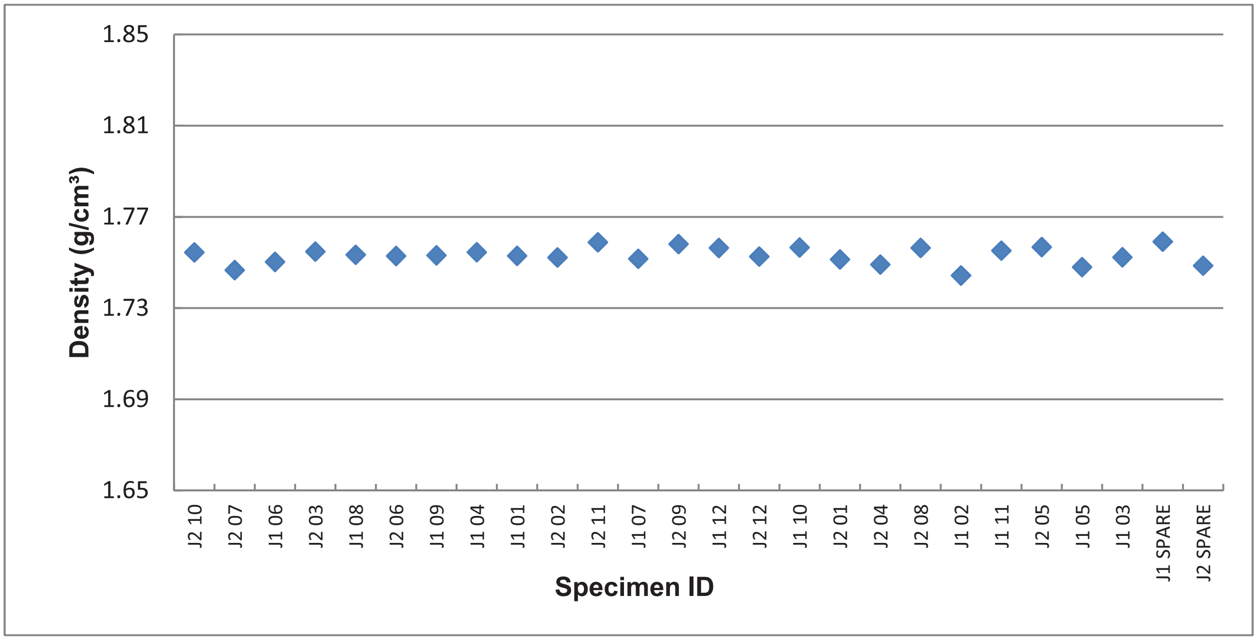


Figure A-45. Density for HLM.

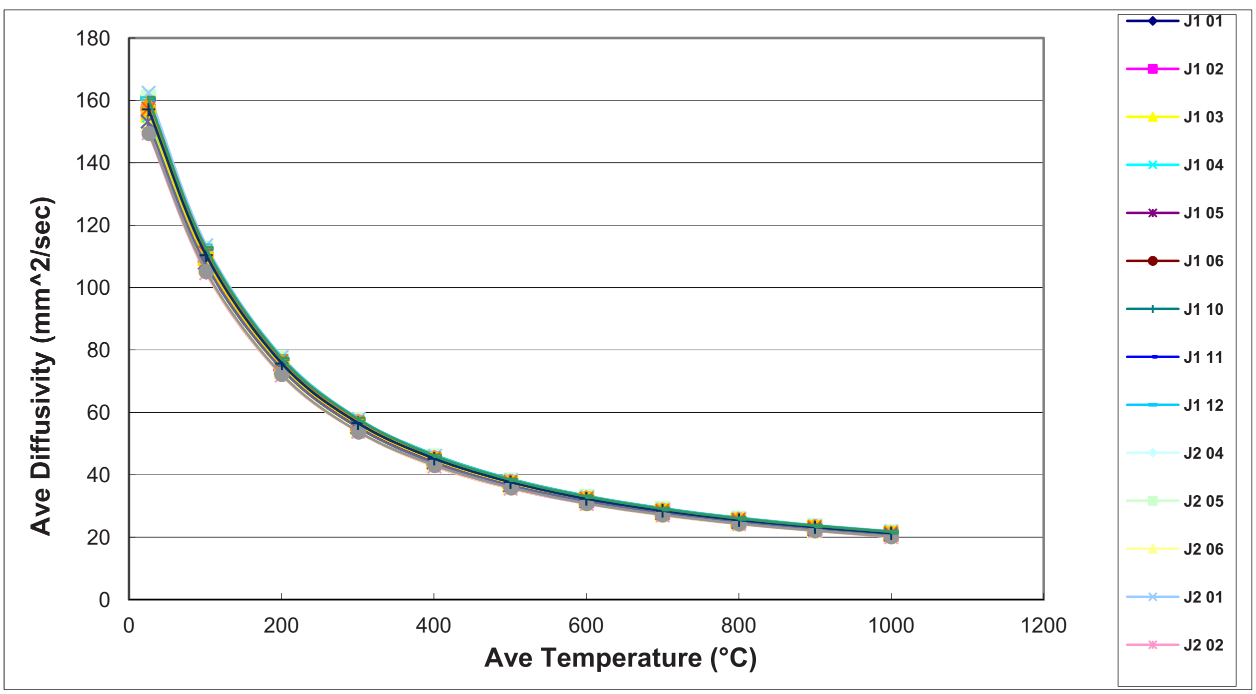


Figure A-46. Thermal diffusivity for HLM.

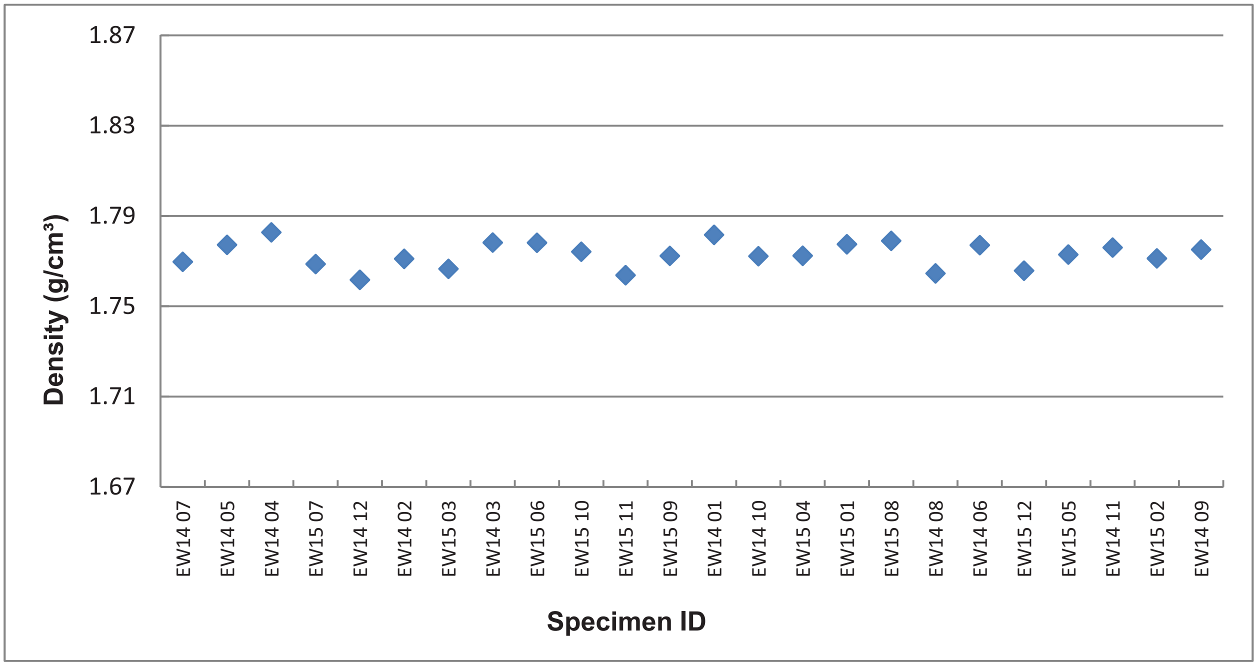


Figure A-47. Density for IG-110.

