The Geopolymer Route to High Tech Ceramics

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Supported by
US Air Force Office of Scientific Research,
Army Research Office, US Army Corps of Engineers and
Dow Chemical Company

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Outline

- Composition and starting materials
- Microstructure
- Processing route to ceramics
  - Oxides with tailorable CTE's
  - Non-oxides nanocrystalline (SiC, Si_3N_4, SiAlON's)

"Geopolymer-based Composites," W. M. Kriven, in Vol. 5, Ceramics and Carbon Matrix Composites, edited by Marina Ruggles-Wrenn. Part of an 8 volume set of books entitled Comprehensive Composite Materials II, Peter Beaumont and Carl Zweben, Co-editors-in-chief. Published by Elsevier, Oxford, UK, in press (2017)

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Terminology

The term "geopolymer" was introduced by Joseph Davidovits to describe alkali aluminosilicate binders formed via the addition of aluminosilicate materials to alkaline silicate solution

J. Davidovits, "Mineral Polymers and Methods of Making Them" U.S.Patent 4,349,386, September 14, (1982)

J. Davidovits, "Geopolymer Chemistry and Properties"; pp.25-48 in Geopolymer'88 First European Conference on Soft Mineralogy, Vol.1 Edited by J. Davidovits and J. Orlinski. Geopolymer Institute and Technical University, Compiegne, France, (1988)

J. Davidovits, "Geopolymers - Inorganic Polymeric New Materials," J. Therm. Anal. **37** 1633-56 (1991)

J. Davidovits, Geopolymer Chemistry and Applications, 4th Edition (2015), published by the Geopolymer Institute, St. Quentin, France

Geopolymer Institute - *www.geopolymer.org*

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Geopolymers (Polysialates)

- *Are a type of chemically bonded ceramics of chemical formula $M_2O \bullet Al_2O_3 \bullet 4SiO_2 \bullet 11H_2O$*
- *Refractory inorganic polymers formed from both aluminum and silicon sources containing AlO_4^- and SiO_4 tetrahedral units, under highly alkaline conditions (NaOH, KOH, CsOH) at room temperature*
- *They are a rigid, hydrated, alumino-silicate solid containing group I, charge-balancing cations*
- *They result in an amorphous, nano-particulate, nanoporous, impervious, acid-resistant, polymeric structure*
- *Metastable sodalite zeolite (when Na-based)*

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Geopolymer Composition

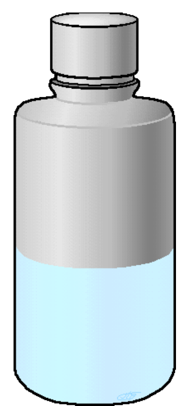
$5Si^{+4}O_2$

$M^{+1}{}_2O \bullet Al^{+3}{}_2O_3 \bullet 4Si^{+4}O_2 \bullet 11H_2O$

$Al^{+3}{}_2O_3 \bullet 2Si^{+4}O_2$

$M^{+1}{}_2O \bullet 2Si^{+4}O_2 \bullet 11H_2O$

Metakaolin clay



"waterglass" or metasilicate solution

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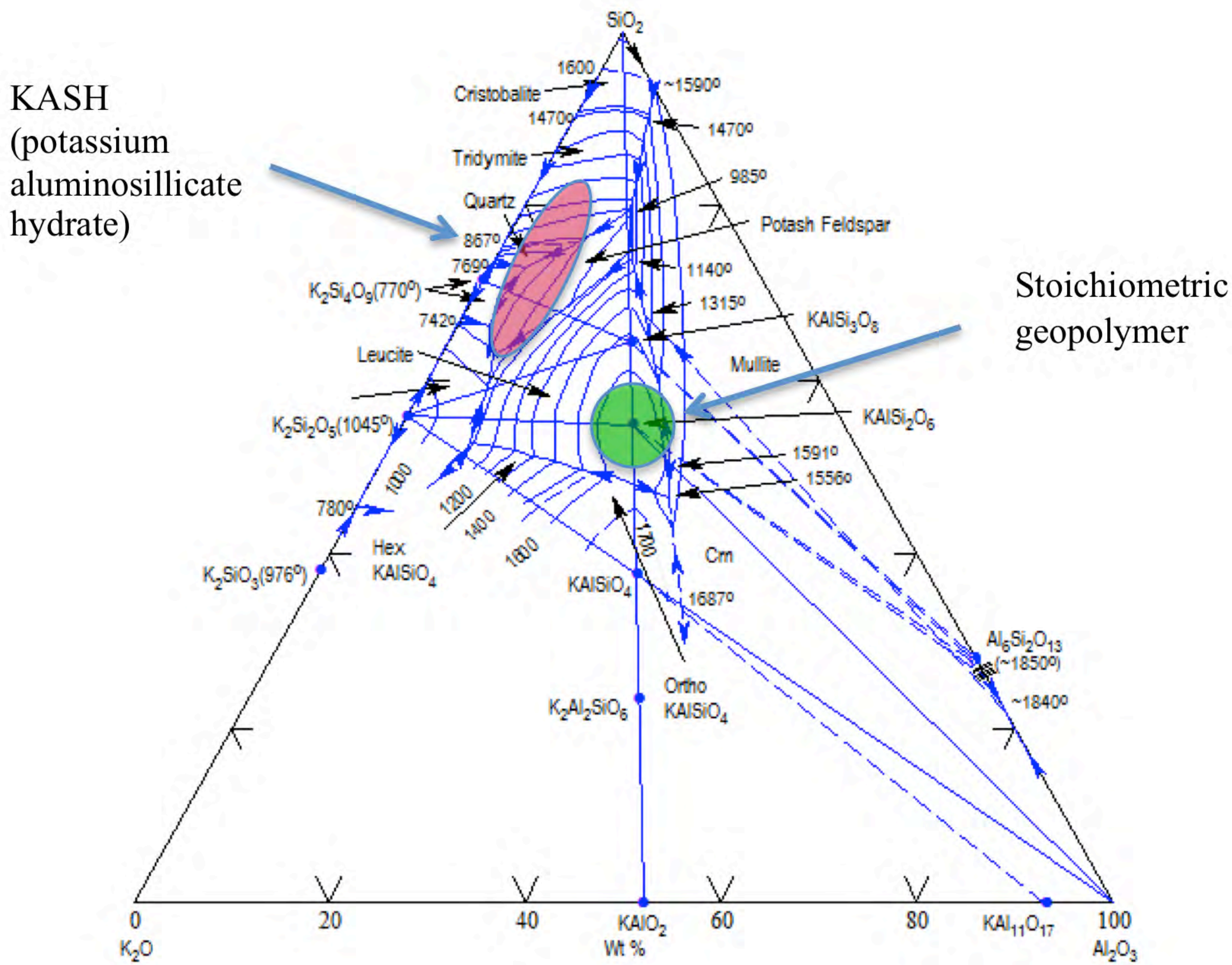
Alkali Activated Cements



Geopolymers are a potential partial solution to global warming!

- The manufacture of 1 ton of Portland cement liberates ~1 ton of CO_2
- Whereas the manufacture of 1 ton of geopolymers liberates ~0.25 tons of CO_2

Comparison of OPC and Geopolymer (GPC) Composites

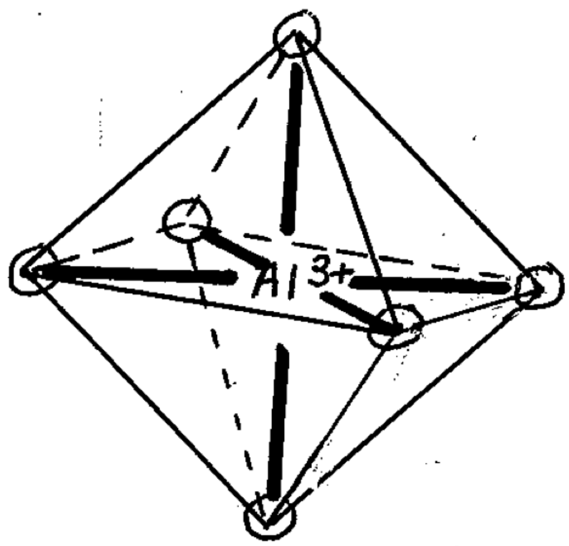
Property	Portland Cement	Geopolymers
Compressive strength (MPa)	60	100
Flexure strength (MPa)	5-6	10-15
Density (g/cc)	2.7	1.4
Setting time (days)	28	1

Synthesis of Geopolymer

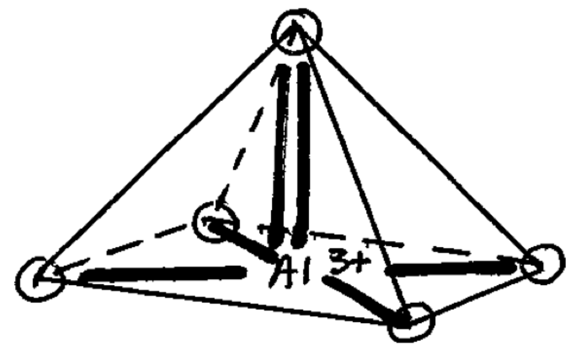
Raw Materials

- Slag (in the former USSR)
- Fly ash (Australia)
- Clays e.g. metakaolin (France, USA)
- Halloysite (New Zealand)
- Plasma incinerated utility waste (black glass) (UK)
- Recycled waste glass powder (cullet)
- Heated (1200 °C) basalt from volcanic tufts
- Calcined rice husks, bamboo leaves, elephant grass

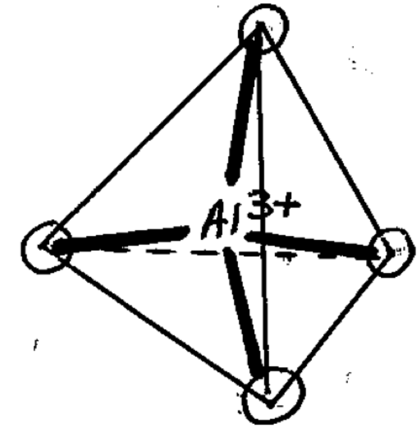
How can a geopolymer form at RT?



Al(VI) in crystalline
(Al_2O_3•$2SiO_2$•$2H_2O$)



Al(V) in amorphous
Al_2O_3•$2SiO_2$ forms
highly strained molecule



AlO_4^- tetrahedra and
SiO_2.AlO_4^- oligomers
in solution

Heat 750 °C/1h →

Dissolve at high pH →

How to make a geopolymer

The term "geopolymer" was introduced by Joseph Davidovits to describe alkali aluminosilicate binders formed via the addition of aluminosilicate materials to alkaline silicate solution

Step 1

+

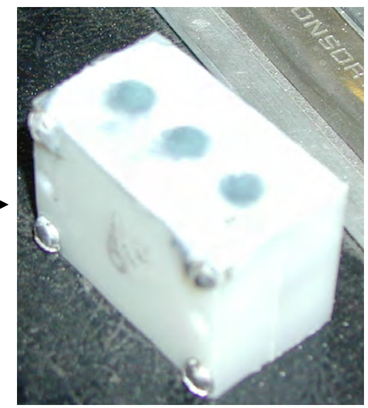
Metakaolin clay

Molar oxide ratio	
SiO_2 / Al_2O_3	4.0
K_2O / SiO_2	0.25
H_2O / K_2O	10

Step 2

mix

Step 3



cast and seal

Step 4

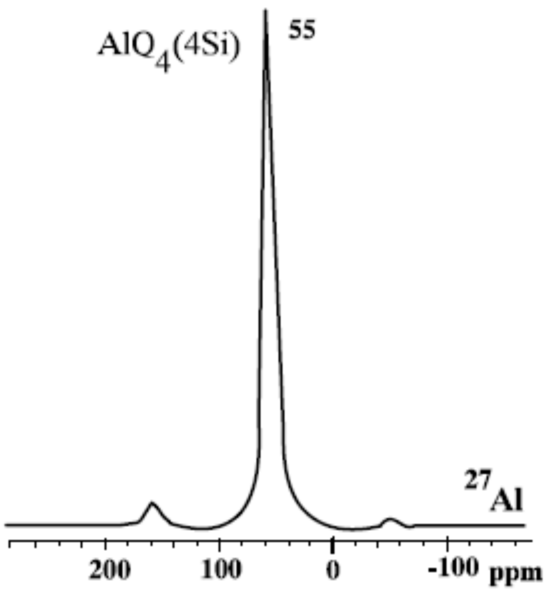
store at RT or in an oven at low T

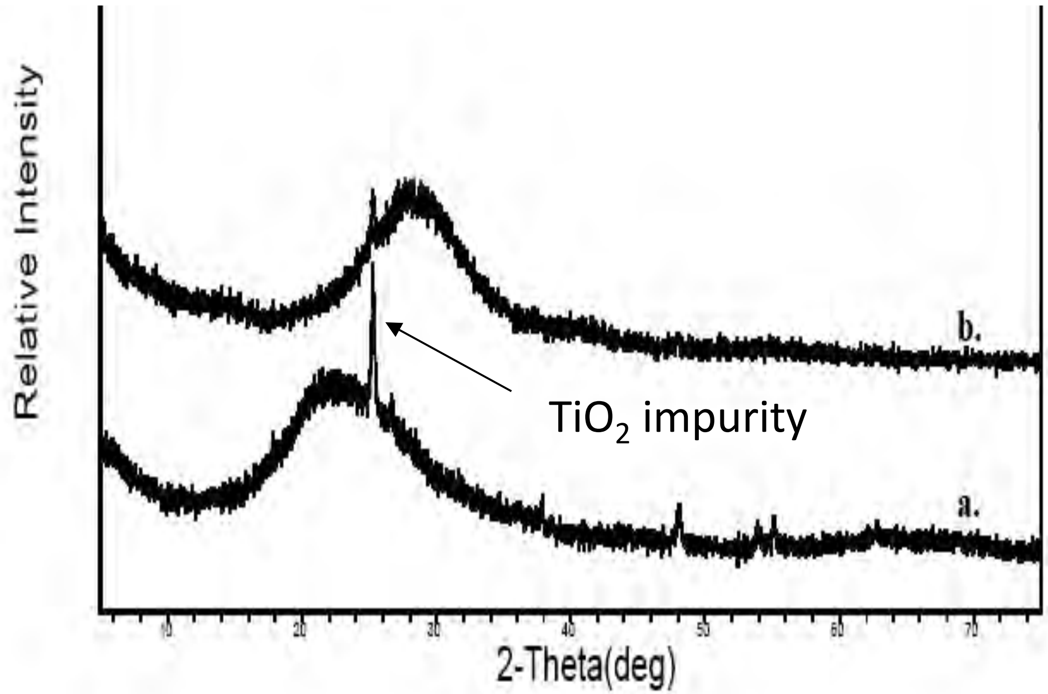

PVA Mesh Used as Fiber Reinforcement (w/ added pigment)
Thick and Rigid
or
Thin and Flexible
Geopolymers
Colored using common paint pigments and
2008/03/08 11:12

Geopolymers can be formed in plastic molds and colored

Microstructure

XRD Characteristic of Geopolymer





NMR gives great local information such as the coordination state of Al, which is predominantly 4-coordinated in geopolymers

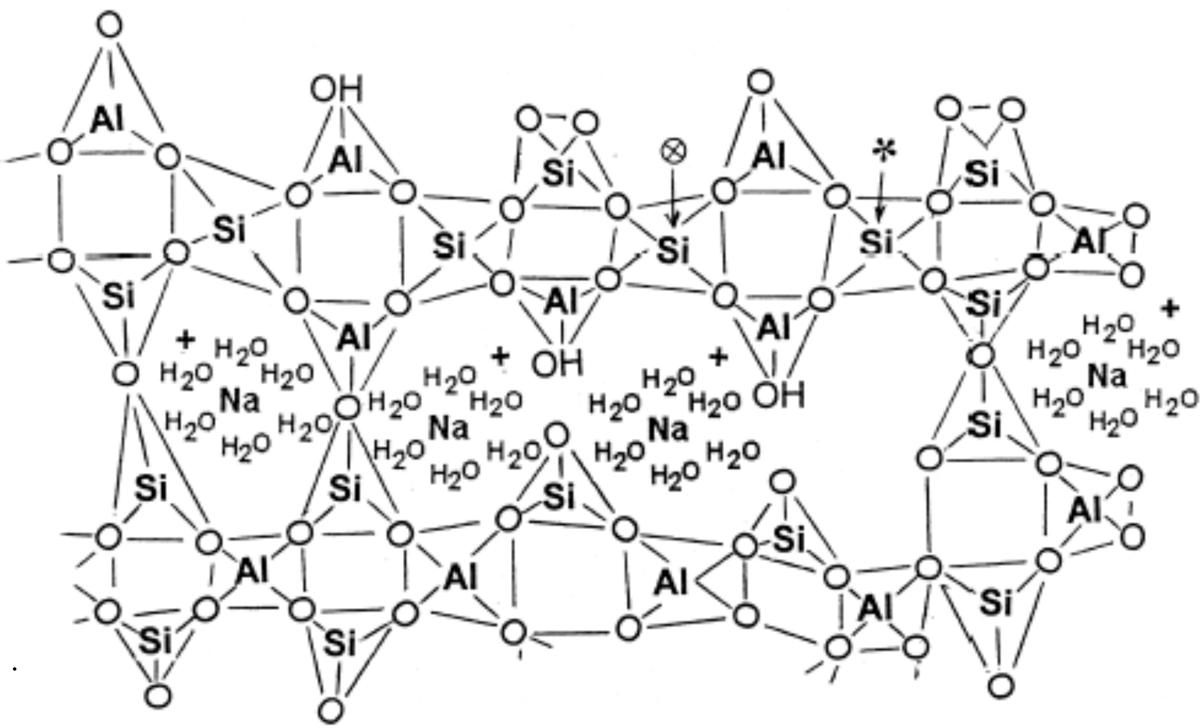
Typical GP XRD pattern shows a broad peak shift from metakaolin (a) to the resultant geopolymer (b), but says little about geopolymer structure other than it is amorphous

Davidovits, J., *Geopolymers - inorganic polymeric new materials.* Journal of Thermal Analysis, 1991. **37**(8): p. 1633-1656.

M. Gordon, J. L. Bell and W. M. Kriven, "Comparison of naturally and synthetically derived, potassium based geopolymers"; pp. 95-103 in Ceramic Transactions, Vol. 165, (2004.)