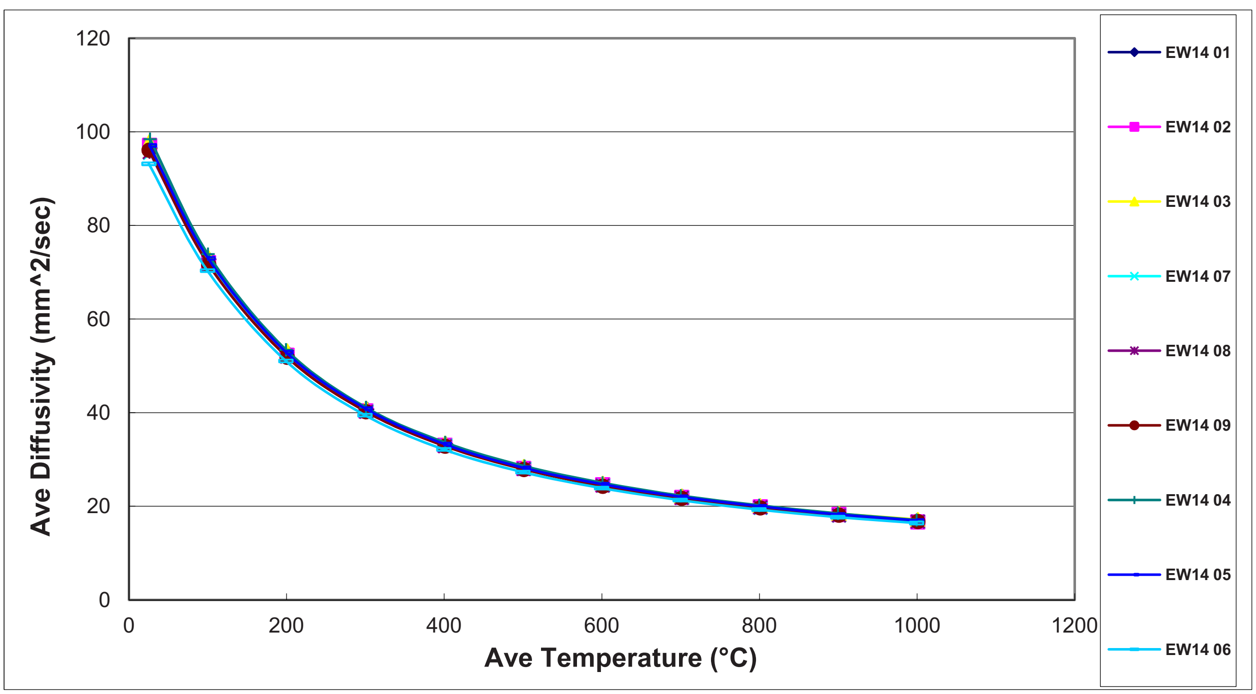


Figure A-48. Thermal diffusivity for IG-110.

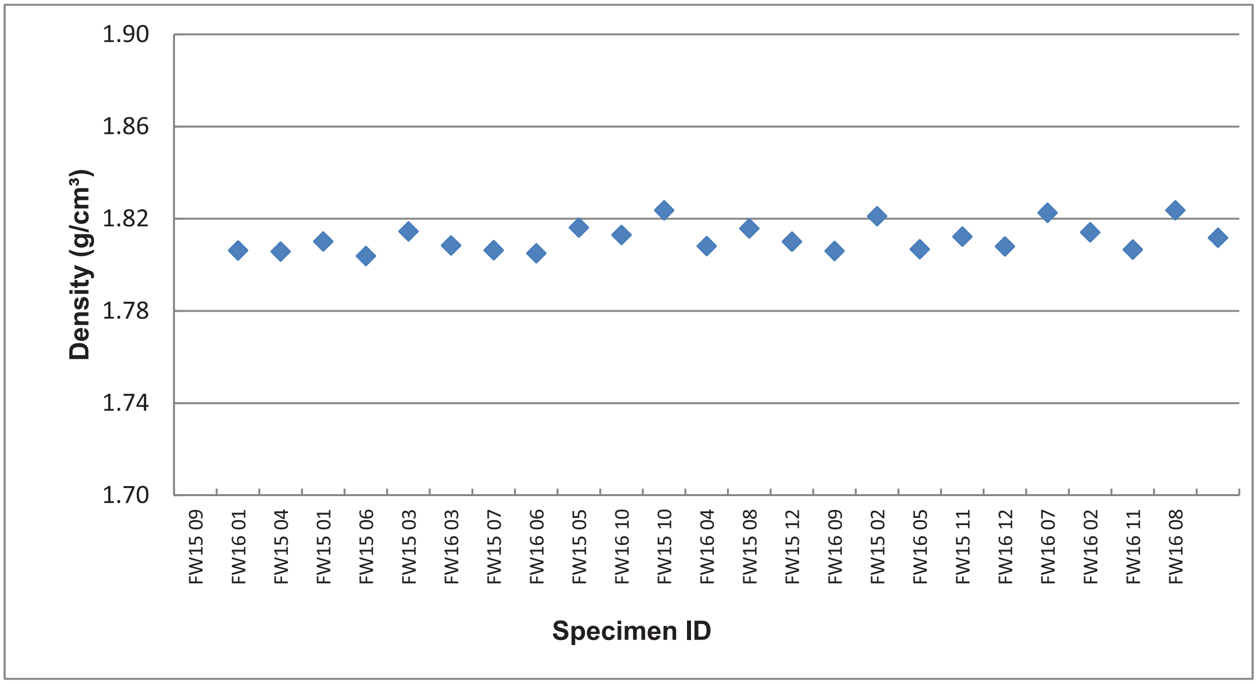


Figure A-49. Density for IG-430.

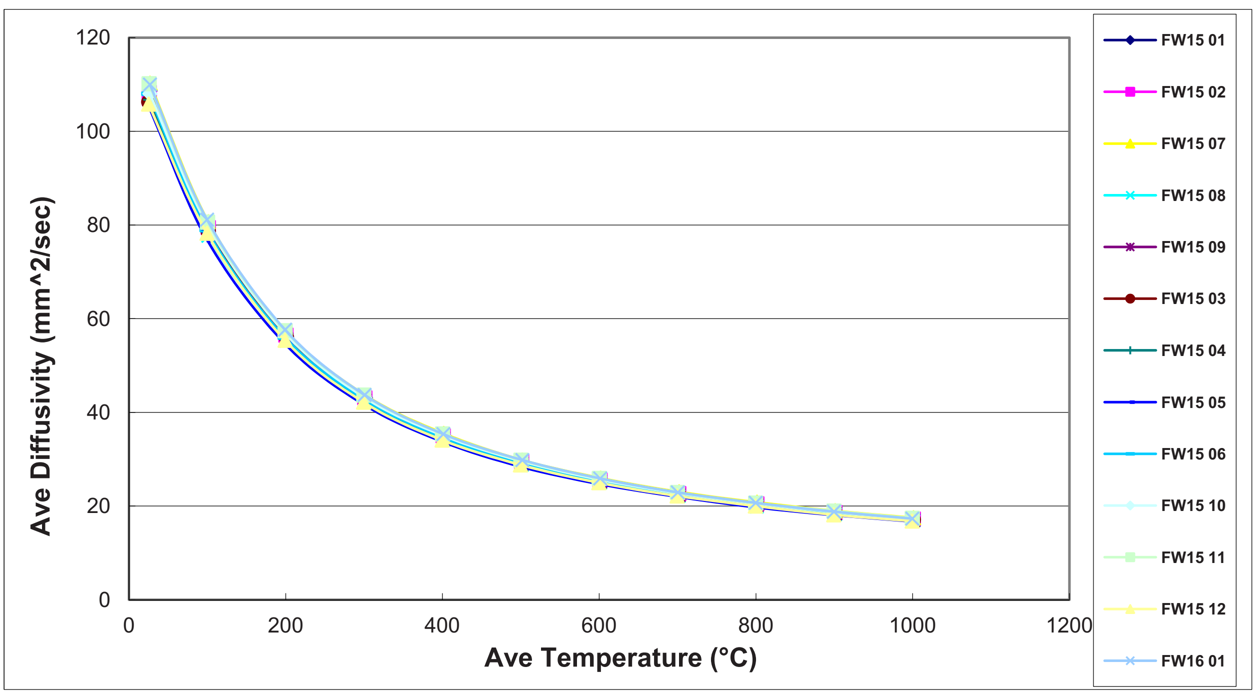


Figure A-50. Thermal diffusivity for IG-430.

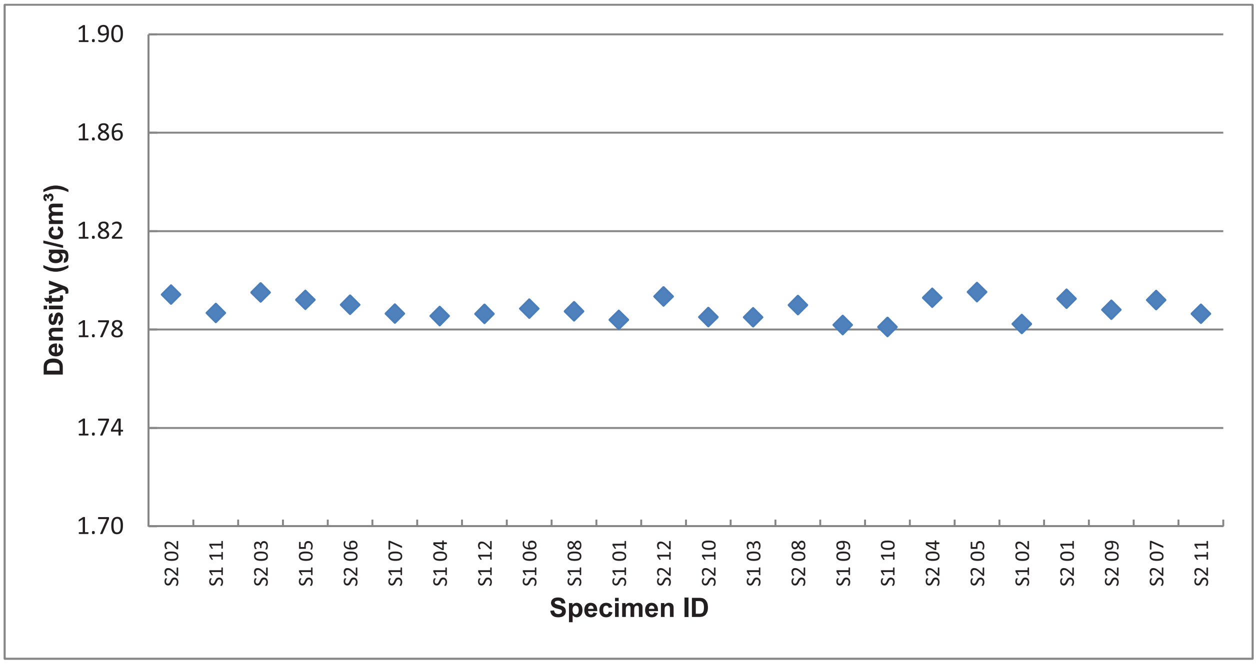


Figure A-51. Density for NBG-10.

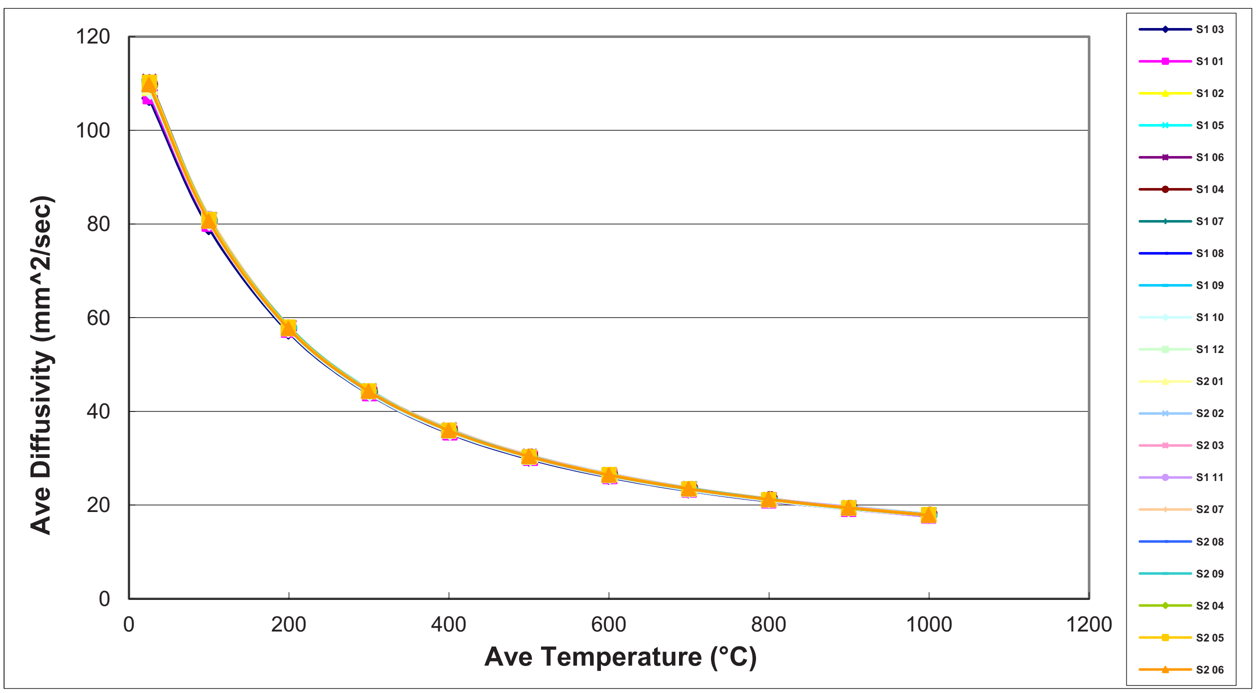


Figure A-52. Thermal diffusivity for NBG-10.

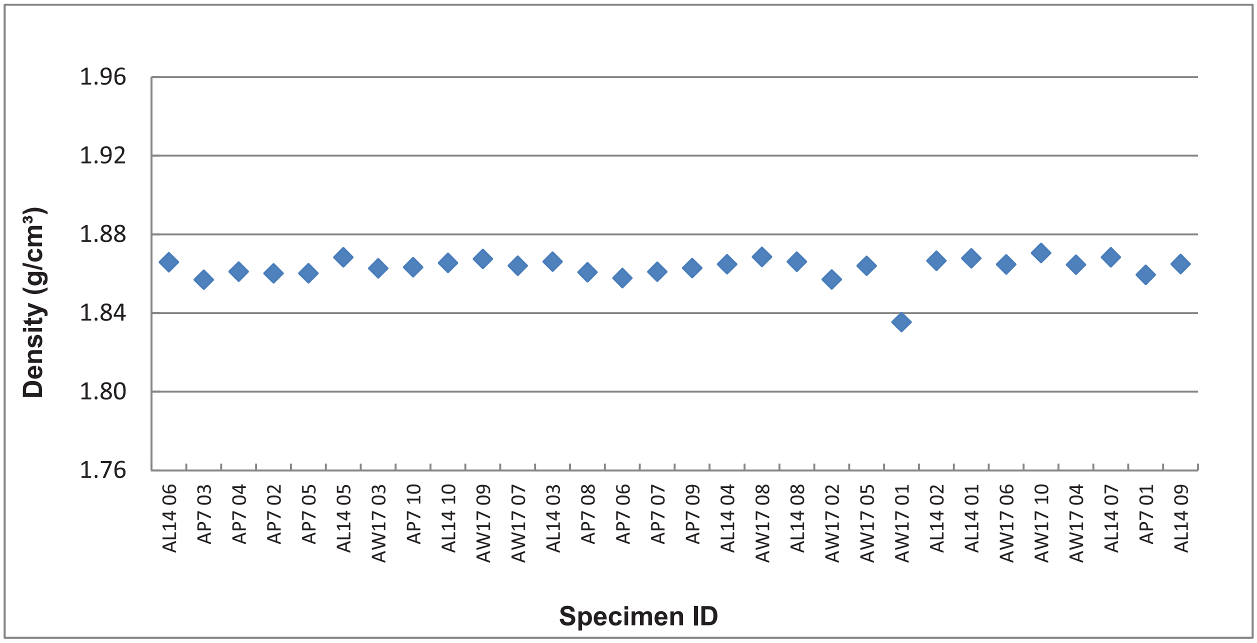


Figure A-53. Density for NBG-17.