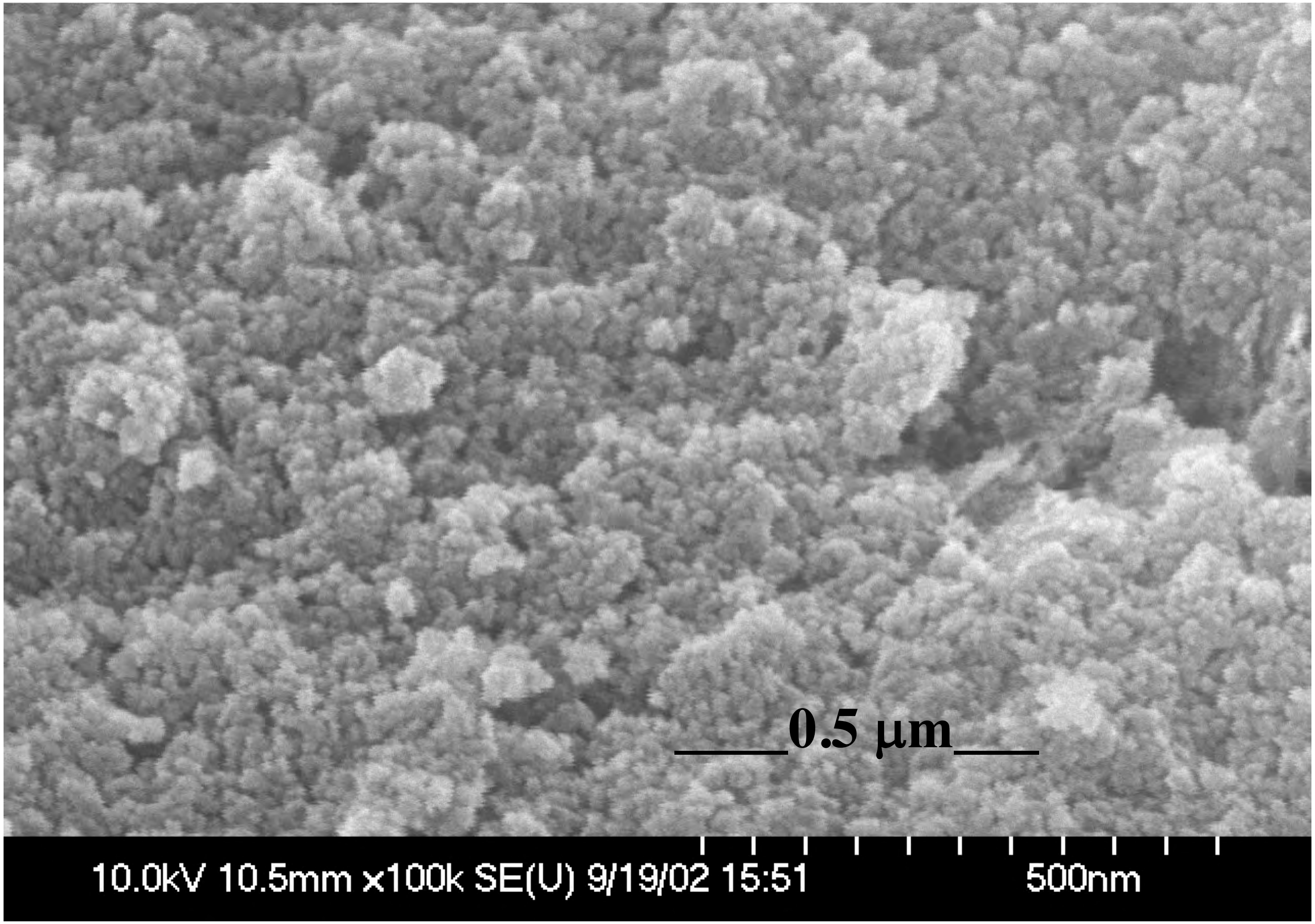
Geopolymer Structure

- X-ray amorphous
- Al is integrated into a network of (IV) AlO_4^- and SiO_4, such that the negative charge on AlO_4^- is balanced by the alkali cation



Davidovits, J. Journal of Thermal Analysis **1991**, *37*, 1633
Barbosa, V.F.F. and K.J.D. MacKenzie, Materials Research Bulletin, 2003. **38**(2): p. 319-331
Barbosa, V.F.F., K.J.D. MacKenzie, and C. Thaumaturgo,. International Journal of Inorganic Materials, 2000. **2**(4): p. 309

SEM micrograph of a fully reacted region of polysialate.



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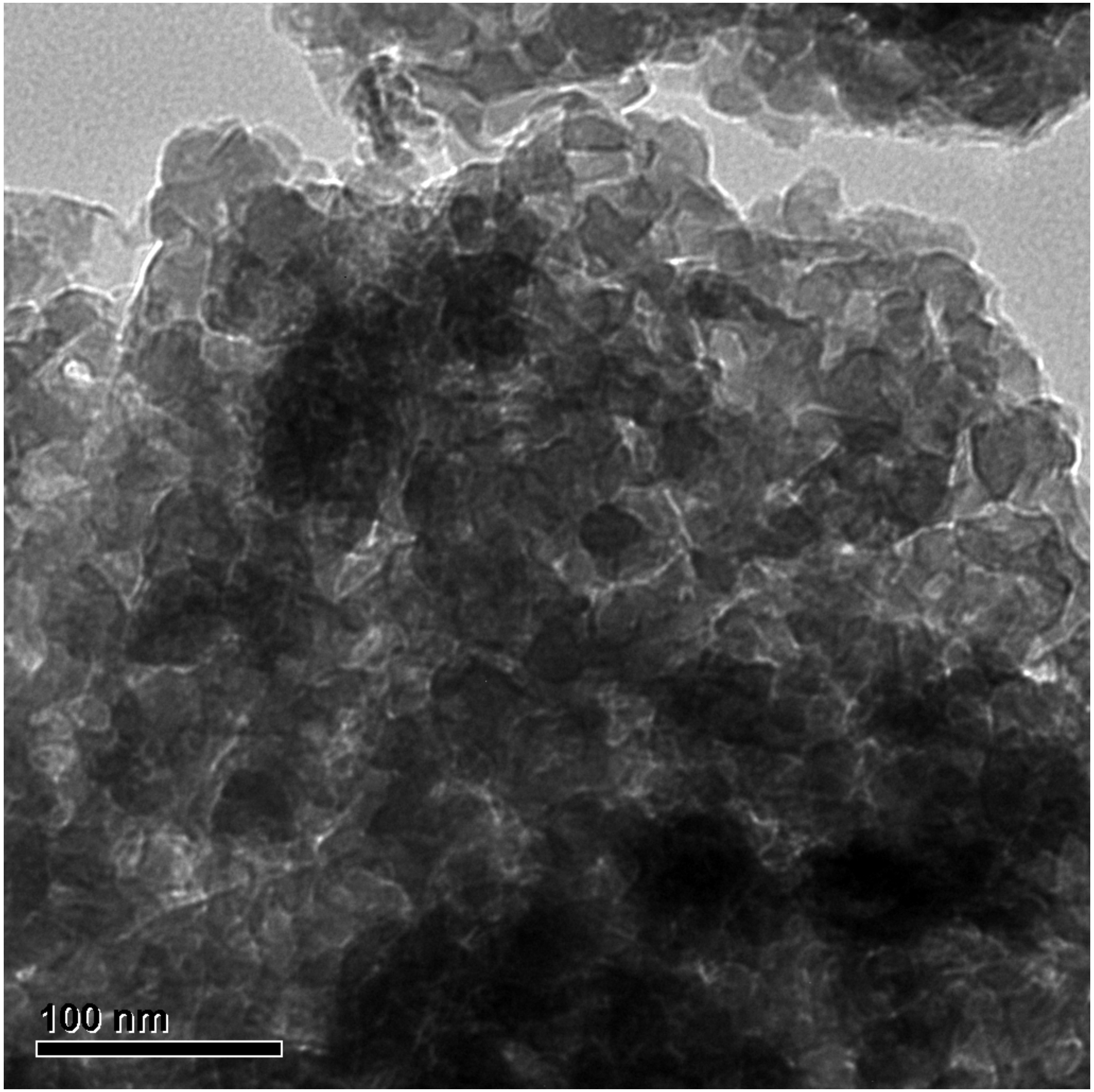
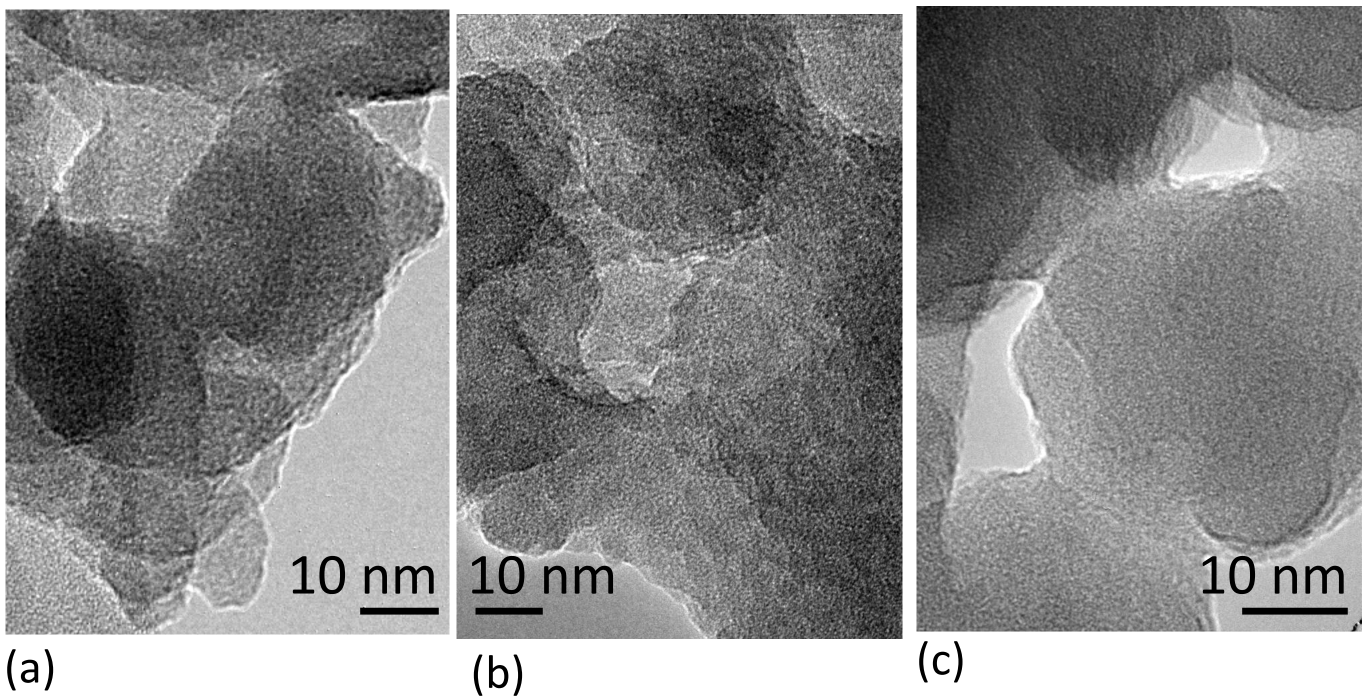
TEM of crushed Na-geopolymer



Microstructure of Precipitates



High resolution transmission electron microscopy (HRTEM) results for (a) NaGP, (b) KGP, and (c) CsGP.

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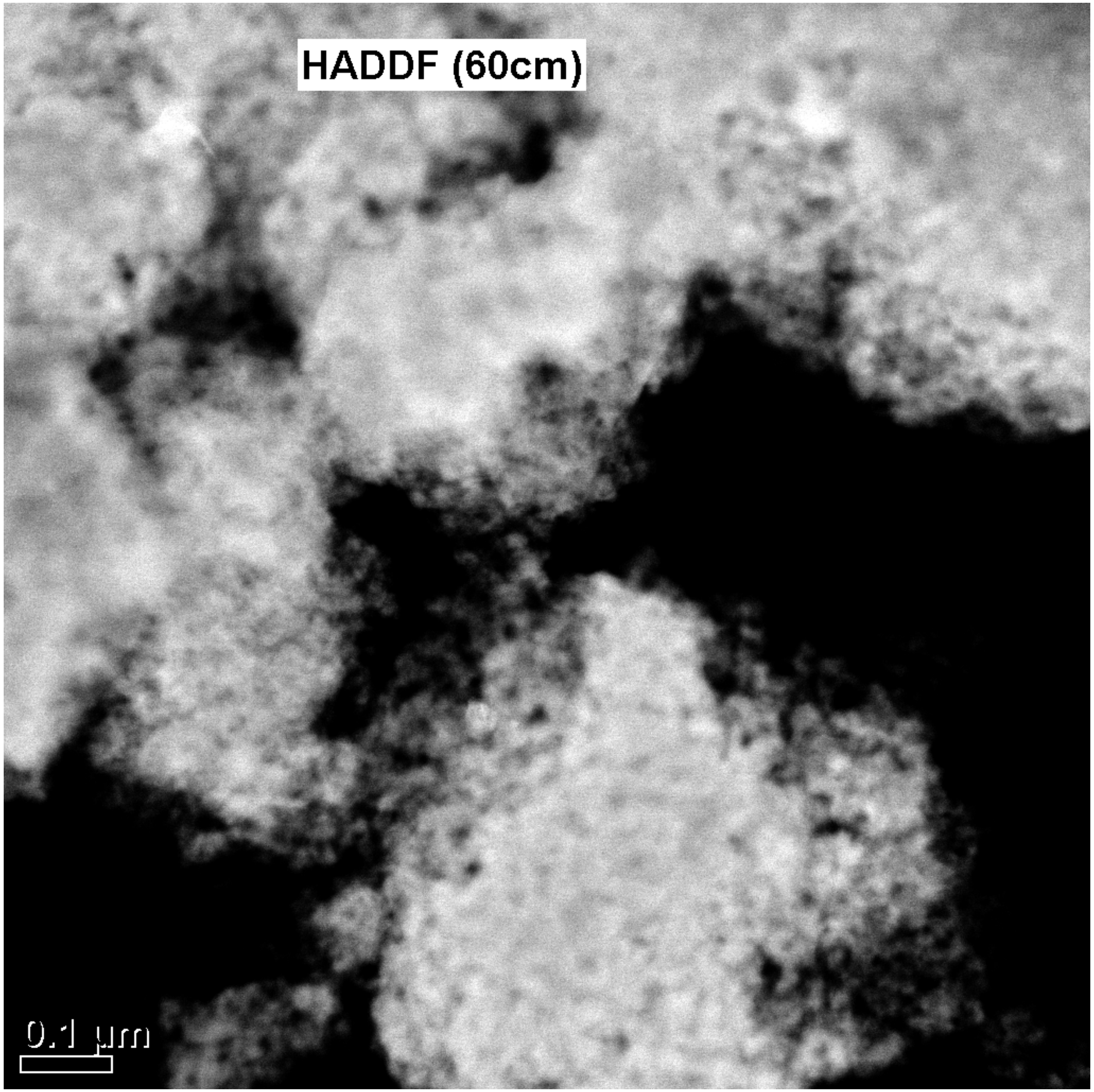
High angle, annular dark field TEM (HAADF)



Nanoporosity in kaolin-based GP

Average logarithmic pore radius : 0.4362 nm

Average pore radius : 3.3711 nm

Porosity over weight : 0.3165 cm^3/g

Porosity over volume : 0.4106 cm^3/cm^3

Meso- and macro-pore surface over weight : 190.5778 m^2/g

Meso- and macro-pore surface over volume : 247.2794 m^2/cm^3

Total pore surface over weight : 274.6912 m^2/g

Total pore surface over volume : 356.4186 m^2/cm^3

Density of solid phase: 2.0481 g/cm^3

Nanoporosity in synthetic-based GP = 0.8 nm

Densities of single phase geopolymer using different Group I cations

Alkali cation	Na	K	Cs
Densities (g/cm^3)	1.51	1.47	1.84

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Porosity in geopolymers:

- H_2O_2 (45 μm)
- Canola oil (100’s μm)
- Kitty litter (bentonite)
- Alkoxy silanes (75 vol % at 1 μm pore size)*
- Excess H_2O (reduces strength)

* “Geopolymer with Hydrogel Characteristics via Silane Coupling Agent Additives,” B. E. Glad and W. M. Kriven, J. Am. Cer. Soc., **97** [1] 295 - 304 (2014).

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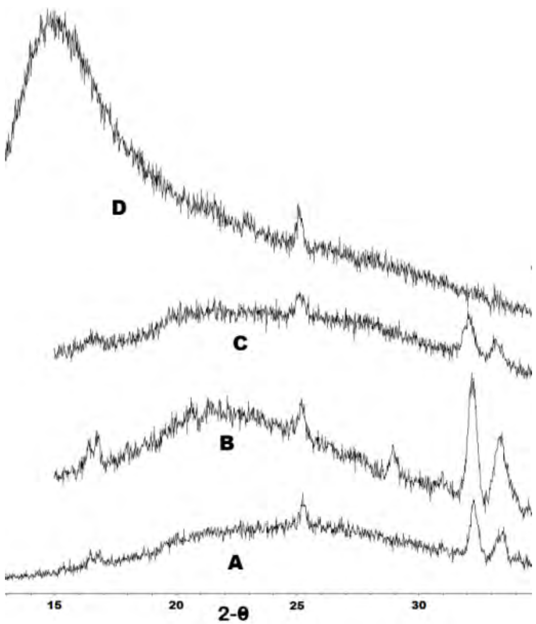
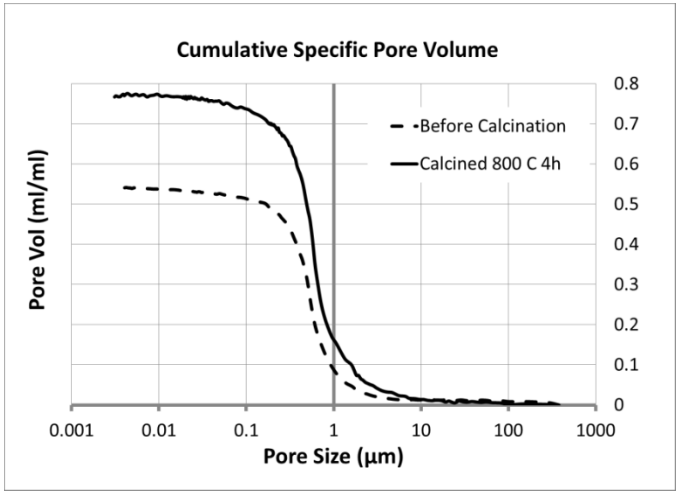
Calcination for Filtration

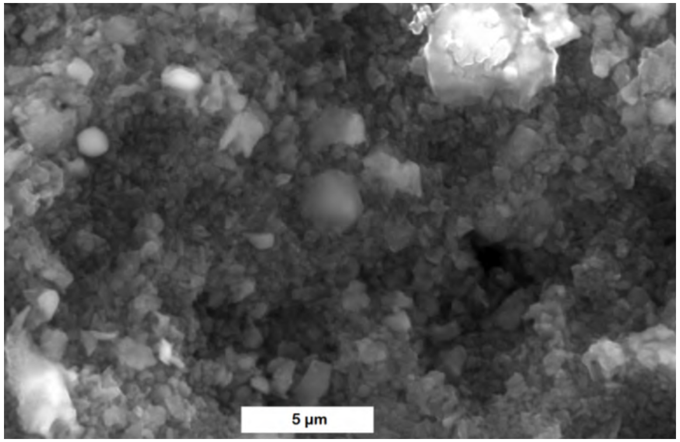
- Calcination (800 °C, 4h) to remove hydrophobic material under inert conditions
- Glassy structure shows substantial morphological change
  - Diffraction spectrum changes
  - Synchrotron data shows formation of cubic SiC