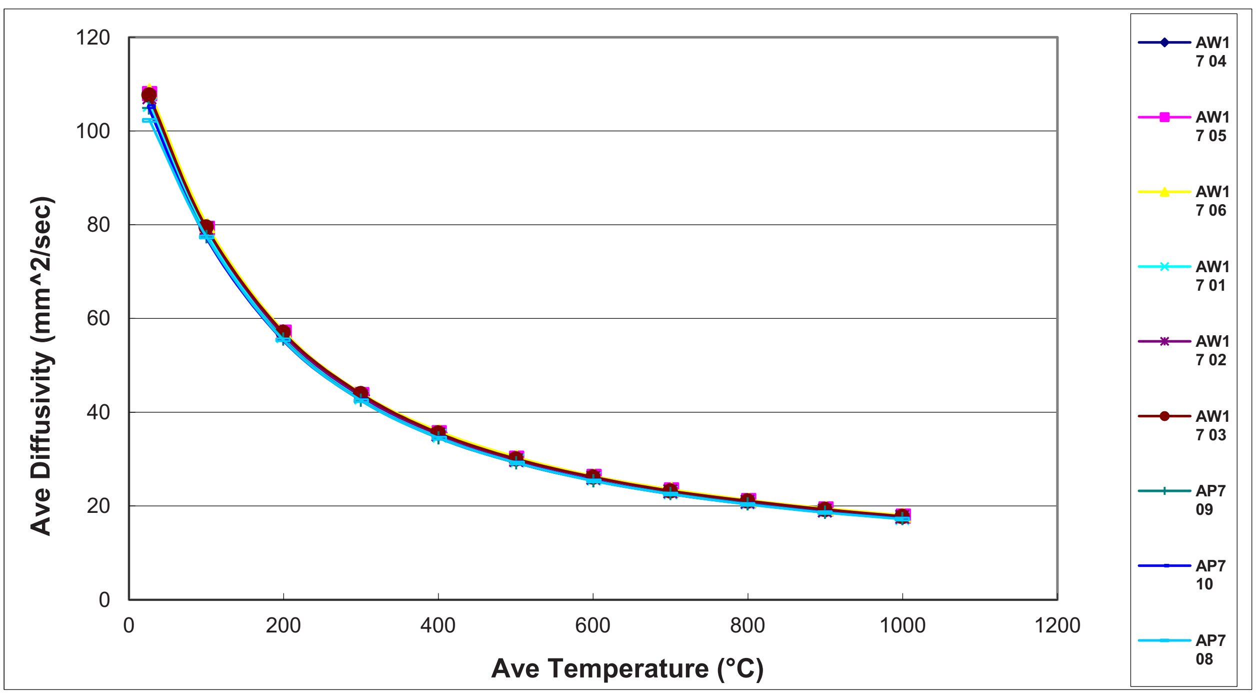


Figure A-54. Thermal diffusivity for NBG-17.

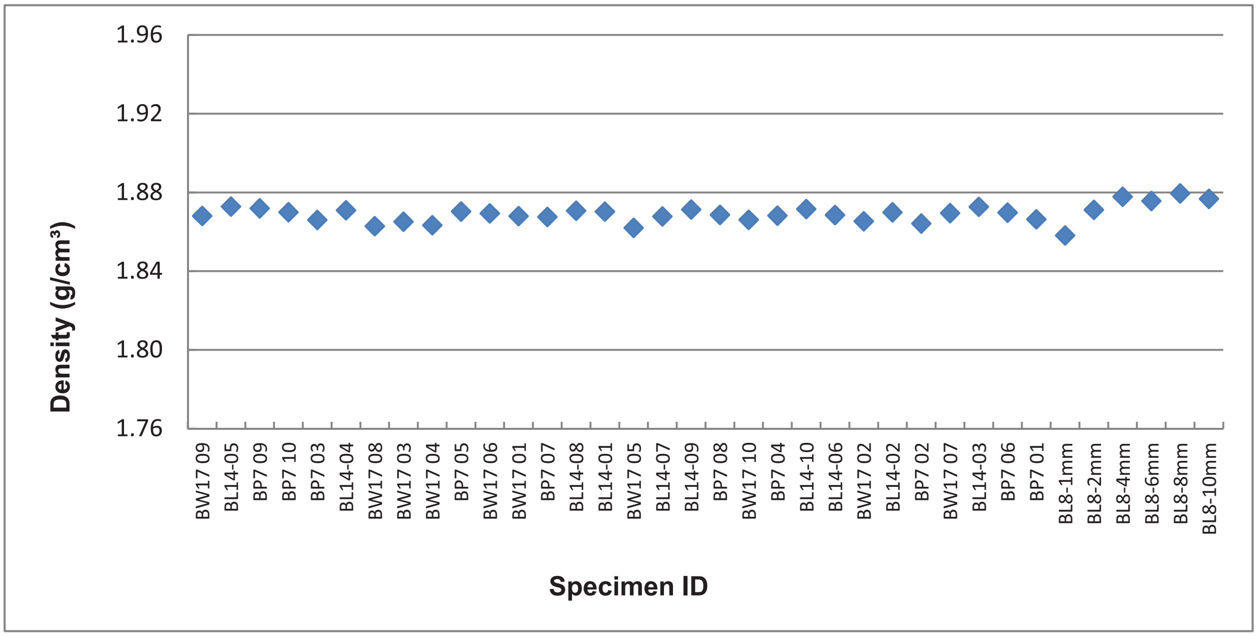


Figure A-55. Density for NBG-18.

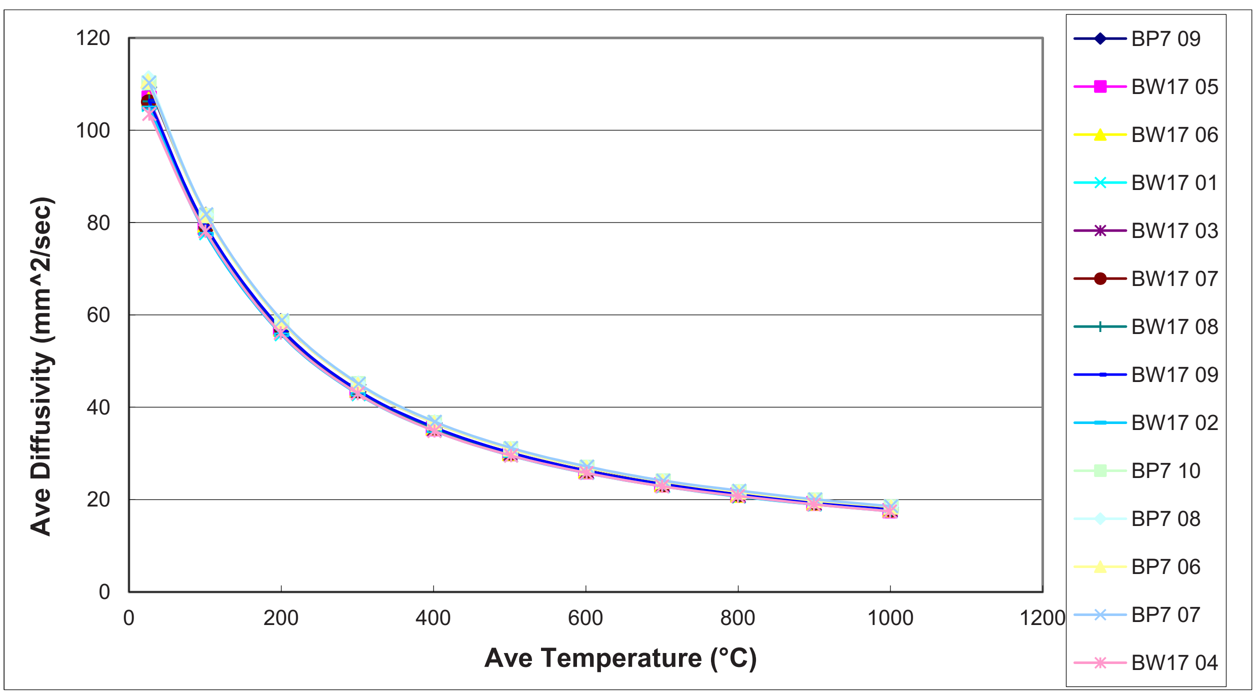


Figure A-56. Thermal diffusivity for NBG-18.

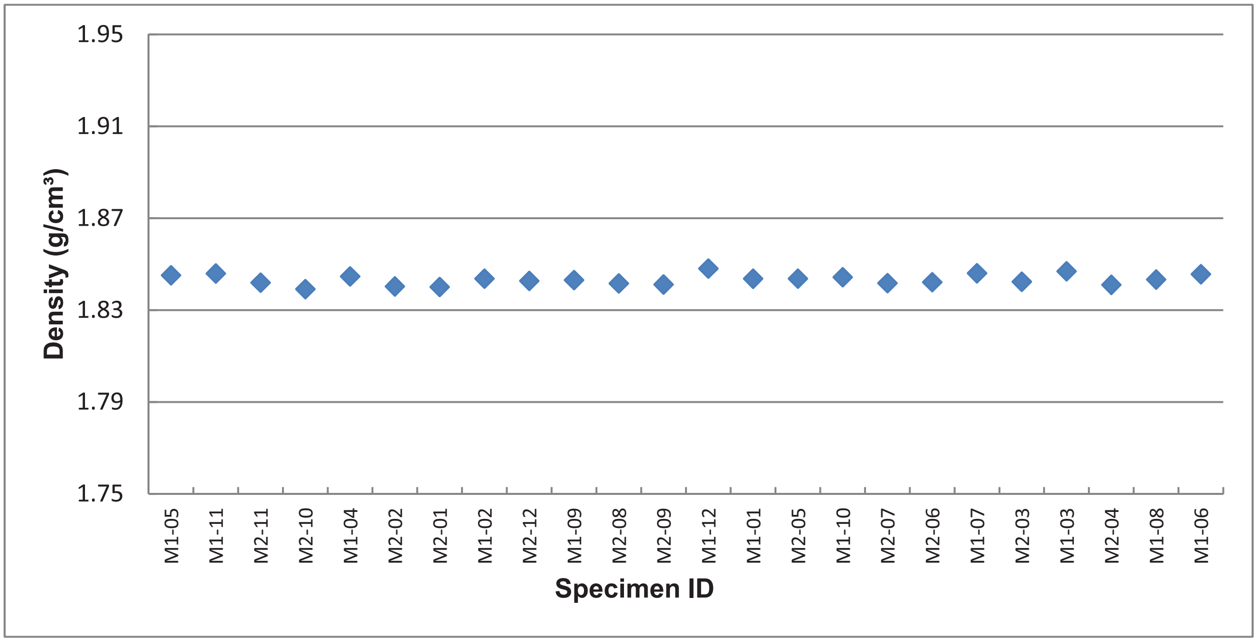


Figure A-57. Density for NBG-25.

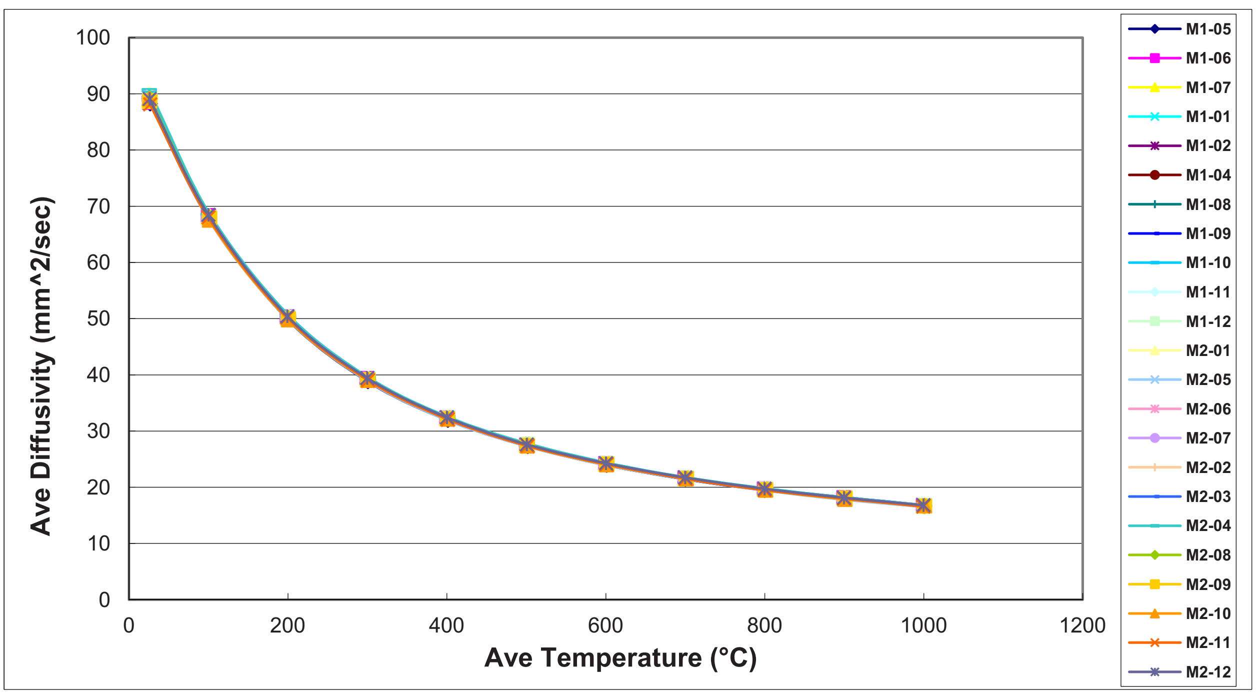


Figure A-58. Thermal diffusivity for NBG-25.

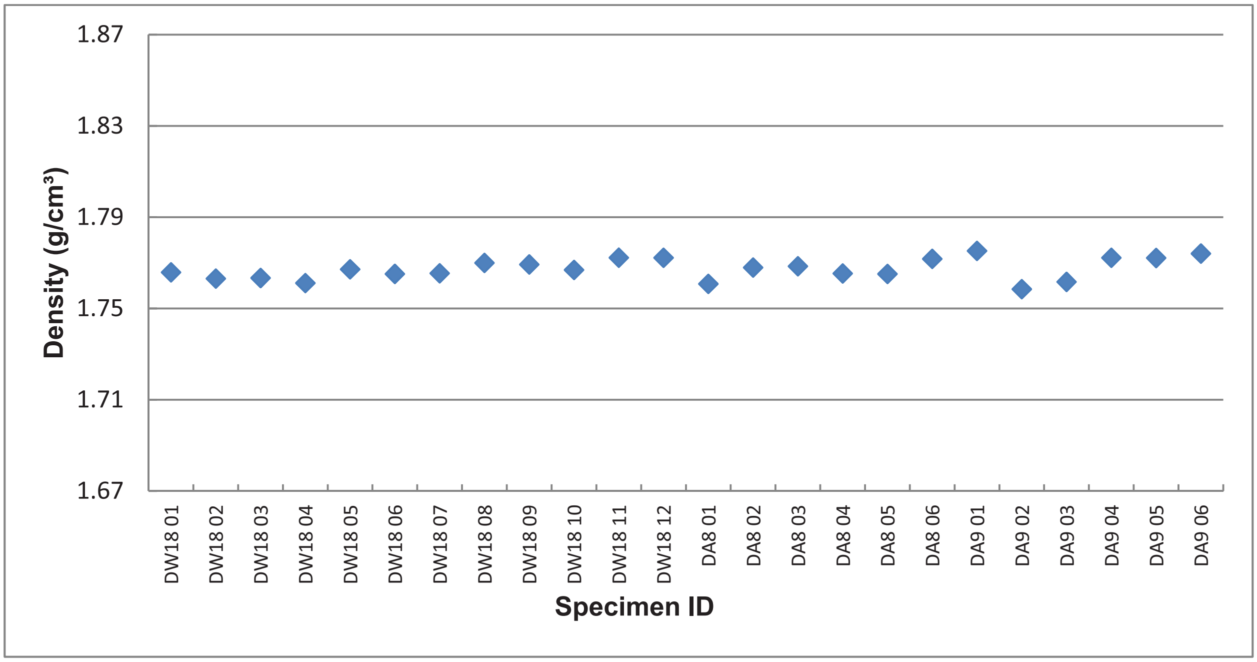


Figure A-59. Density for PCEA.