Premix peak at 24 2-Θ moves to 14 2-Θ Upon calcination. SiC is a trace phase



Noticeably increased porosity and slightly wider pores implies removal of film



No film is visible for even a 2.67 mol DIDE/mol GP sample after calcination

Pair Distribution Function (PDF) Work

- Novel materials are often disordered/complex on a local level
- PDF method – allow us to sit on an atom and look at our neighborhood
- PDF procedure:
  1. Collect total scattering data (X-ray or neutron) for material
  2. Subtract background and apply appropriate corrections to raw data
  3. This gives us the structure function, S(Q)
  4. Apply Fourier transform to get the PDF, G(r)

$$S(Q)=\frac{I_{el,coh}(Q)+\left[\left\langle f(Q)\right\rangle^2-\left\langle f(Q)^2\right\rangle\right]}{\left\langle f(Q)\right\rangle^2}$$

$$G(r)=\frac{2}{\pi}\int_0^\infty Q\left[S(Q)-1\right]\sin(Qr)\,dQ$$

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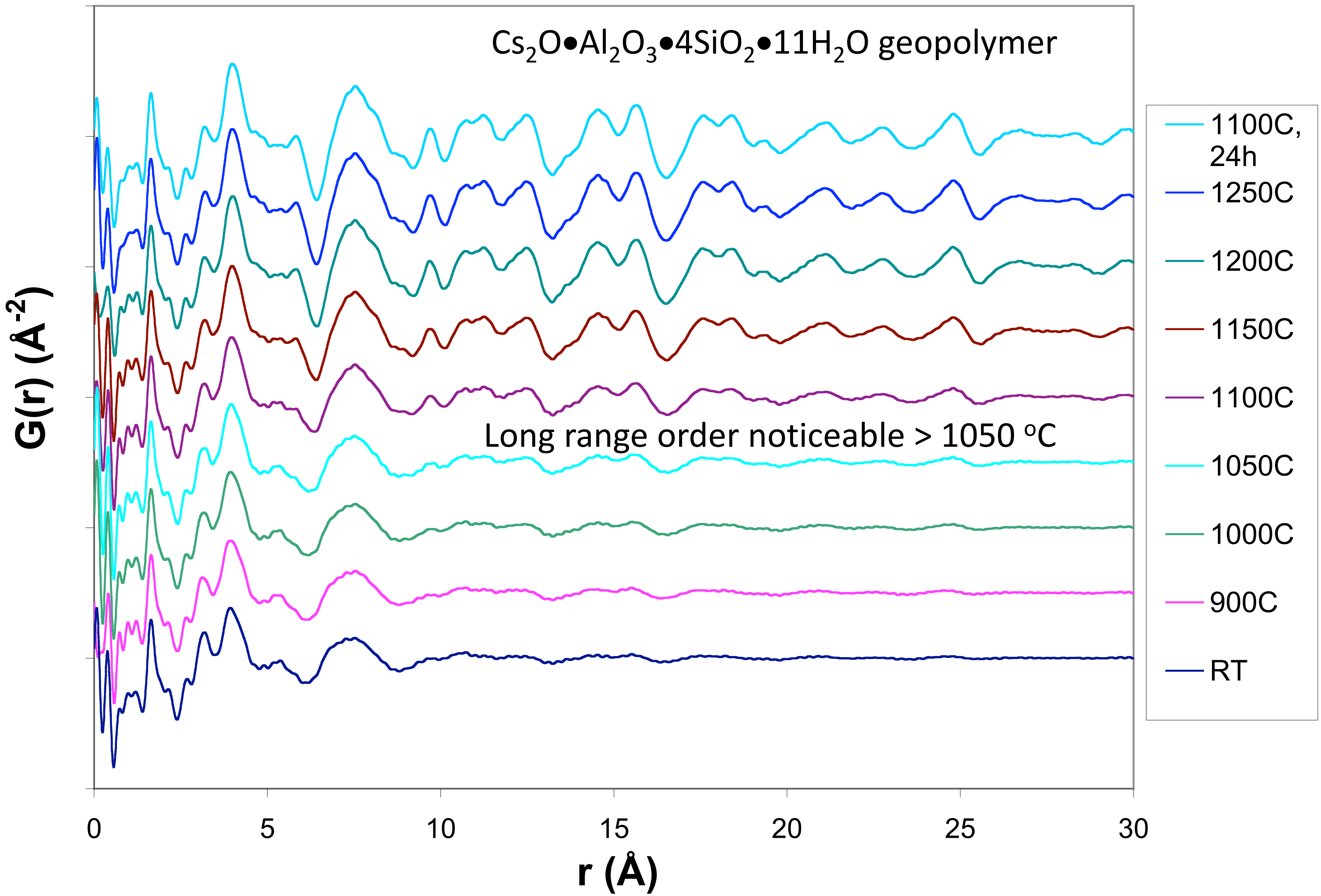
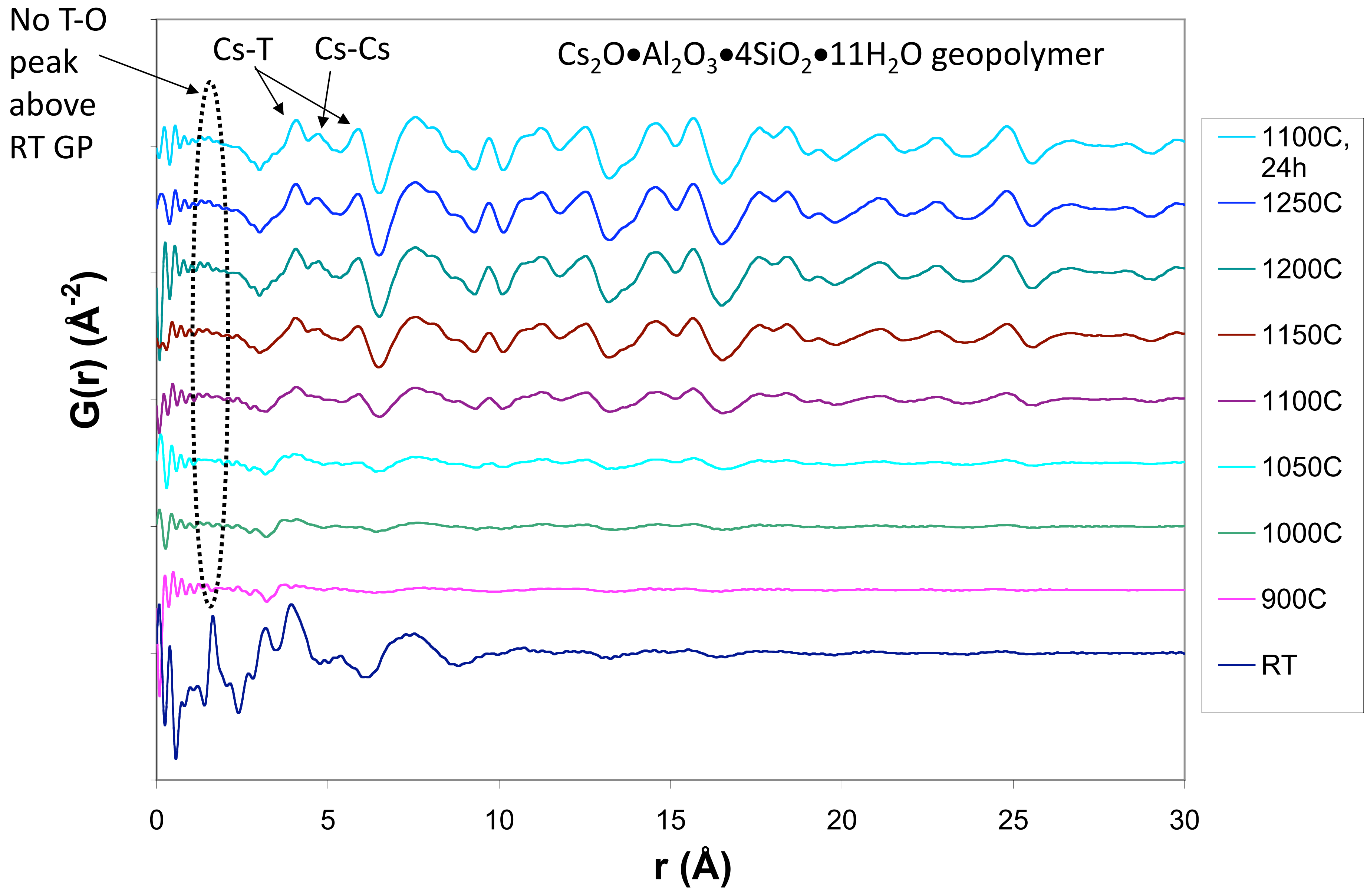
Pollucite ($CsSi_2AlO_6$) Analysis and Modeling

PDFs for experimental GP samples heated to specified T, no soak

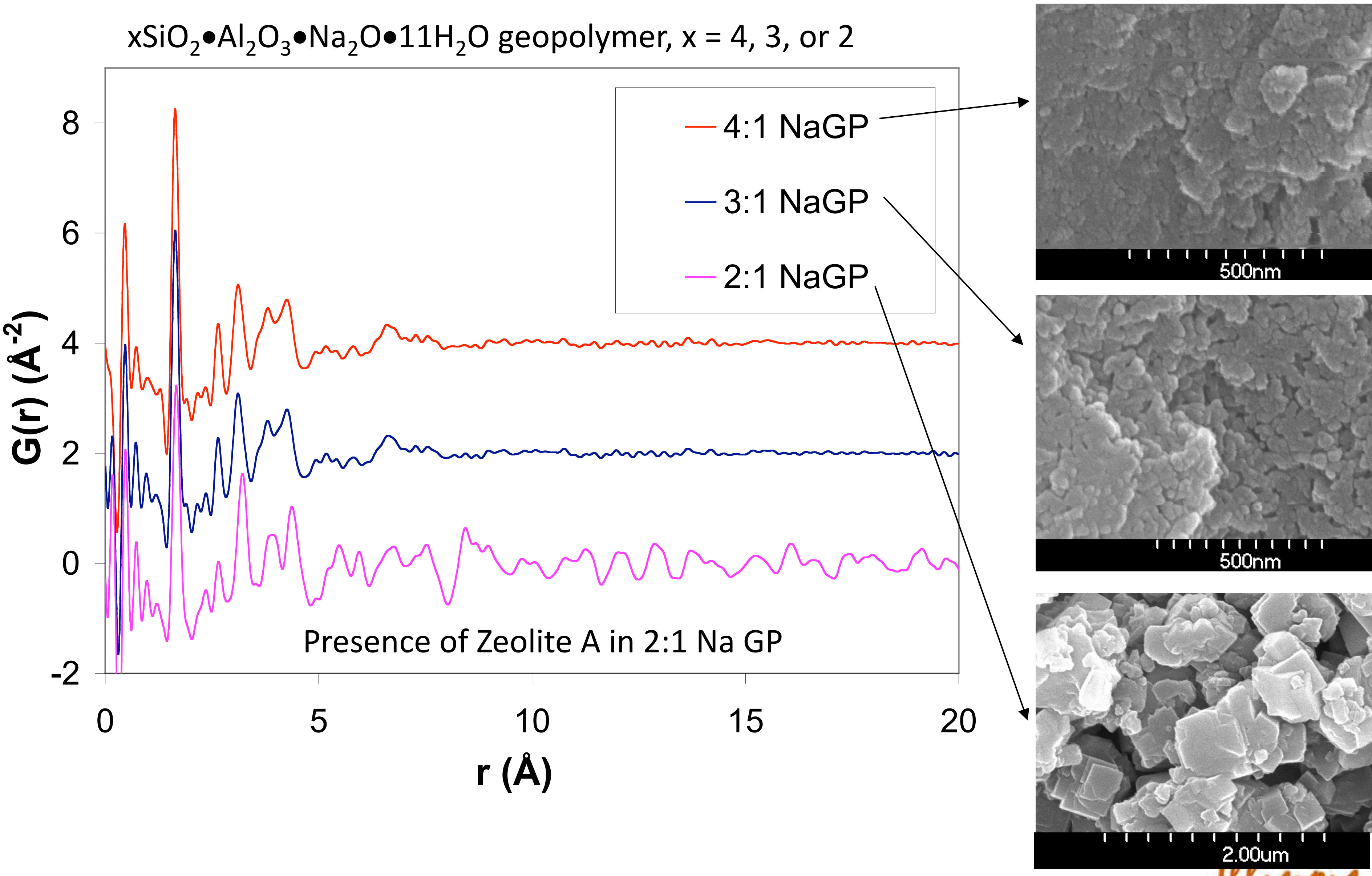


Pollucite ($CsSi_2AlO_6$) Analysis and Modeling

Subtraction of RT experimental geopolymer PDF from heated PDF patterns

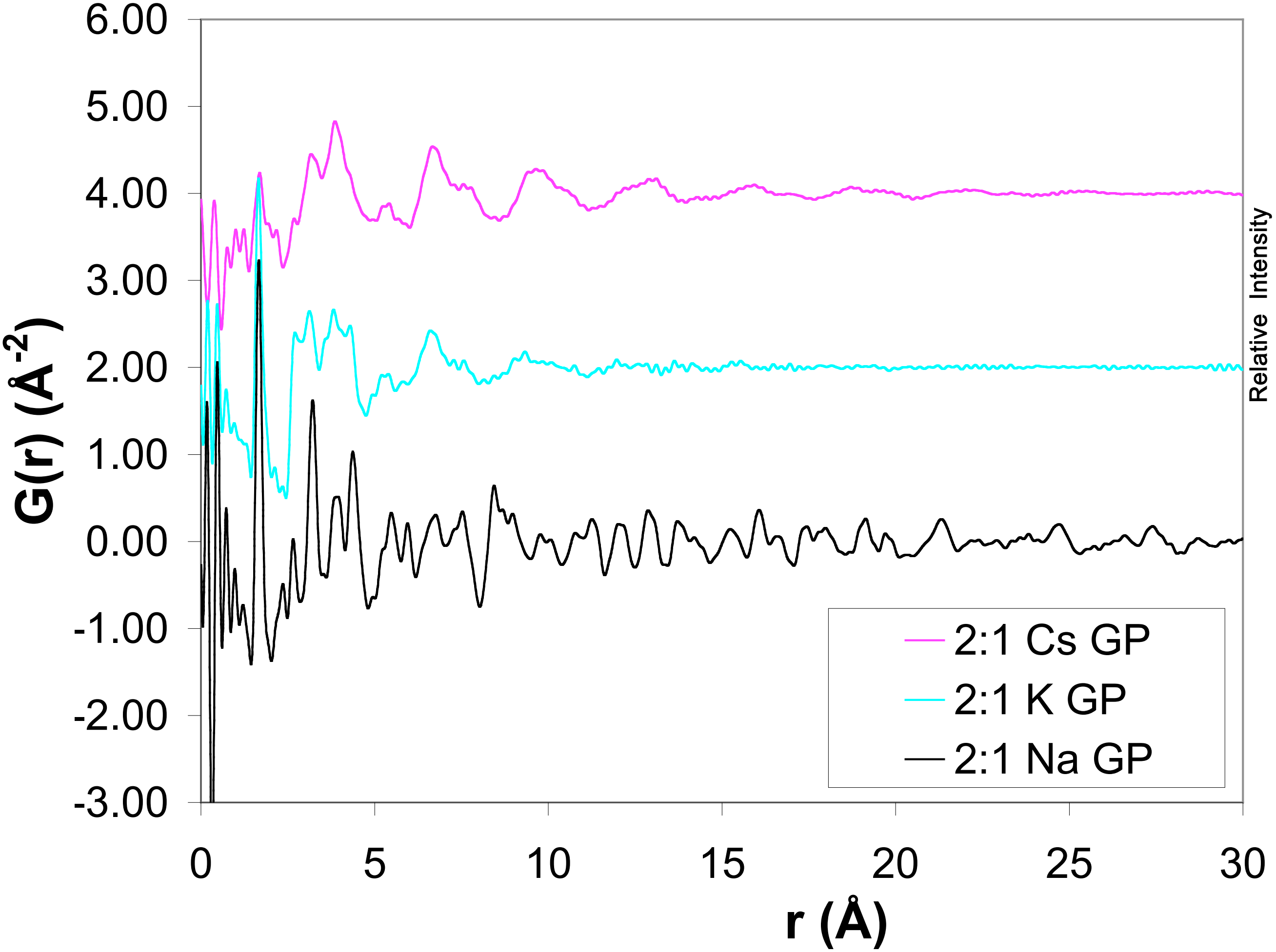


Na based geopolymer – Ordering in Na-GP

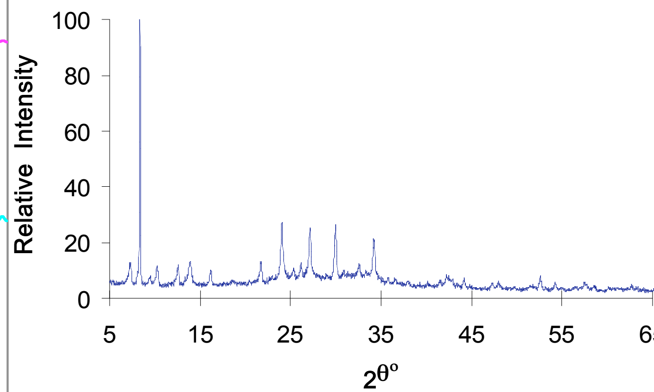


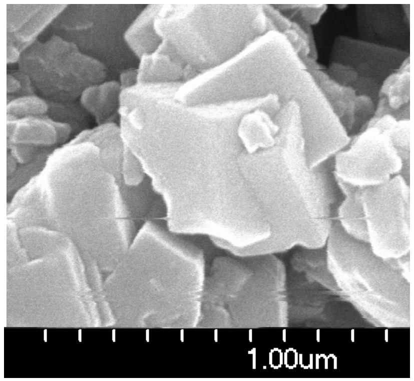
Geopolymer – PDF as function of Alkali Choice

$2SiO_2 \bullet Al_2O_3 \bullet X_2O \bullet 11H_2O$ geopolymer, x = Cs, K, or Na



Presence of Zeolite A in 2:1 Na GP





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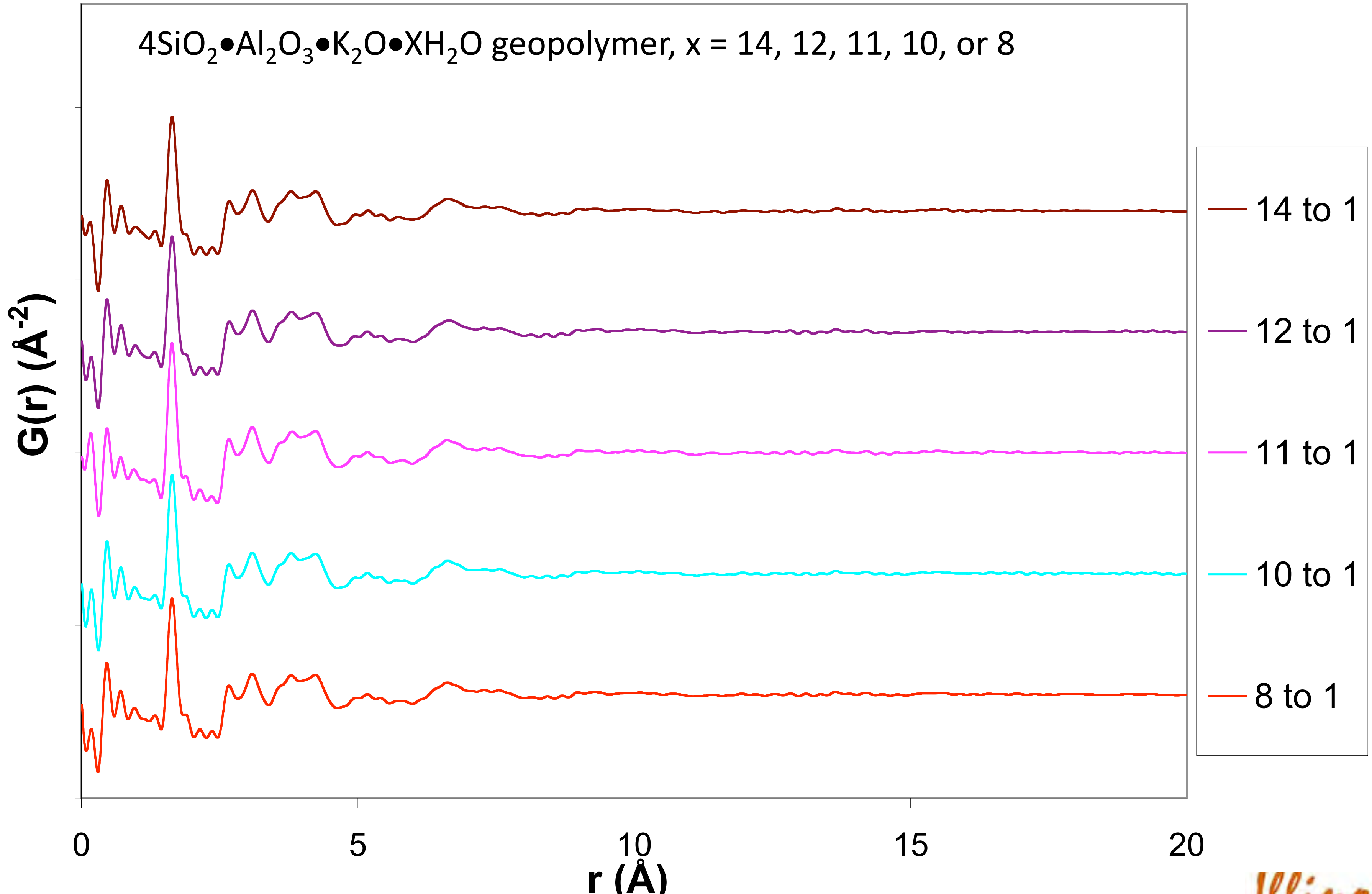
Geopolymer – PDF as function of water for K-GP