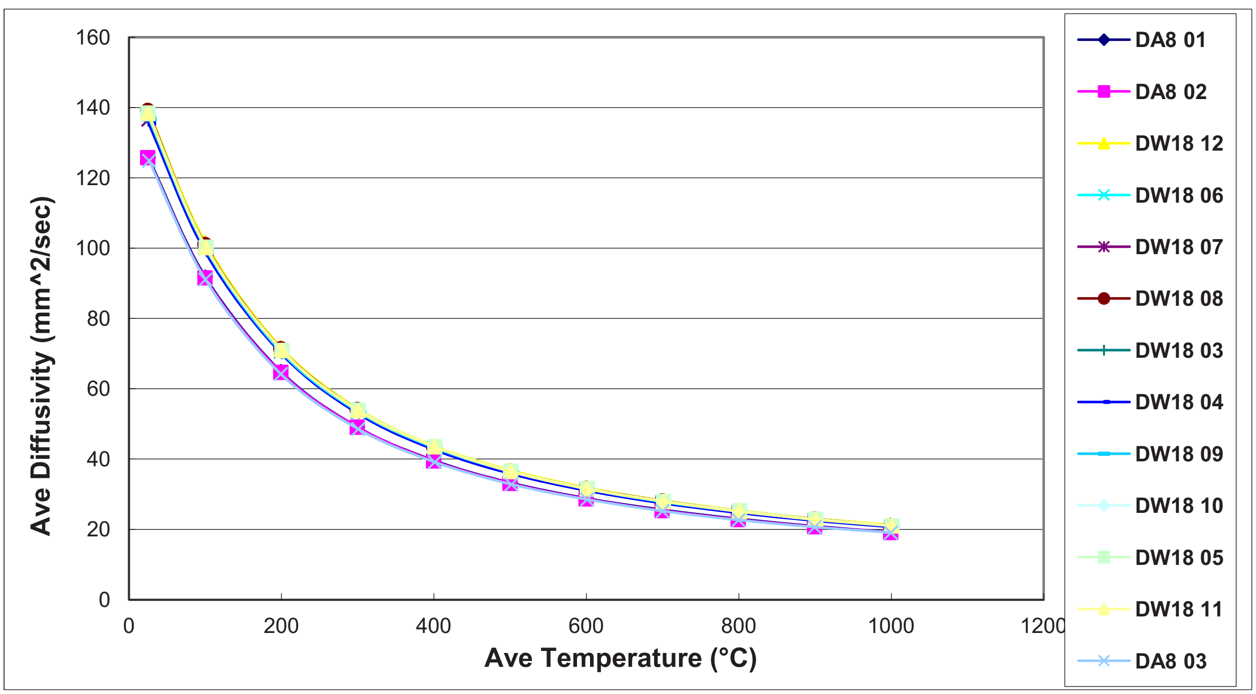


Figure A-60. Thermal diffusivity for PCEA.

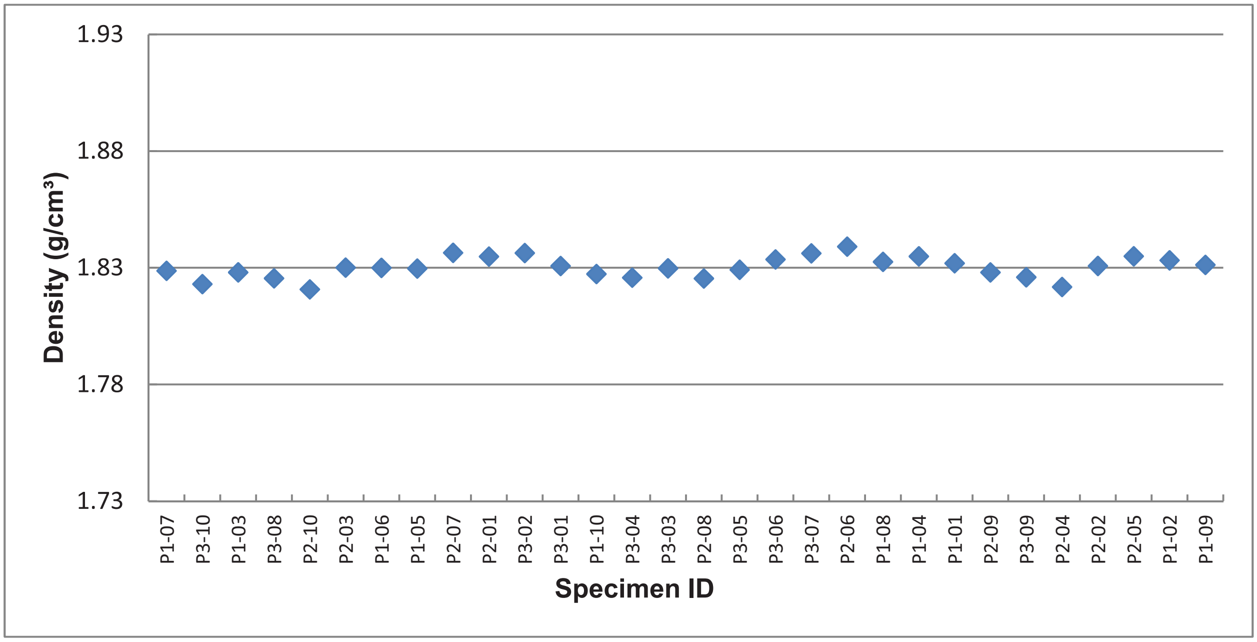


Figure A-61. Density for PCIB.

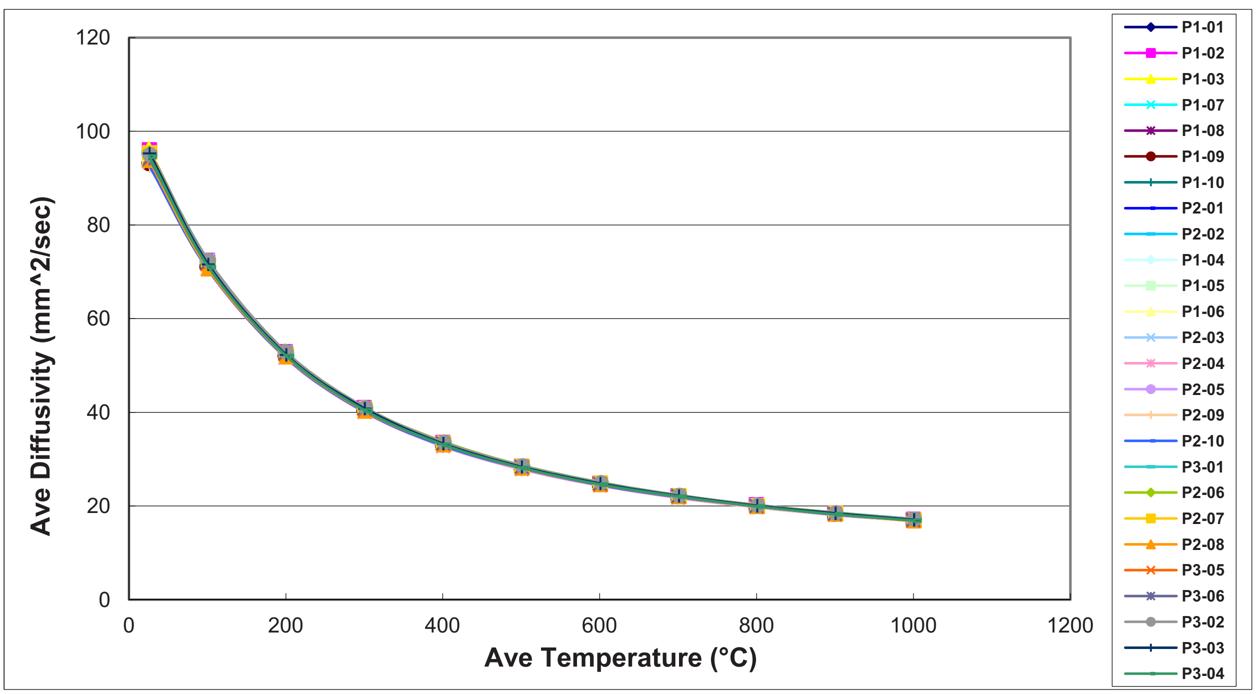


Figure A-62. Thermal diffusivity for PCIB.