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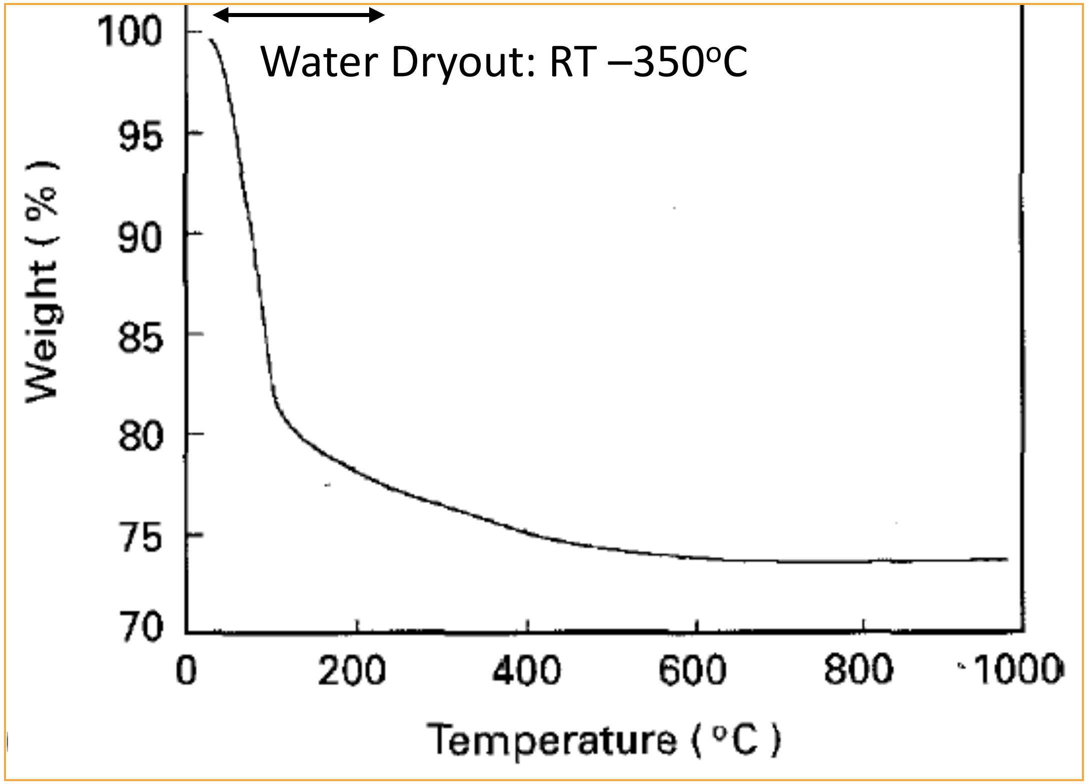
WATER REMOVAL

TGA Results*



Most of water evaporated below 250°C leading to a 5% shrinkage*

This includes free water at surface/pores, adsorbed water, and chemically bound water*

*Rahier, H., B. VanMele, and J. Wastiels, Low-temperature synthesized aluminosilicate glasses: Part II: Rheological transformations during low-temperature cure and high-temperature properties of a model compound. Journal of Materials Science, 1996. **31** 80-85, (1996)

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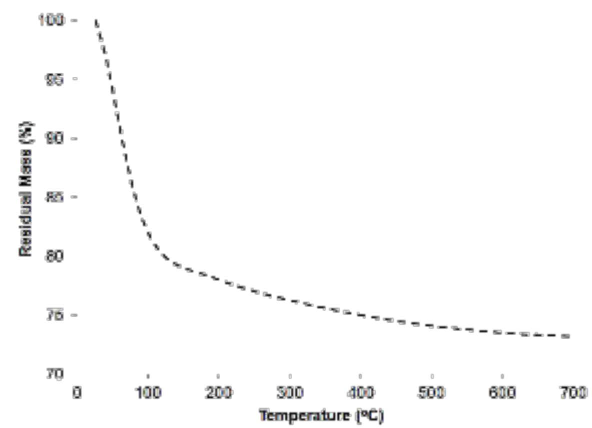
Dehydration Cracking

- Geopolymers undergo shrinkage upon heating due to water loss[1]
  - RT to 100°C: Dehydration of physically bonded (free) water
  - 100 to 300°C: Dehydration of chemically bonded (interstitial) water
  - >300°C: Dehydroxylation of OH groups

- Dehydration shrinkage causes cracking of monolithic geopolymer

- Reinforcing or filler phases can be utilized to maintain structural integrity during shrinkage by crack-bridging and offering pathways for more graceful dehydration



[1]J. Davidovits, *Geopolymer Chemistry and Applications*, 2008.

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Reinforcements

- Chamotte/mullite particulates, granite, dolomite sediment
- Chopped fibers
  - Alumina (13 μm D x 100 μm long)
  - Basalt (50 μm D x ¼”, ½” long)
  - Carbon (7 μm D x 60 or 100 μm long)
- Alumina platelets (D = 50 μm)
- Woven fabric
  - Carbon fiber
  - Nextel 610 alumina, 720 mullite + alumina, 550 mullite
  - Basalt weaves and felts
- Mullite single crystal fibers (Moscow)
- Polymeric chopped fibers – polyproplyene (½”, 1”, 2”)
- Biological fibers
  - Corn husk fiber bundles - Cordgrass (Illinois)
  - Jute (China, India) - Abaca (Manila hemp) and Hemp
  - Fique (Colombia) - Malva (Amazon)
  - Cork - Curaua (Amaon)

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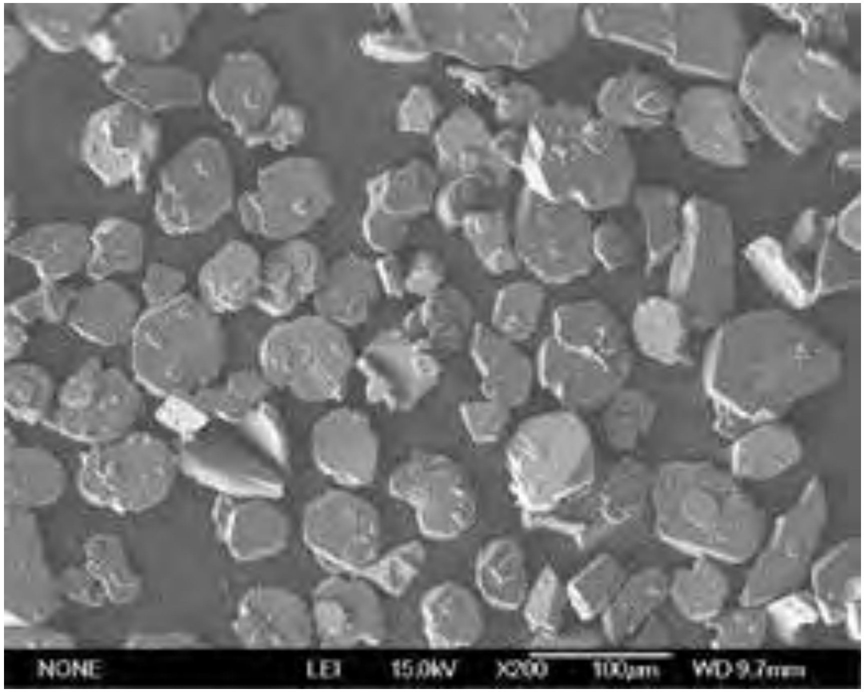
Alumina Platelets

- Microgrit® WCA 50
  - Manufactured by Micro Abrasives Corp., Westfield, Massachusetts, USA
  - Aspect ratio of 5:1



- Diameter:
  - 6% less than 16.12 µm
  - 50% between 42.81-52.50 µm
  - 3% greater than 102.00 µm

- Miscellaneous
  - Purity: 99.20% Al2O3
  - Density: 3.95 g/cm^3
  - http://www.microgrit.com/microgrit%20wca.html

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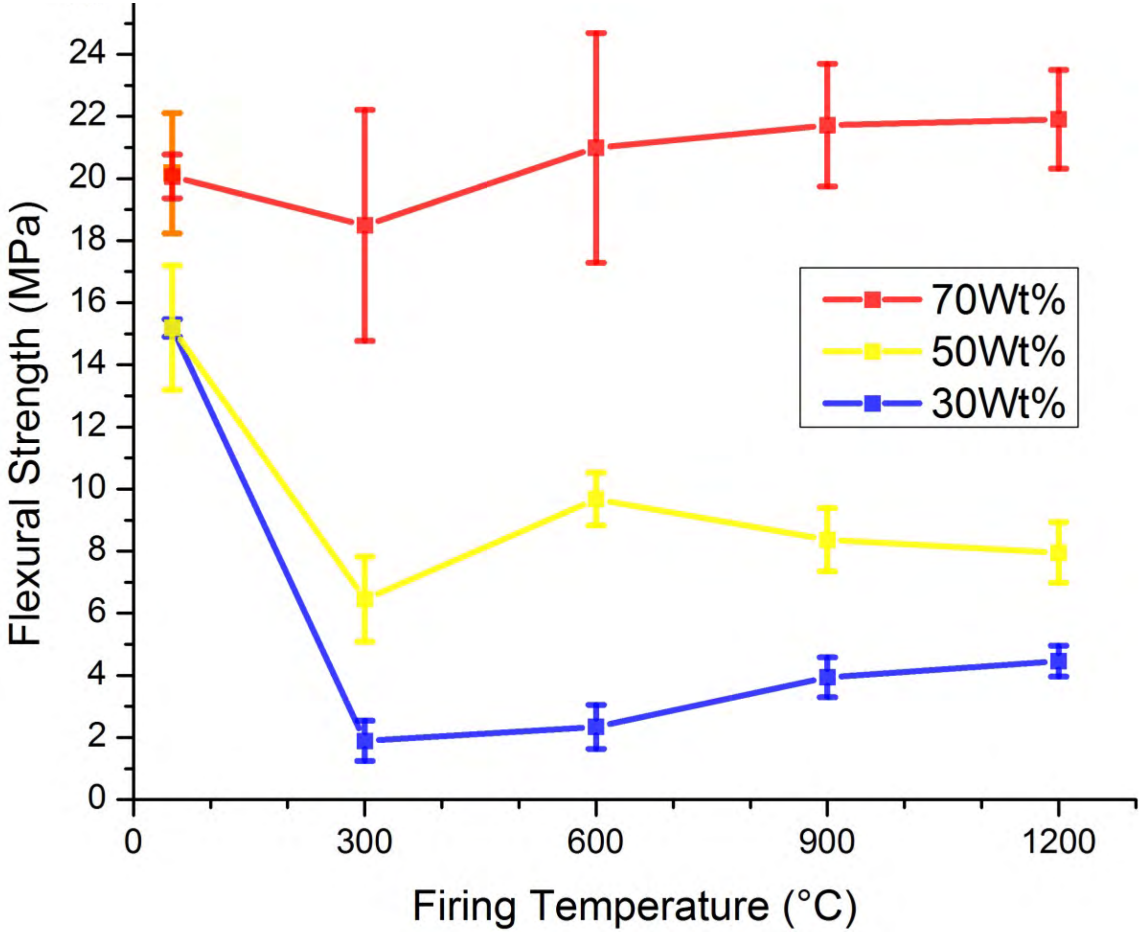
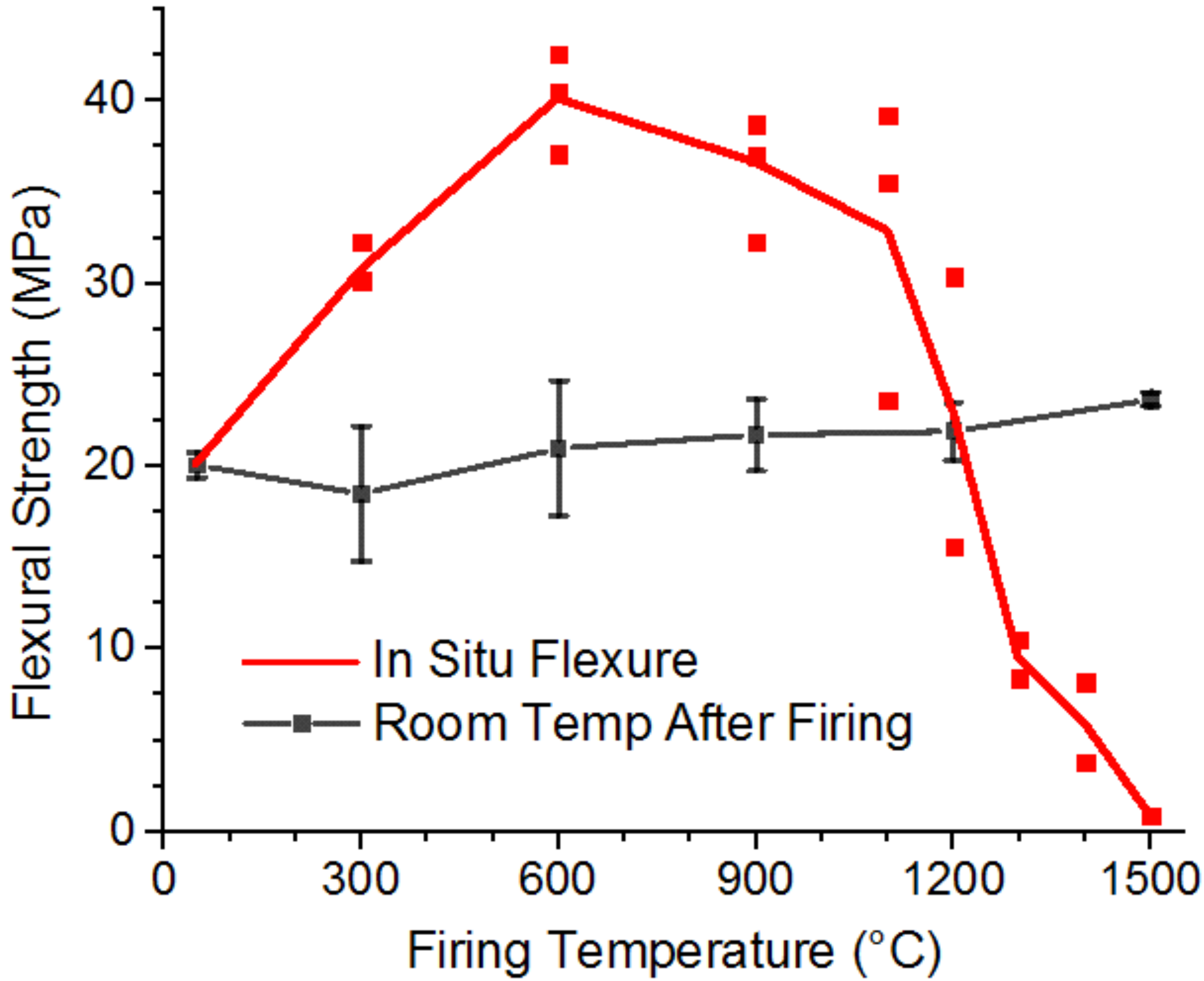
Residual Strength after Heat Treatment

- Competing effects on heating
  - Elevated diffusion promotes dehydration crack filling, densification
  - Differential thermal shrinkage creates new, larger cracks and residual strains
  - No apparent leucite transition weakening



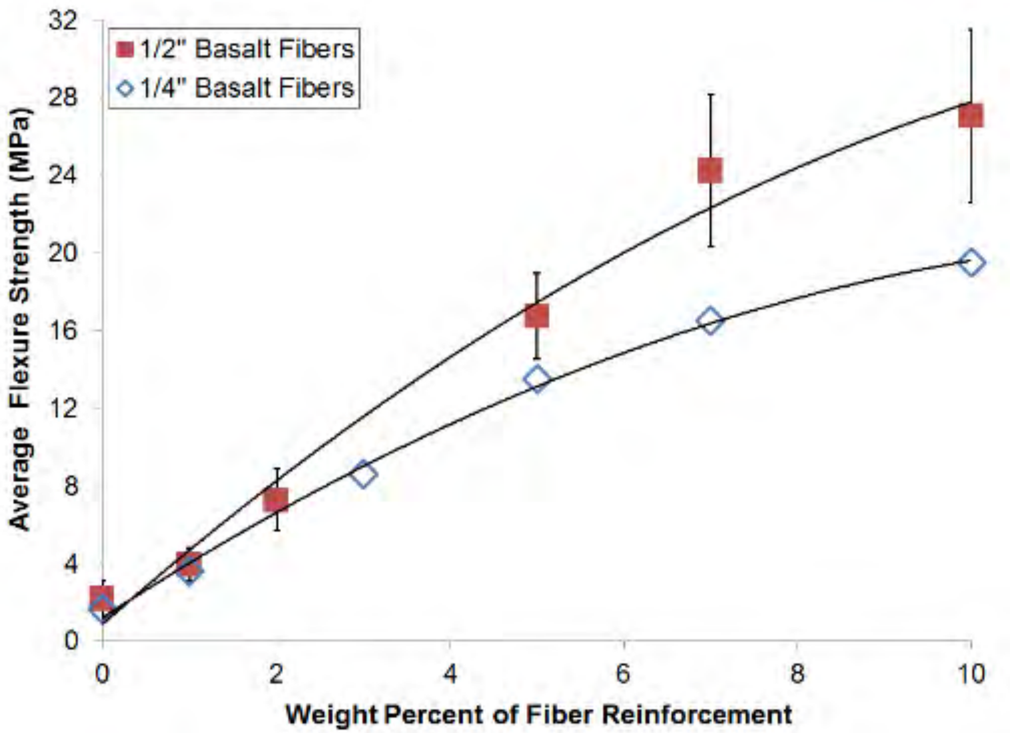
Strength vs Temperature

- In-situ strength remained greater than 5MPa until over 1300°C
- Samples at 900°C deformed plastically



Strength by Fiber Weight Percent

- Composite strength increases rapidly with increasing fiber weight percent
- Modest strength increase for ½ inch long fibers compared to ¼ inch long fibers for the same weight percent



Fiber Length (in)	Fiber Weight (%)	Average Strength (MPa)	Strength Increase ¼ to ½ in (%)
-	0	2.2	
¼	1	3.6[1]	9.0
½	1	3.9	
½	2	7.3	
¼	3	8.6[1]	
¼	5	13.5[1]	24.1
½	5	16.8	
¼	7	16.5[1]	46.9
½	7	24.2	
¼	10	19.5[1]	38.8
½	10	27.1	

[1]E. Rill et al., “Properties of Basalt Fiber Reinforced Geopolymer Composites,” *Cer. Eng. and Sci. Proc.*, **31** [10] (2010) 57-67.

Thermal shock structural materials for VLO runway

Geopolymer composite pellets of 2 inches diameter, after thermal shock for several minutes with an oxy-acetylene torch

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BENCHMARK STRUCTURAL PROPERTIES of GP COMPOSITES

Material	Flexure strength (MPa)
KGP-chamotte particulate	2.1 → 15.3 for 50 wt%
KGP-chopped basalt ¼” ϕ =13 μm	1.7 → 19.5 for 10 wt%
½” ϕ=13 μm	2.2 → 27 for 10 wt%
Chopped Al_2O_3 fiber CsGP ϕ = 3 μm	10 → 20 for 20 wt%
Chopped C fiber 60 μm ϕ =7 μm	8.8 → 14.1 for max loading
Nextel 610 weave	8.7 → 50 for 33 vol%
Nextel 720 weave	8.7 → 40 for 27.3 vol %
Basalt plain weave	4.5 → 41.38 for 30 vol%
	Tensile strength (MPa)
Nextel 610 weave in KGP	2.5 → 205
Nextel 720 weave in KGP	2.5 → 125
Plain basalt weave in KGP	1.2 → 38
Nextel 610/monazite in alumina	0.25 → 117

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Processing route to ceramics
- Oxides with tailorable CTE's

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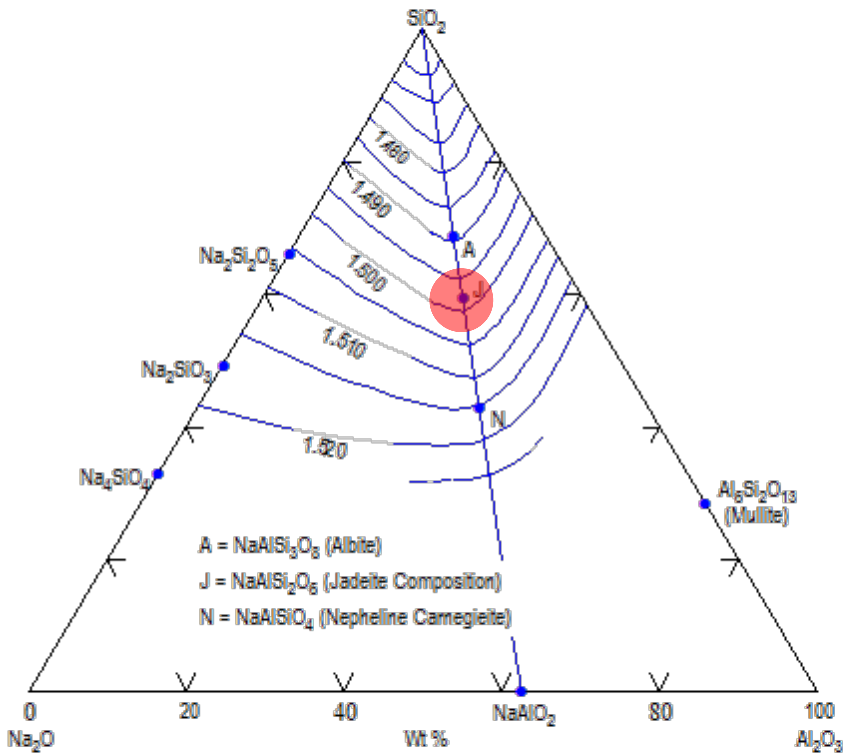
Geopolymers as a processing route to aluminosilicate oxides

Sodium geopolymer crystallizes into nepheline ($NaAlSi_2O_6$), on heating at 750°C

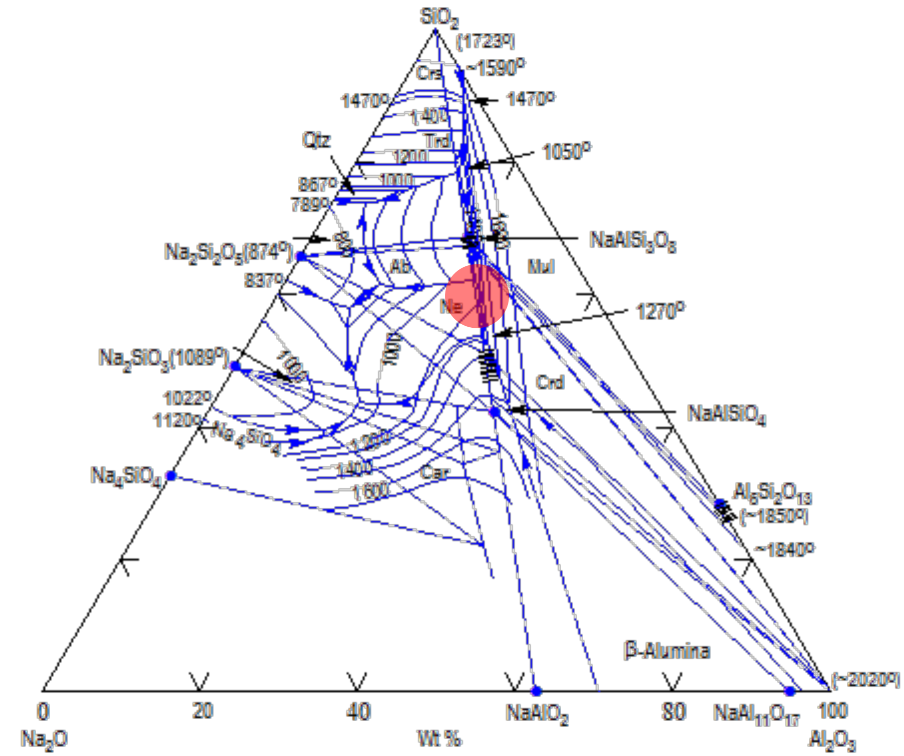
Potassium geopolymer crystallizes into leucite ($KAlSi_2O_6$), on heating at 950°C

Cesium geopolymer crystallizes into pollucite ($CsAlSi_2O_6$) on heating at 1100 °C.

Phase Diagram: Na



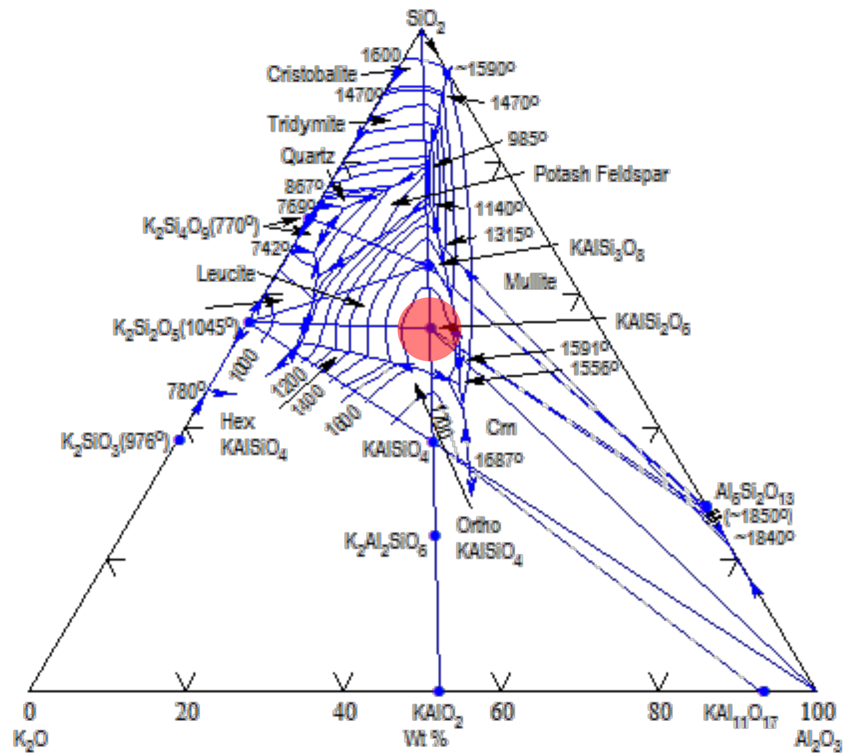
"System Na_2O-Al_2O_3-SiO_2; isofracts," J. F. Schairer and N. L. Bowen, *Am. J. Sci.*, **254** [3] 129-195 (1956).



"System Na_2O-Al_2O_3-SiO_2; composite," E. F. Osborn and A. Muan, revised and redrawn, "Phase Equilibrium Diagrams of Oxide Systems," Plate 4, published by the American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, 1960.

Phase Diagrams: K

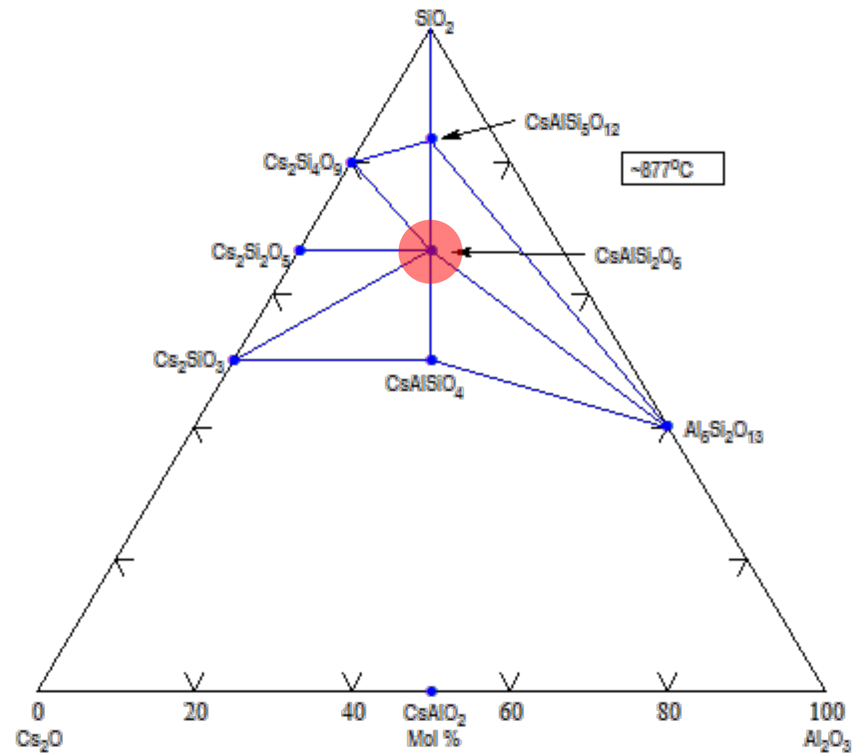
- **Leucite ($KAlSi_2O_6$)**
  - Refractory (T_m ~ 1693°C)
  - High thermal expansion ($15.1 – 31 \times 10^{-6}$ $^oK^{-1}$)
  - High fracture toughness
  - Useful as a cermet due to high thermal expansion
  - Used widely in dentistry
  - Potential as a thermal barrier coating or ceramic matrix composite
  - Leucite crystals enhance the toughness of glass ceramics



"System K_2O-Al_2O_3-SiO_2; composite," E. F. Osborn and A. Muan, revised and redrawn Phase Equilibrium Diagrams of Oxide Systems, Plate 5, published by the American Ceramic Society and the Edward Orton, Jr., Ceramic Foundation, 1960.

Phase Diagrams: Cs

- **Pollucite ($CsAlSi_2O_6$)**
  - Very refractory (T_m ~ 1940°C)
  - Exceptional creep resistance comparable to YAG
  - Low thermal expansion (0.45% from 25 – 1000°C) or (1.2 – 3.3 x 10^{-6} °K^{-1})
  - Relatively low density (2.9 g/cm^3)
  - High thermal shock resistance
  - Useful for ceramic matrix composites and thermal barrier coatings



"System Cs_2O-SiO_2-Al_2O_3. Calculated subsolidus at about 877°C," T. B. Lindemer, T. M. Besmann, and C. E. Johnson, *J. Nucl. Mater.*, **100** [1-3] 176-226 (1981).

Tailorable thermal expansion ceramics

- NaGP has CTE = 50 x 10^{-6} °C^{-1}
- KGP has CTE = 26 x 10^{-6} °C^{-1}
- Cs has CTE = 0.45 x 10^{-6} ° C^{-1}
- Li, Rb and mixtures of Group I ions enable variation of CTE in crystallized geopolymer between 0.45 x 10^{-6} C^{-1} to ~50 x 10^{-6} C^{-1}

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Processing route to ceramics – carbothermal reduction and carbothermal nitridization of geopolymers

Acheson Process to make SiC

2,500 °C / (days)

Grind SiC
(itself a grinding material)

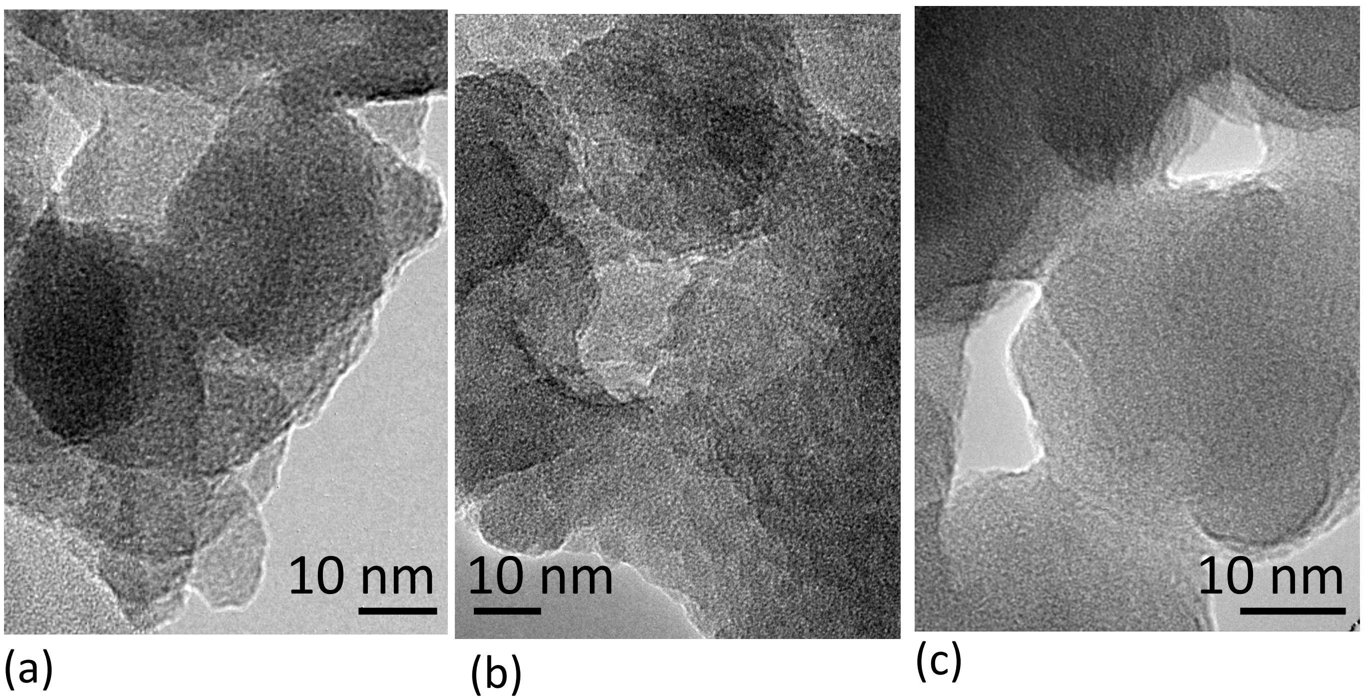
Grind
SiO_2 + C (coke)

(1,500 °C/ flowing Ar or N_2)

Grind
geopolymers

Nano SIC, Si_3N_4 or SiAlON

Microstructure of Precipitates



High resolution transmission electron microscopy (HRTEM) results for (a) NaGP, (b) KGP, and (c) CsGP.

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Hypothesis

It is well known that:
sodium geopolymer crystallizes into nepheline ($NaAlSi_2O_6$), on heating at 900-1100 °C,
potassium geopolymer crystallizes into leucite ($KAlSi_2O_6$), on heating at 900-1200 °C,
cesium geopolymer crystallizes into pollucite ($CsAlSi_2O_6$) on heating at 900 °C.

So, one question arises:

Can we convert a geopolymer to its carbide and nitride analogues by carbothermal reduction using it a precursor?

⇨ This study investigated the feasibility of producing SiC, Si_3N_4 and SiAlON ceramics by *carbothermal reduction* under flowing Ar or *carbothermal nitridizationation* under flowing N_2 gas.

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Experimental procedures

Route-1

MK+ (Na, K, and Cs)WG → (Na, K, and Cs) GP resin → Green compacts

Green compacts → curing 50 °C/24h → GPs

GPs → Further drying 300 °C/1h → Dried compact

Dried compact → Grinding → Powdered GPs precursor

Powdered GPs precursor → Ball milling with 18C/5h → GPs+18C powder

GPs+18C powder → DSC/Ar

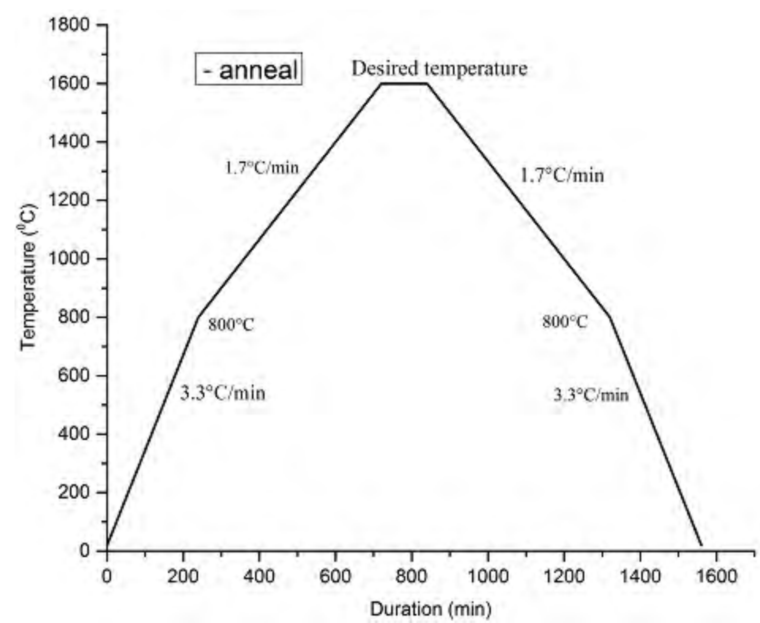
1400°,1500°,1600°C/2h

CTR* under argon

CTRN** under nitrogen

→ As-treated compact

As-treated compact → Microstructural characterization by XRD and SEM

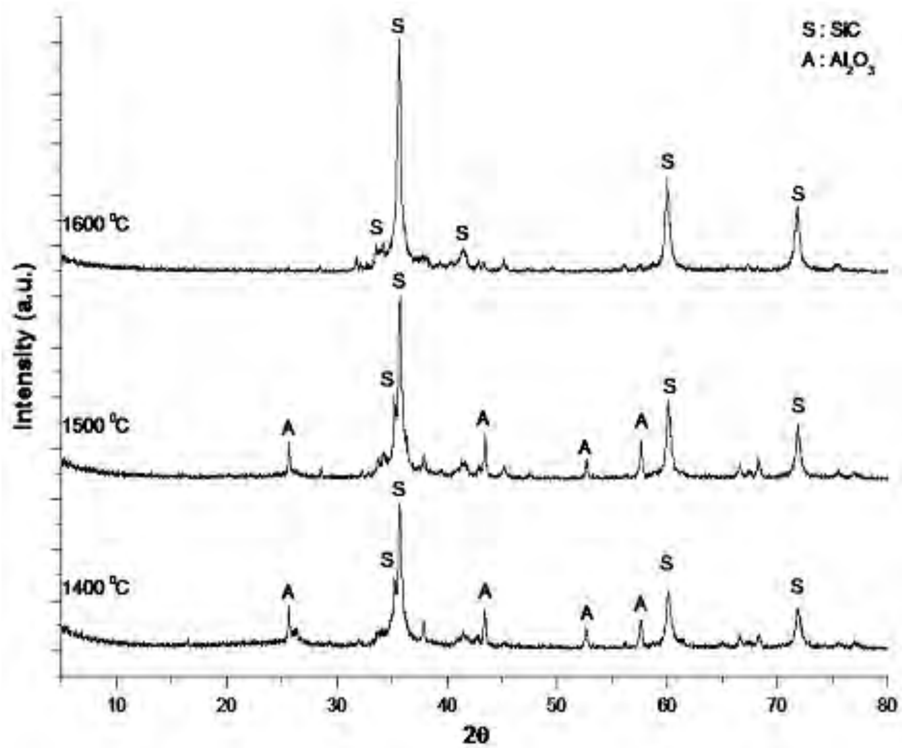


*CTR: Carbothermal Reduction

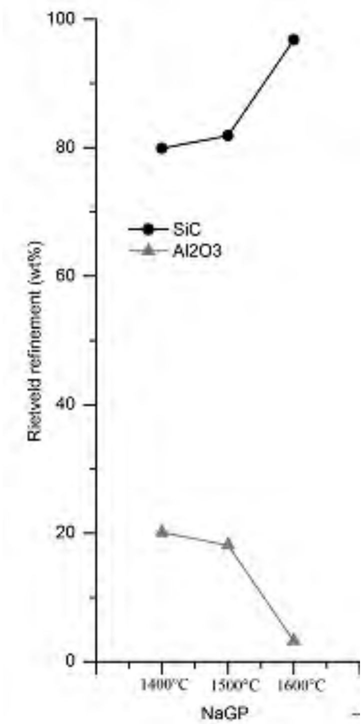
**CTRN: Carbothermal Reduction and Nitridation

Results

X-ray diffraction patterns of *NaGP+18C* precursor after being carbothermally reacted between the temperature range of 1400˚C-1600˚C in argon.