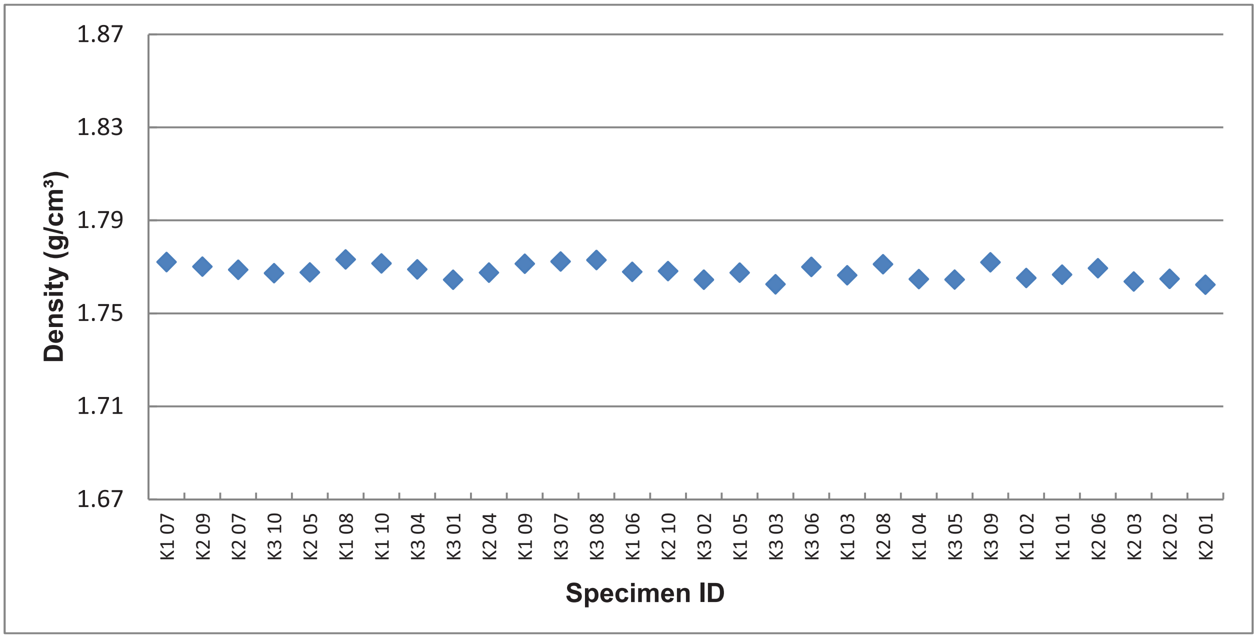


Figure A-63. Density for PGX.

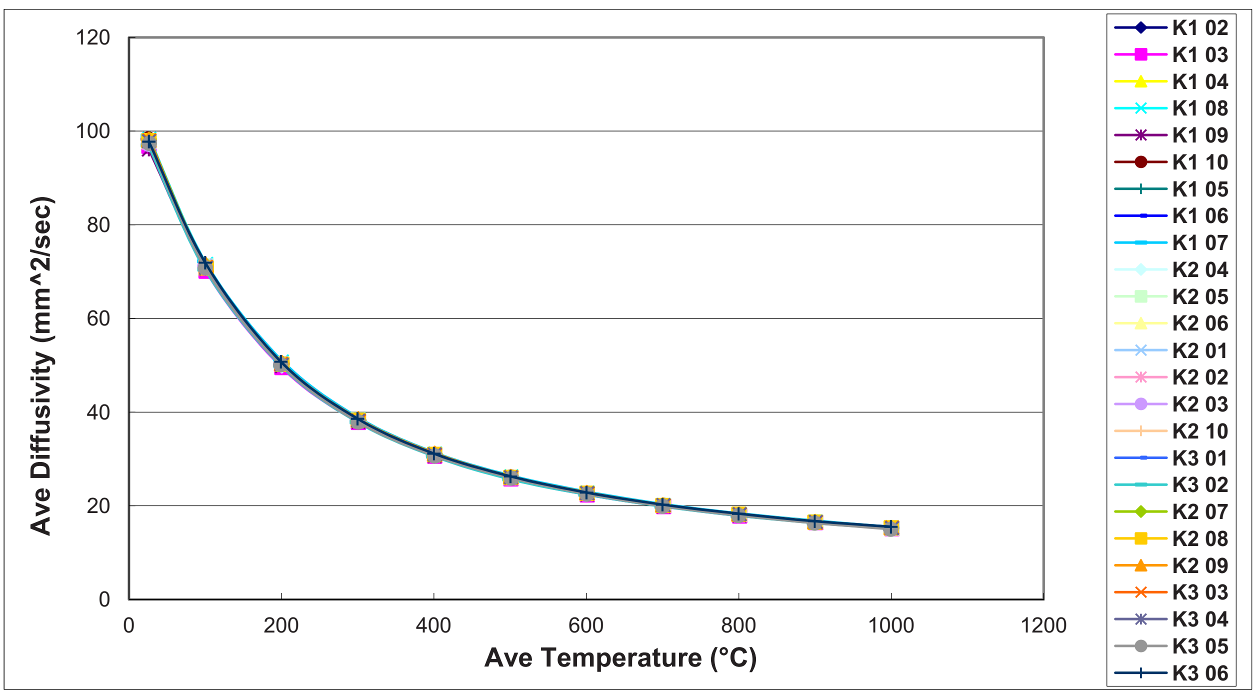


Figure A-64. Thermal diffusivity for PGX.

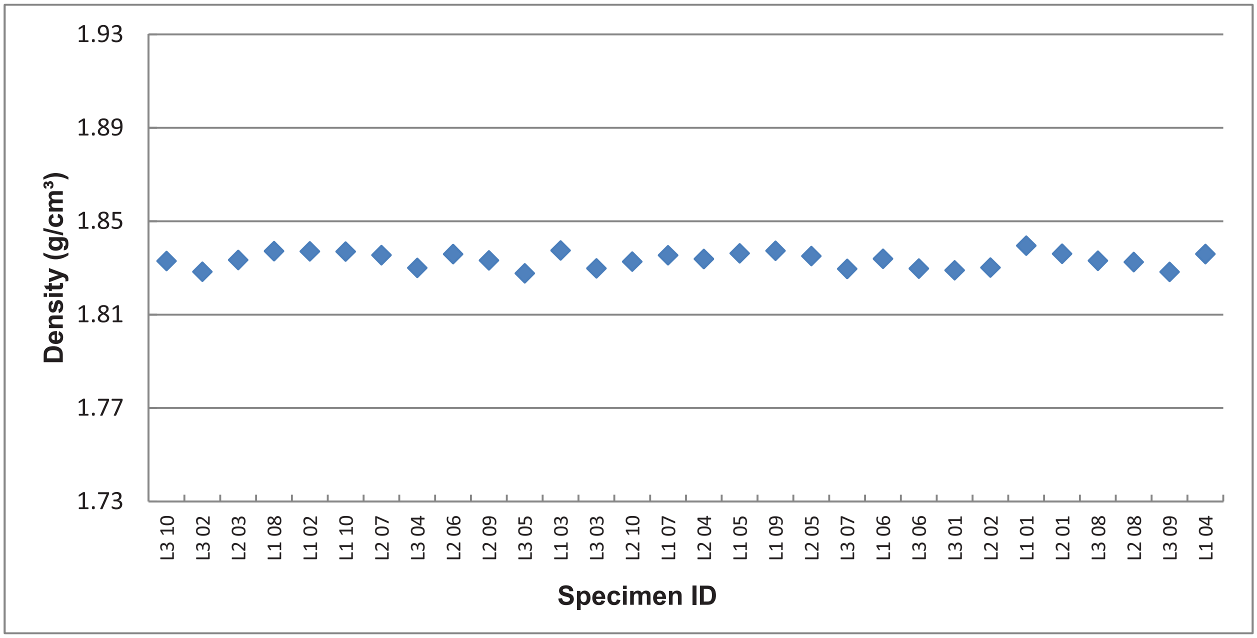


Figure A-65. Density for PPEA.