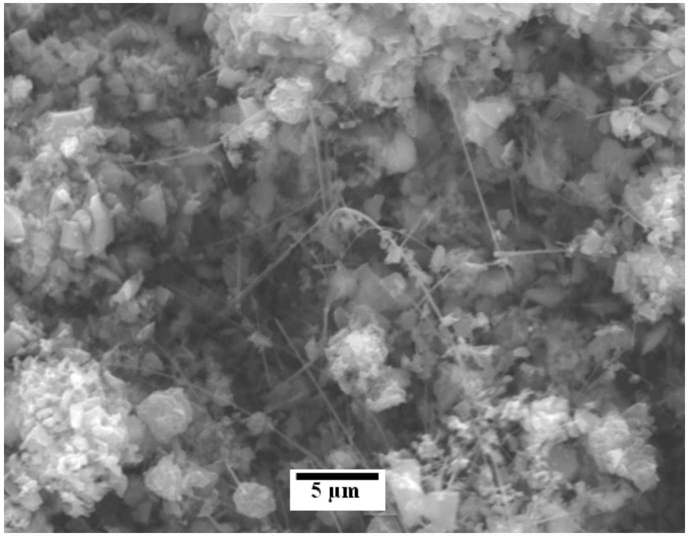


Rietveld refinement results

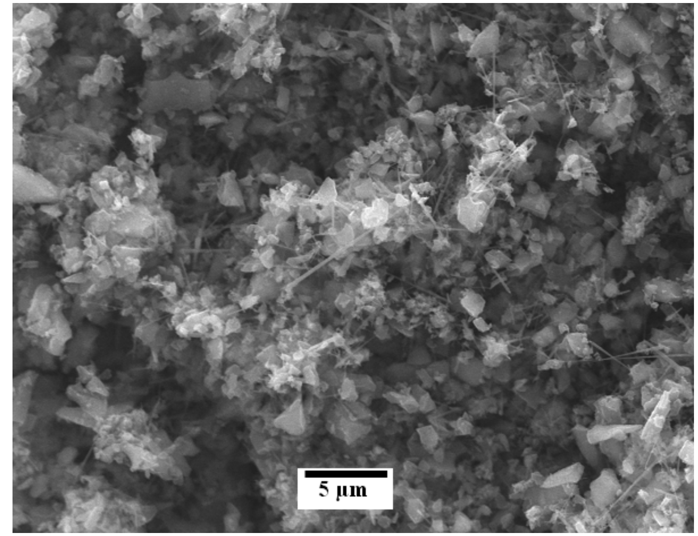


3.2 Phase analysis and microstructural transformation of products made from GP+18C by carbothermal reduction under Ar

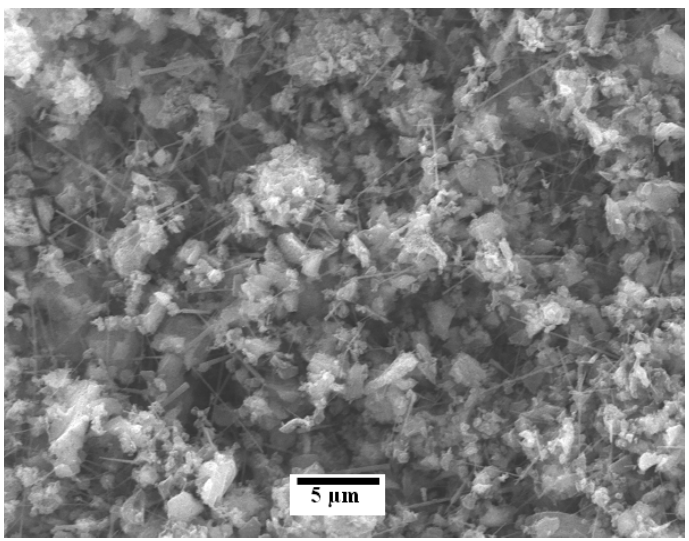
1400˚C



1500˚C



1600˚C



SEM micrographs of NaGP+18C precursor after being carbothermally reacted at between the temperature range of 1400˚C-1600˚C in argon.

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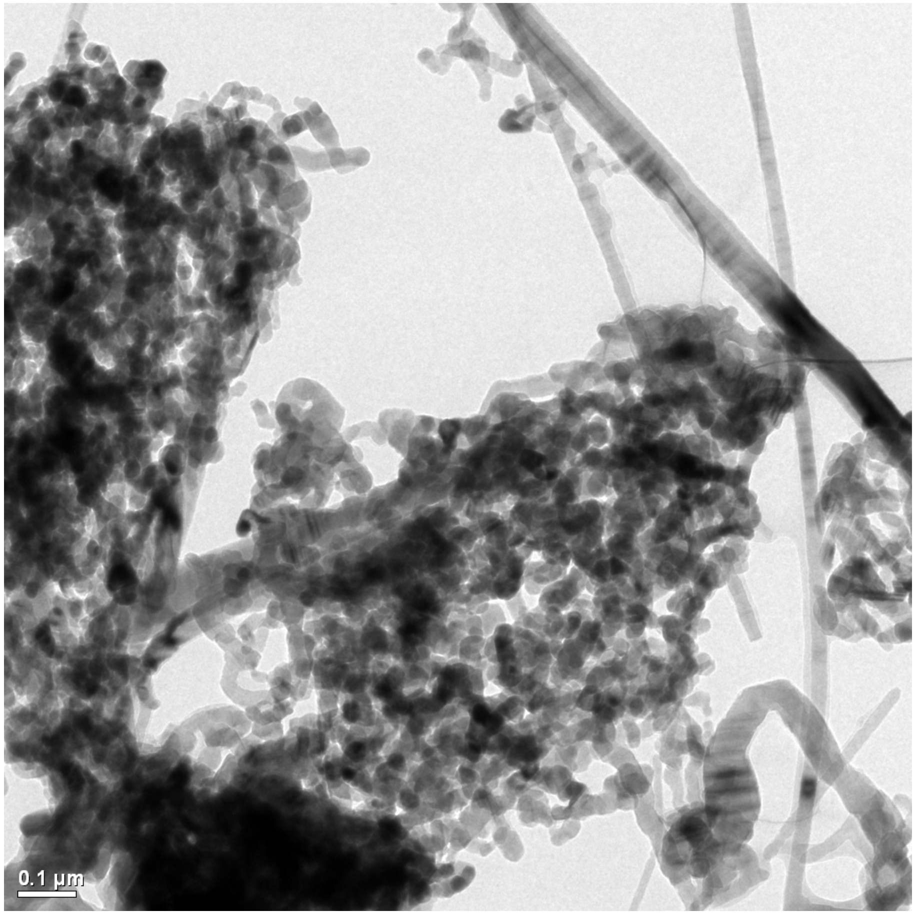
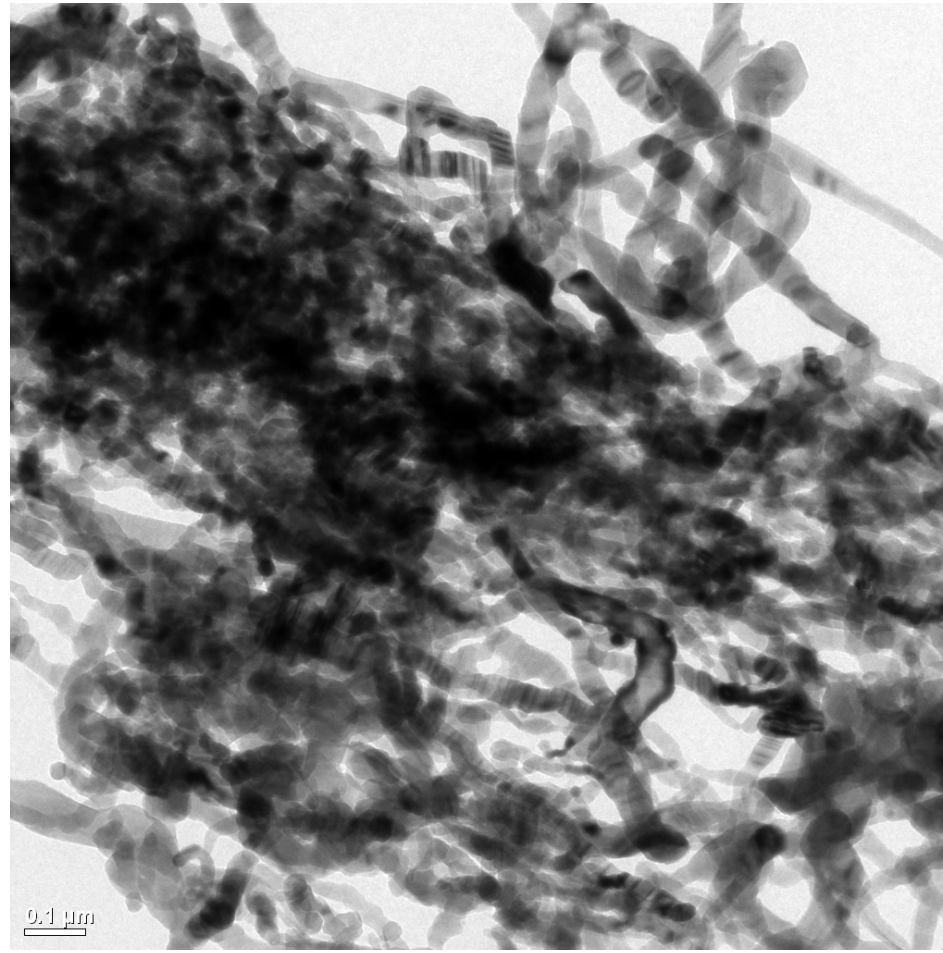
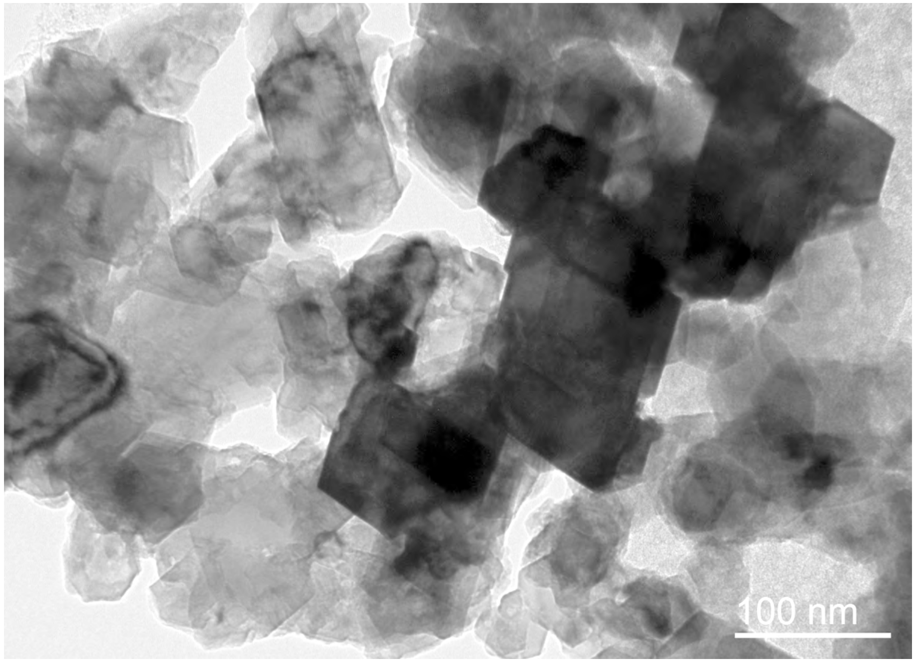
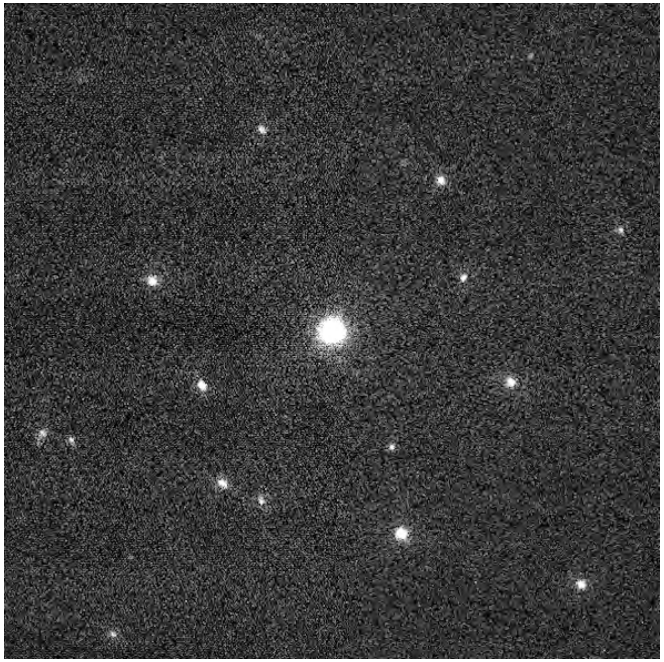
Carbothermal reduction of NaGP under Ar producing globular or elongated grains



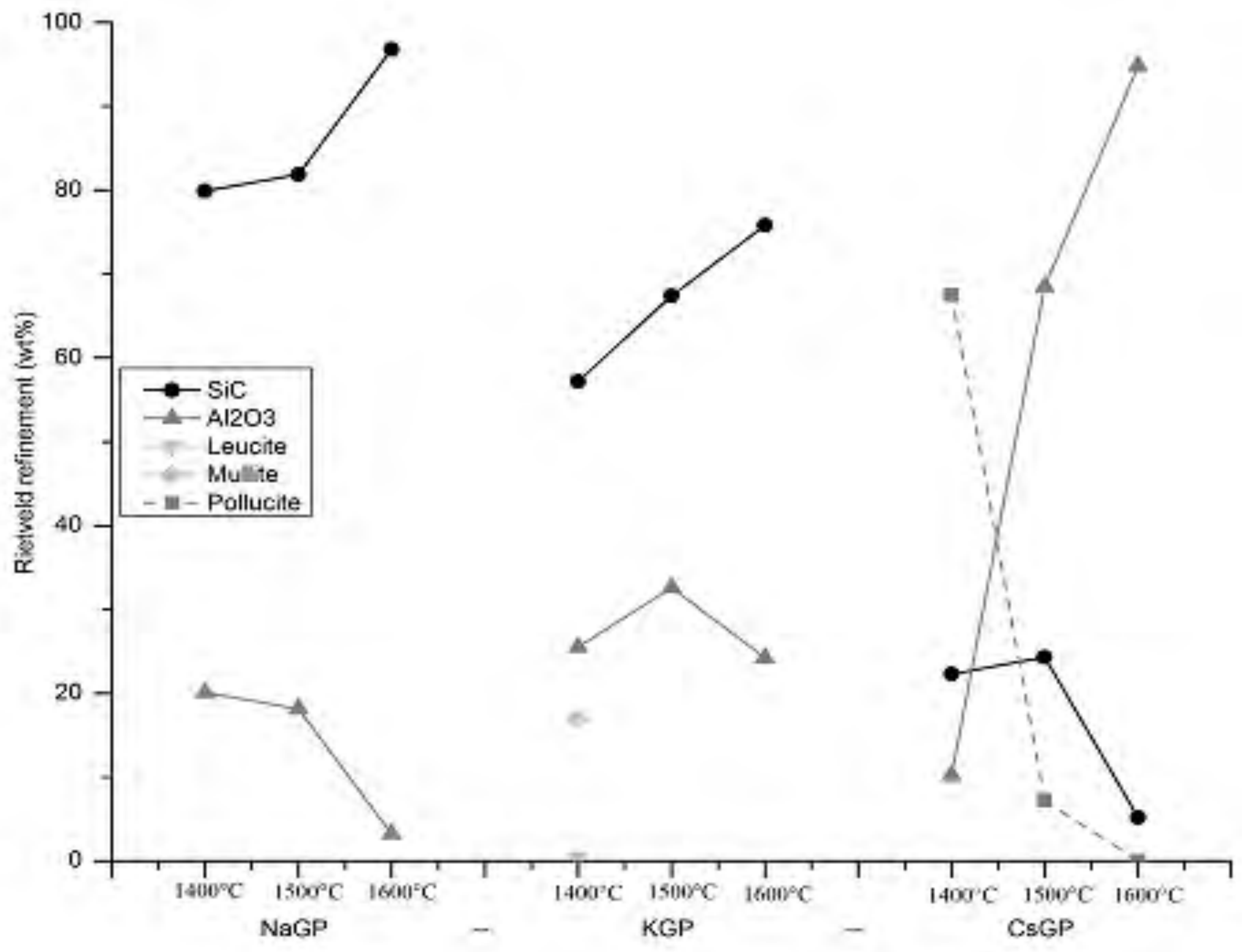


SiC Nano particles





Phase analysis and microstructural transformation of products made from GP+18C by carbothermal reduction for 2h under Ar



Rietveld refinement results of products after being argon-fired in tube furnace.

Heat Treatment in N_2

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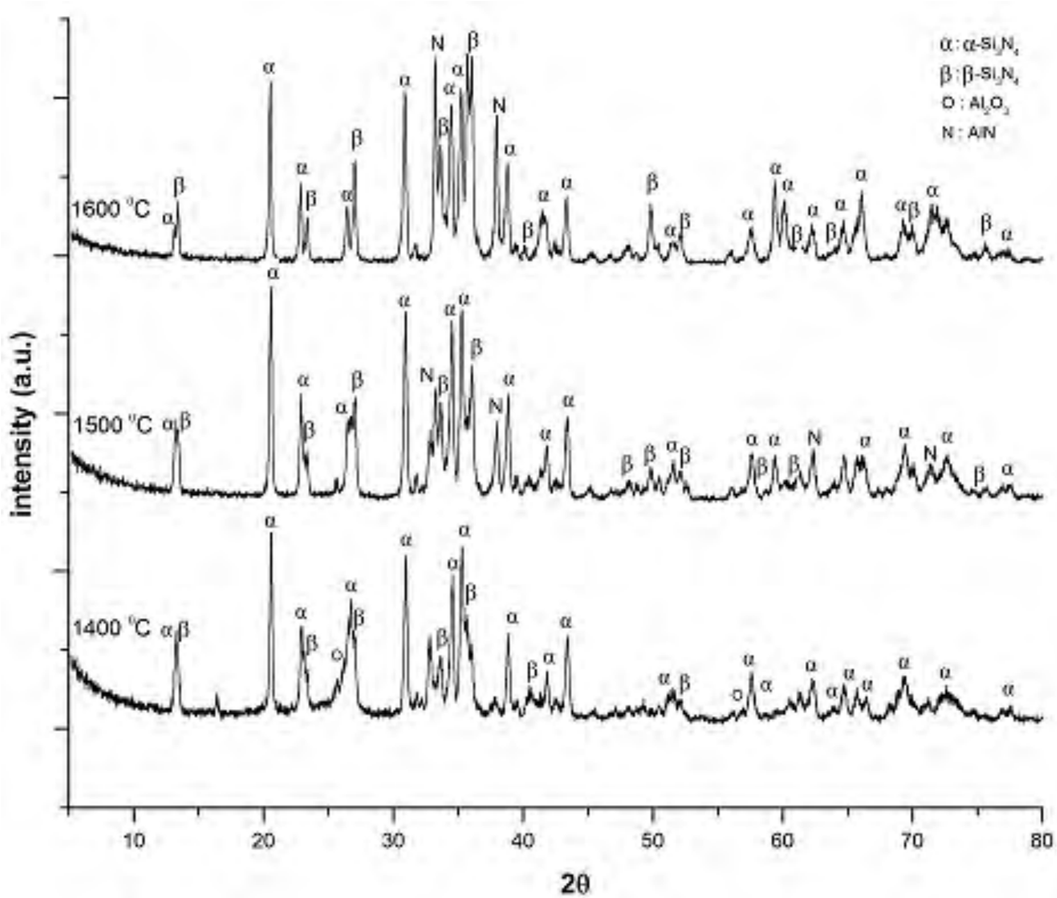
- NaGP+18C heat at 1400-1600 °C in N_2



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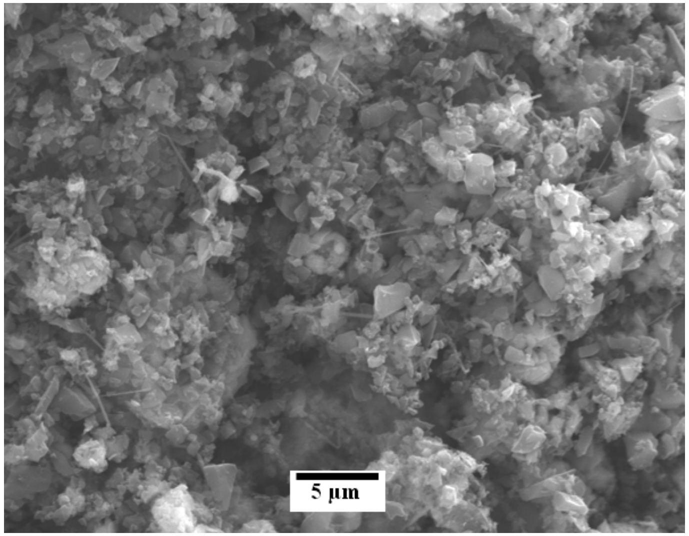
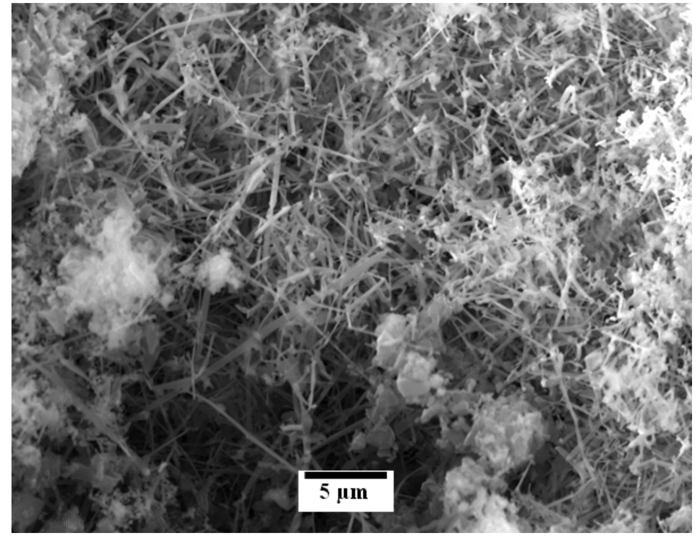
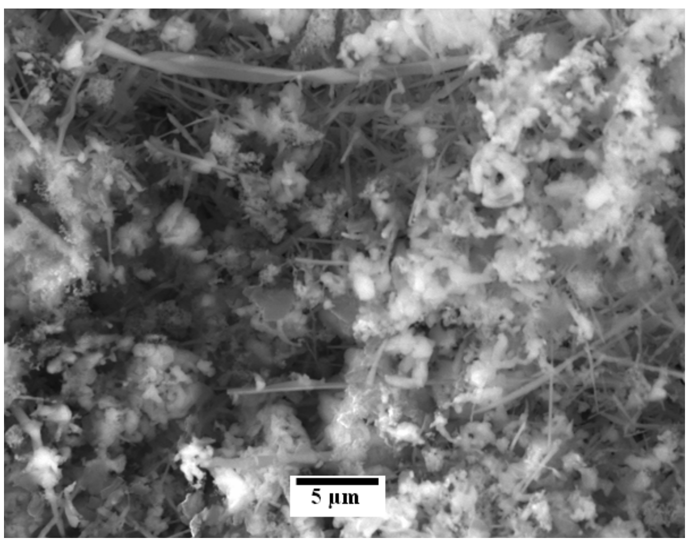
1400˚C



1500˚C



1600˚C



SEM micrographs of NaGP+18C precursor after being carbothermally reacted at between the temperature range of 1400˚C-1600˚C in nitrogen.

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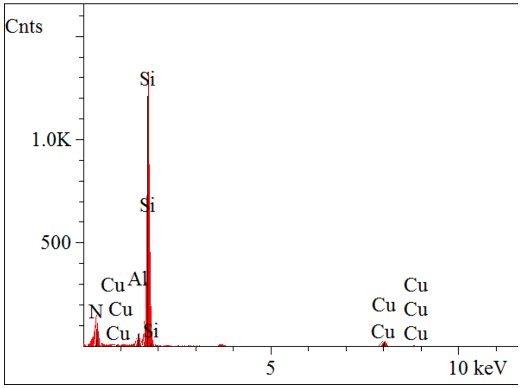
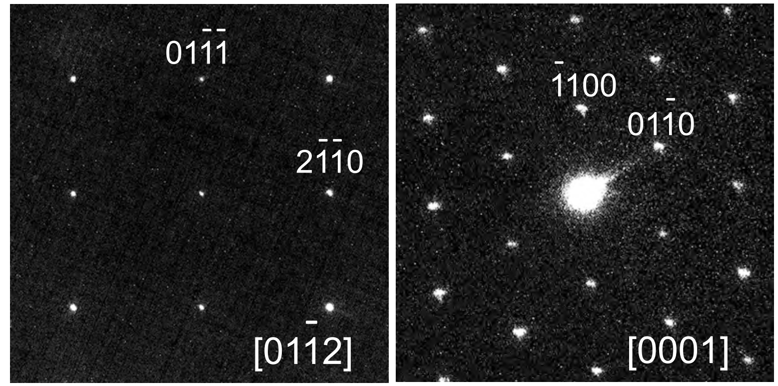
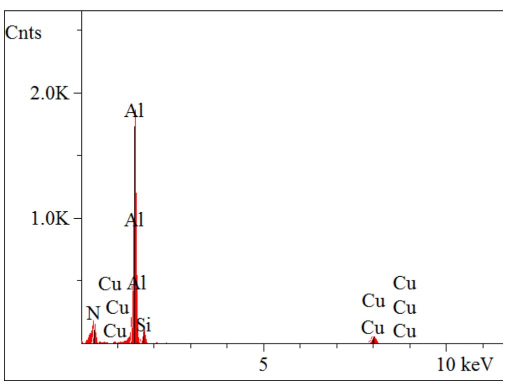
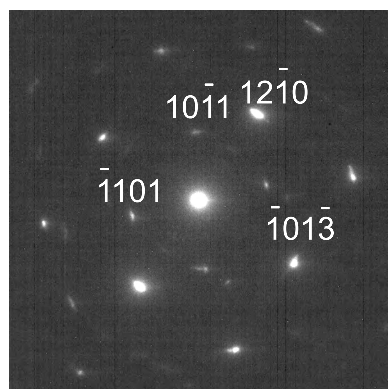
1: α-Si_3N_4





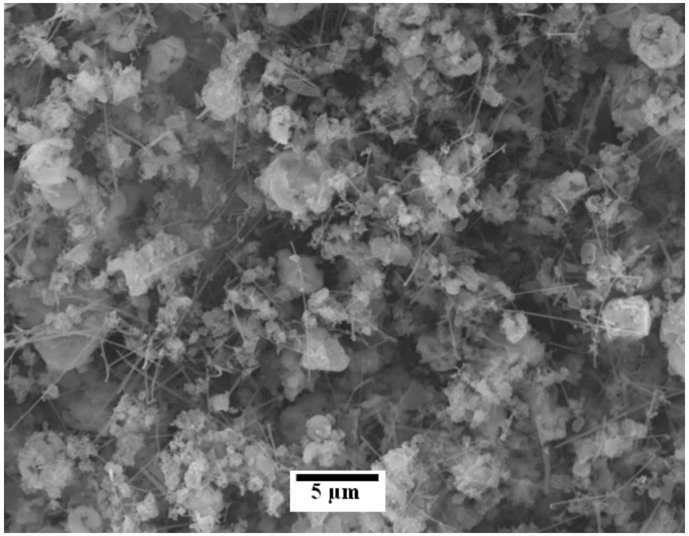
2: hex-AlN



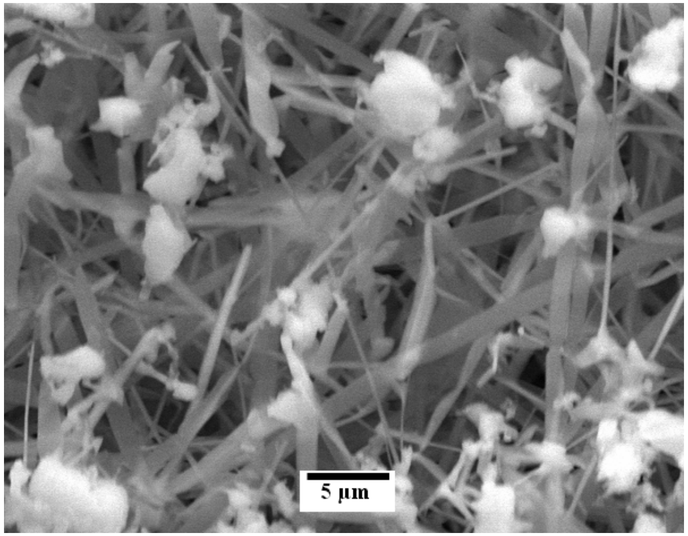


Phase analysis and microstructural transformation of products made from GP+18C by carbothermal reduction under N_2

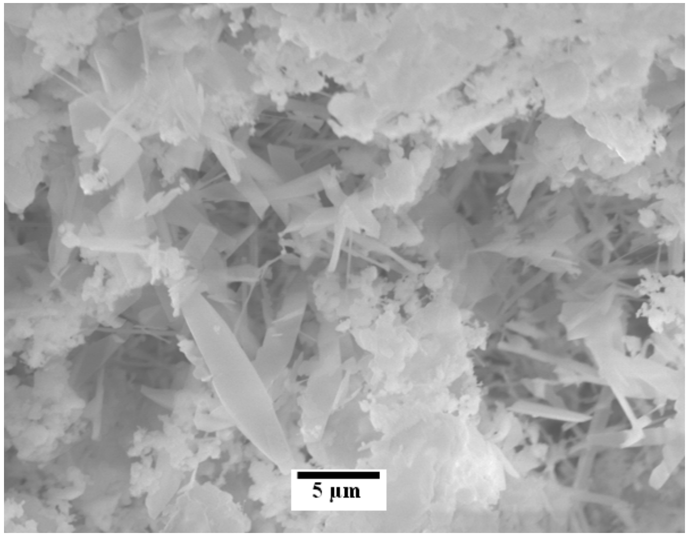
1400˚C



1500˚C

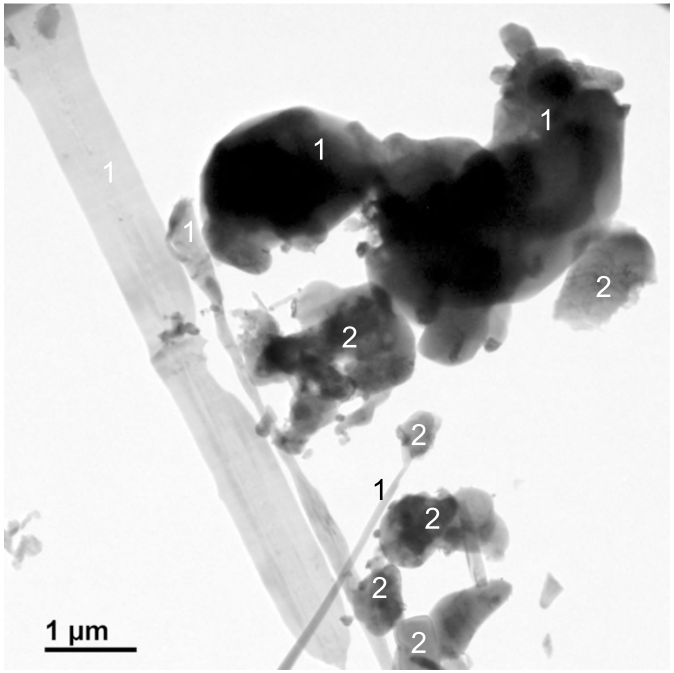


1600˚C



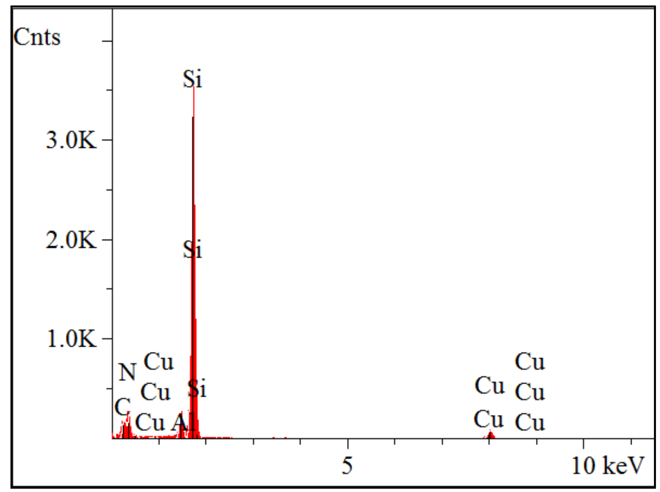
SEM micrographs of KGP+18C precursor after being carbothermally reacted at between the temperature range of 1400˚C-1600˚C in nitrogen.