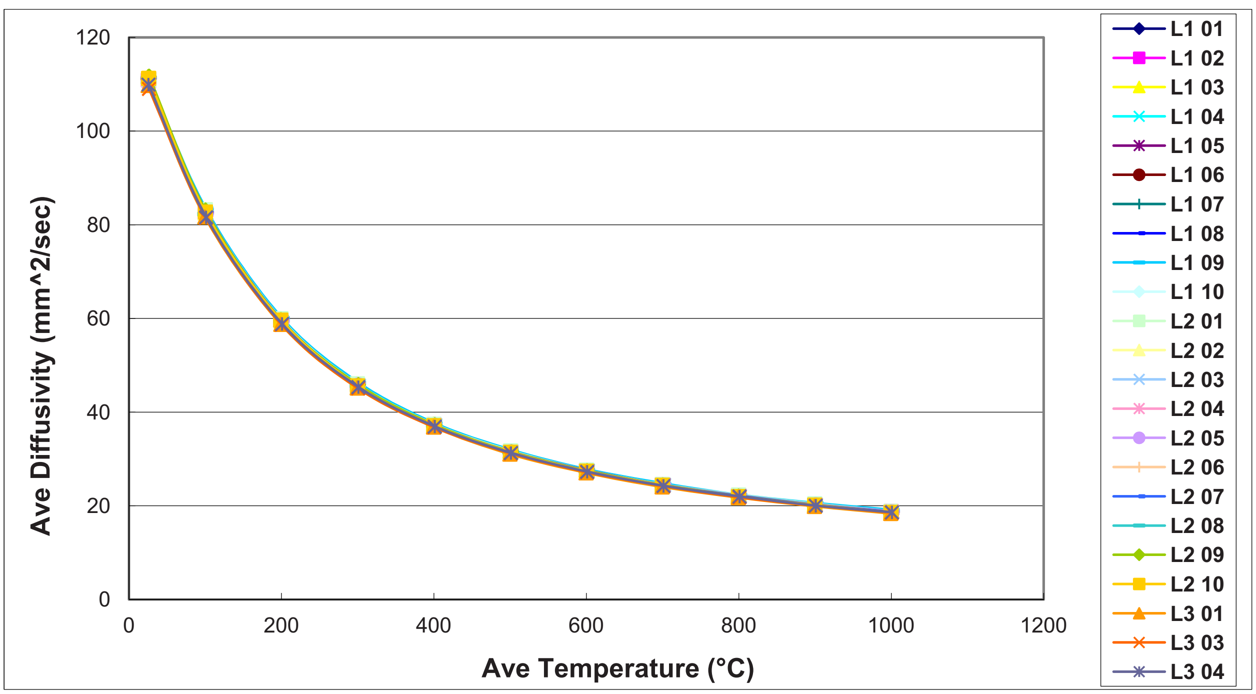


Figure A-66. Thermal diffusivity for PPEA.

This page is intentionally left blank

Appendix B

Source/Receiving Inspection Instruction for AGC-2 Specimens

Appendix B
Source/Receiving Inspection Instruction for AGC-2 Specimens

SOURCE/RECEIVING INSPECTION INSTRUCTION (S/RII)

S/RII No.: N/A	Rev: N/A	Category: QL-2	Commodity: AGC-2 Graphite Specimens	☐ Standard RII ☒ Non-Standard S/RII
PO No.: 00259349	Rev: N/A	Contract ID0083107		

Originator: David Swank	Date: 6/28/10	APPROVALS	
Notes:		PSQ: Gary Roberts Kirk Bailey for	Date: 7-6-10
		Technical Representative: Dave Swank W. D. Swank	Date: 7/6/10
		Other: N/A	Date: N/A

- **The purpose of this inspection is to verify that identification of specimens and to verify the condition of the specimens at the time of this inspection. This activity is not a conformance based activity. This activity will take place in Lab C-20 at the IRC.**
- **The inspector will wear white cotton gloves or powderless Nitrile gloves.**
- **It is acceptable for the place holder 0's to not be present on specimen Identification Numbers or on the container Identification Number, such as DW01-01 to read DW1-1. It is not acceptable for the ten's 0 to be missing such as DW10-10 to read DW1-1. It is acceptable for the dash to not be present on the specimen or the specimen container. If ID number is in question consult project personnel for acceptance or guidance.**

Special Instructions:
- Careful handling of the specimens is required as they can break or be chipped if dropped or mishandled.
- The inspector may change the order of the inspections steps as deemed appropriate.

Step	Instructions, Attributes and/or Characteristics	Reference	Results S	Results U	Results N/A	By/Date
1	• While wearing appropriate gloves, open AGC-2 specimen container to verify that the specimen identification number on the specimen matches the container identification number for each specimen. If the identification numbers do not match note this in the comments section and notify project personnel. • Verify Bar Code identification number is correct for each specimen. Place a check mark in the Bar Code section of the log sheet as acceptance. If bar code identification number does not match specimen Identification number note this in the comments section and notify project personnel. • Document any anomalies such as chips, cracks or obvious foreign material. If anomaly is identified note this in the comments section of the log sheet and contact project personnel. Consult project personnel for minor anomalies such as porous voids and markings. • Note only one specimen will be out of its container at any time during the inspection.	✓ ✓ ✓ ✓	☒	☐	☐	JC 7.12.2010

SEE LOG REPORT FOR ALL NOTES:

THIS IS NOT AN INSPECTION FOR CONFORMANCE. REVIEW TO DOCUMENT SPECIMEN CONDITION AND VERIFY CORRECT SPECIMEN AND CONTAINER NUMBER.

JC 7.12.2010

SOURCE/RECEIVING INSPECTION INSTRUCTION (S/RII)

S/RII No.: N/A	Rev: N/A	Category: QL-2	Commodity: AGC-2 Graphite Specimens	☐ Standard RII ☒ Non-Standard S/RII
PO No.: 00259349	Rev: N/A	Contract ID0083107		

2	• Using the provided camera, photograph the specimen four times. • Place each specimen in the cradle with the identification number to the left and toward the camera. • Take the first picture which will have the identification number shown. Turn the specimen clockwise approximately 90degrees (as looking at the specimen Identification number) in its cradle take second picture. Turn specimen approximately 90 degrees clockwise take third picture. Turn specimen approximately 90 degrees clockwise take fourth picture. • Each picture will have a unique identification number. • File the raw image under the specimen identification number and verify there are four separate pictures with the correct specimen identification number. • Inspector will sign or initial attached inspection sheet.	✓ ✓ ✓ ✓ ✓	☒ ☐ ☐	JC / 7.12.2010
3	• Place specimen back into the plastic container which is marked with identical identification number and place that container into the appropriate container.	✓	☒ ☐ ☐	JC / 7.12.2010
4	• Repeat steps until all specimens have been verified.	✓	☒ ☐ ☐	JC / 7.12.2010
5	• Sign and date log sheets when completed.	✓	☒ ☐ ☐	JC / 7.12.2010
			☐ ☐ ☐	/
			☐ ☐ ☐	/
			☐ ☐ ☐	/
			☐ ☐ ☐	/
			☐ ☐ ☐	/
			☐ ☐ ☐	/
			☐ ☐ ☐	/
			☐ ☐ ☐	/

NOTE: See MCP-13327, Development and Control of Inspection Instructions, Appendix B, for information on S/RII Numbering, Category, Commodity, and Extension.