KGP-18C-N_2 – 1600°C

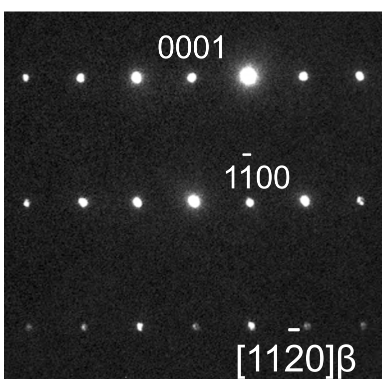


1: β-Si_3N_4 , needles or globular

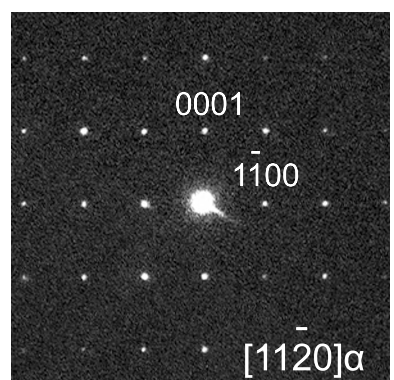
2: α-Si_3N_4, needles or globular



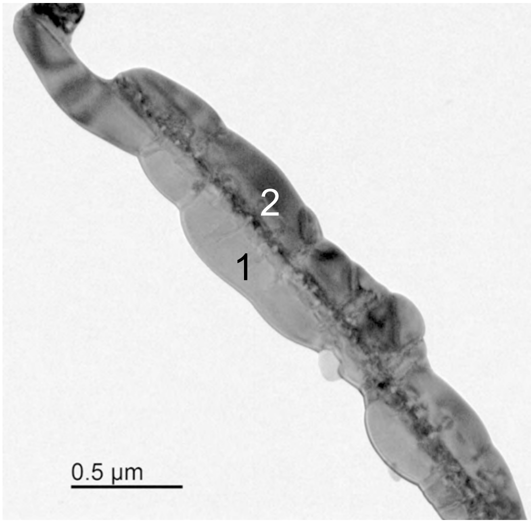
β-Si_3N_4

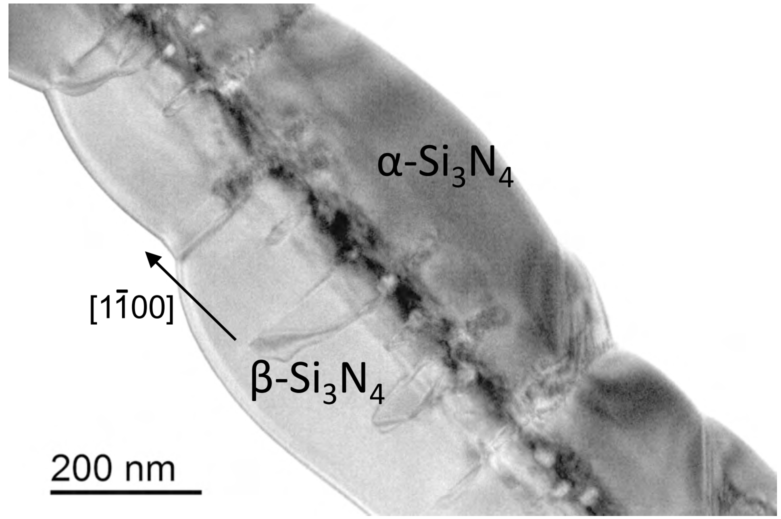


α-Si_3N_4

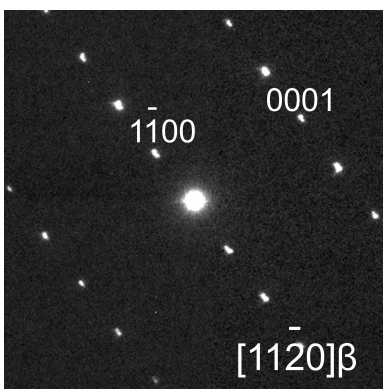


Coexistence of α- and β-Si_3N_4 in needle, interfacial defects

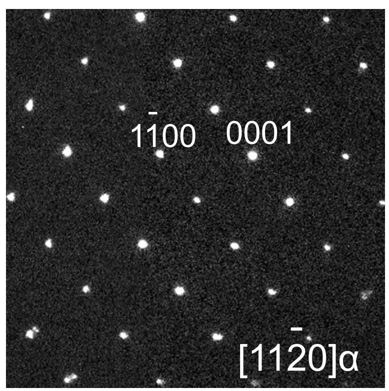




1

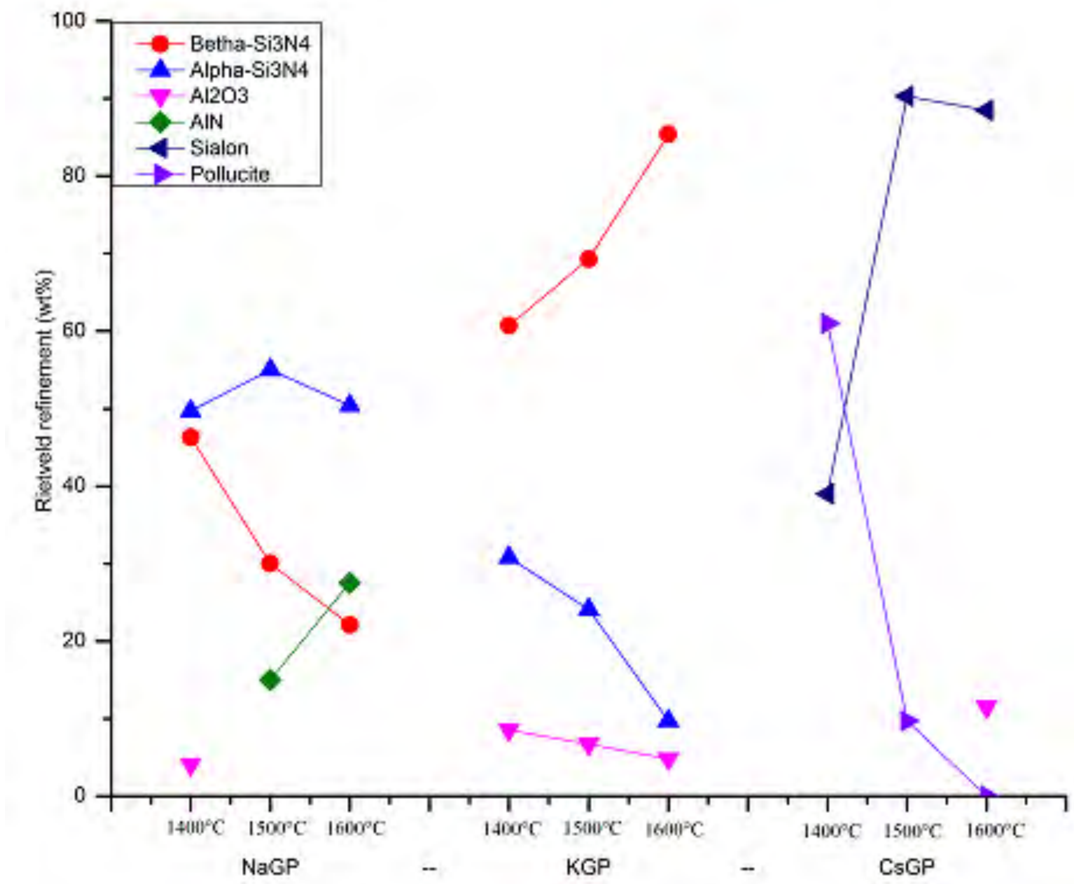


2



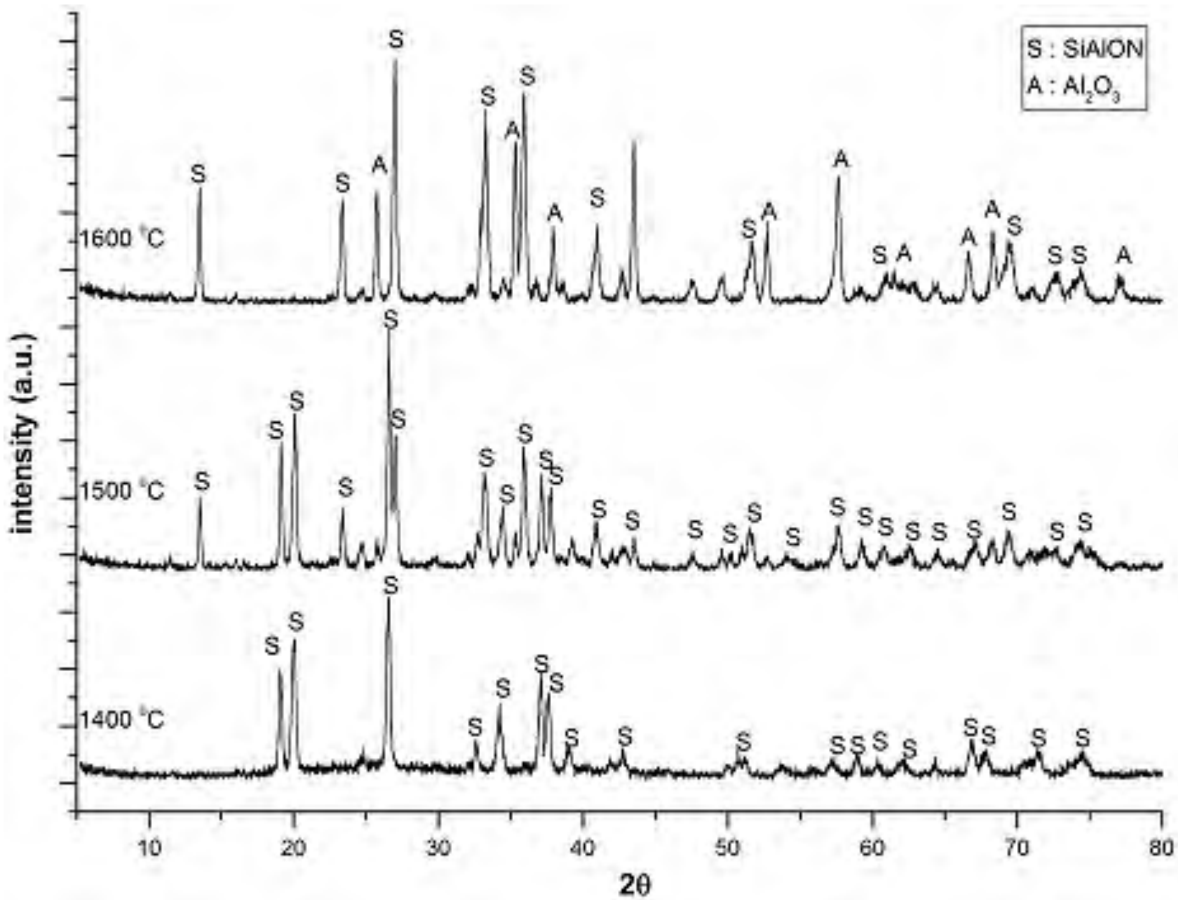
The hardly observed β-Si_3N_4 in NaGP-18C-N_2-1600^{o}C may be a small region located near the well developed α-Si_3N_4 needles

Phase analysis and microstructural transformation of products made from GP+18C by carbothermal reduction under N_2



Rietveld refinement results of products from GP+18C after being nitrogen-fired in tube furnace.

3.2 XRD pattern and SEM migrograph of products made from GP+9C by carbothermal reduction and nitridation



X-ray diffraction patterns of NaGP+9C precursor after being carbothermally reacted between the temperature range of 1400˚C-1600˚C in nitrogen

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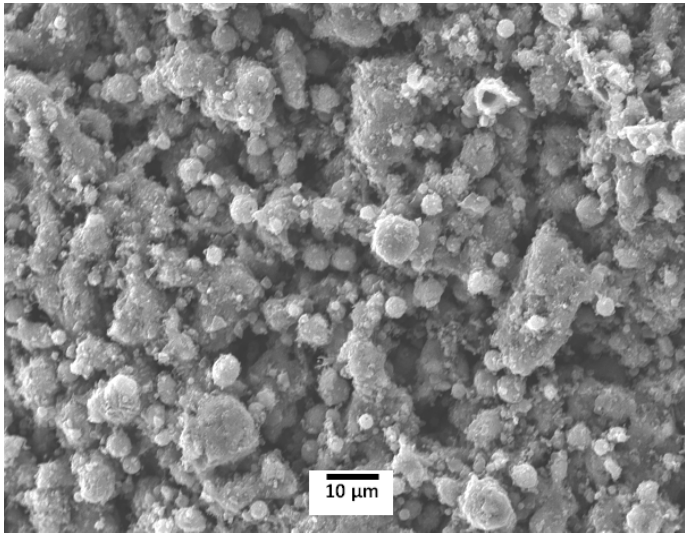
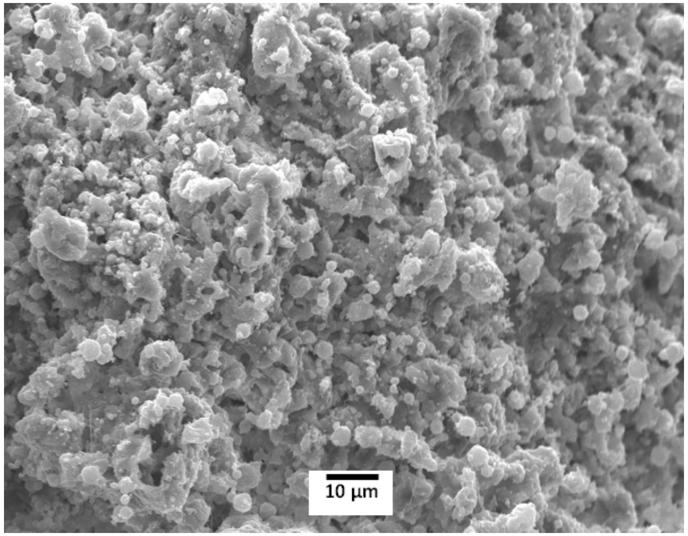
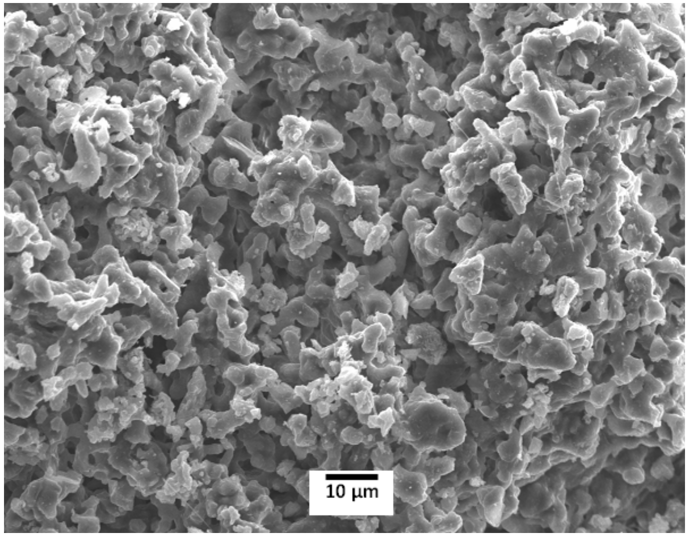
1400˚C



1500˚C

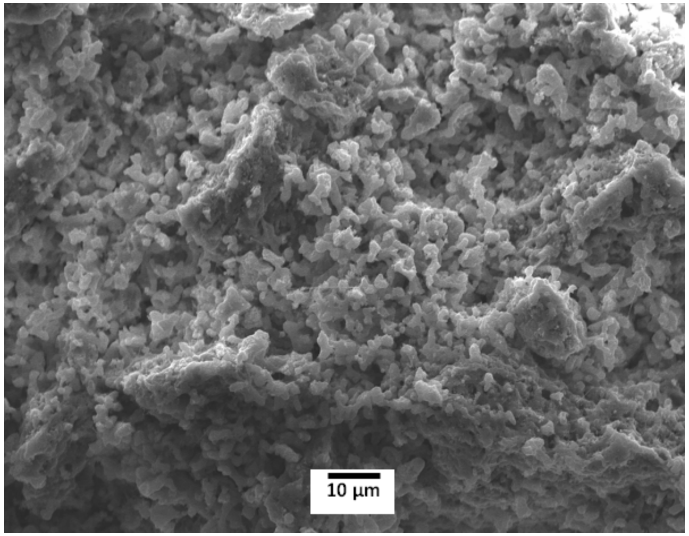


1600˚C

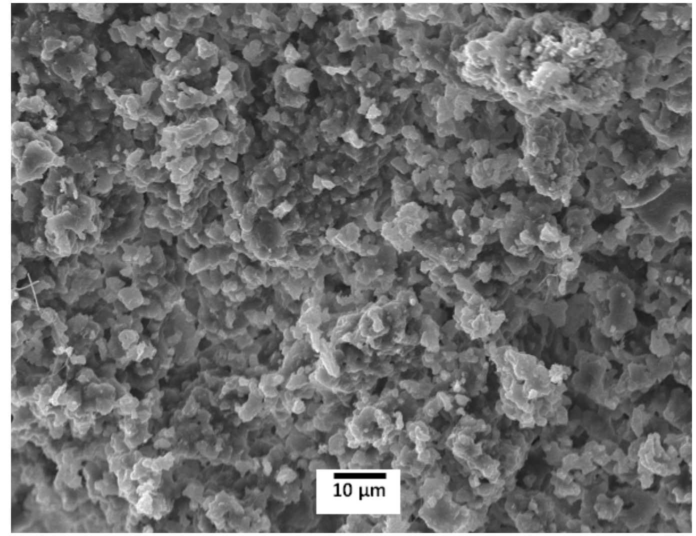


SEM micrographs of NaGP+9C precursor after being carbothermally reacted between the temperature range of 1400˚C-1600˚C in nitrogen.

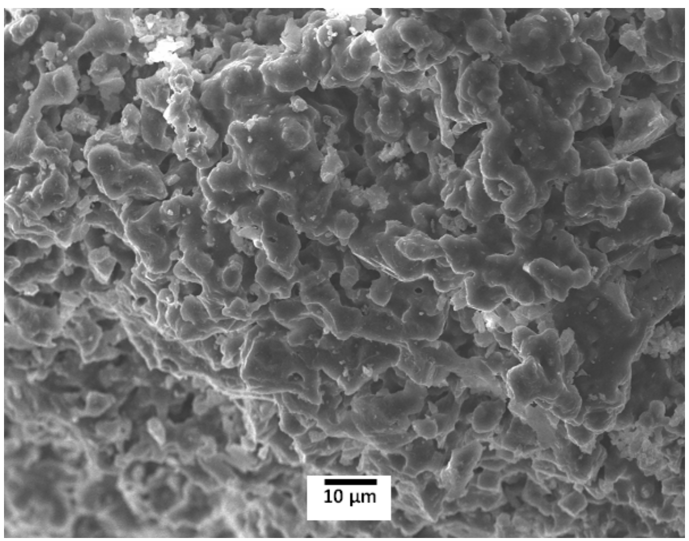
1400˚C



1500˚C

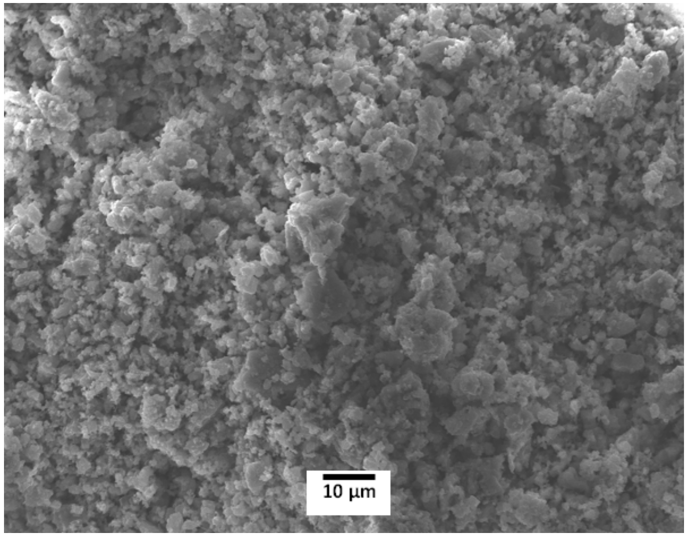


1600˚C

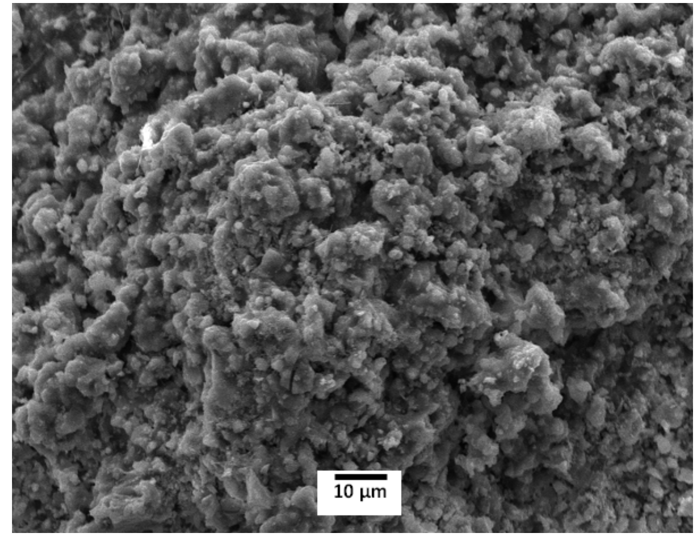


SEM micrographs of KGP+9C precursor after being carbothermally reacted between the temperature range of 1400˚C-1600˚C in nitrogen.

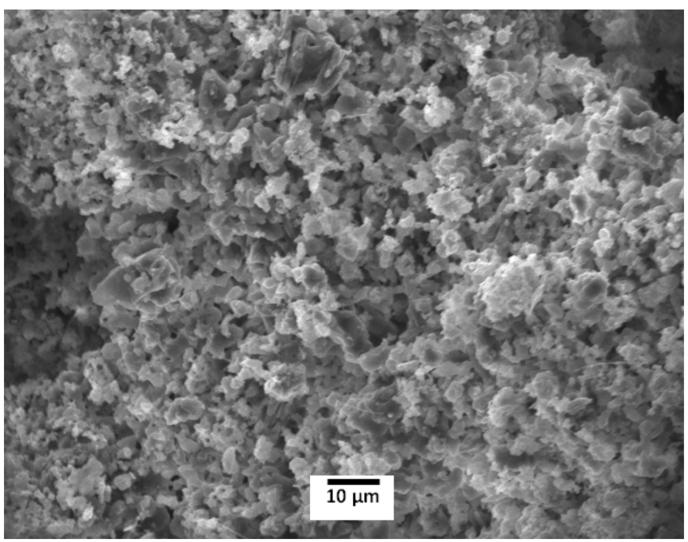
1400˚C



1500˚C

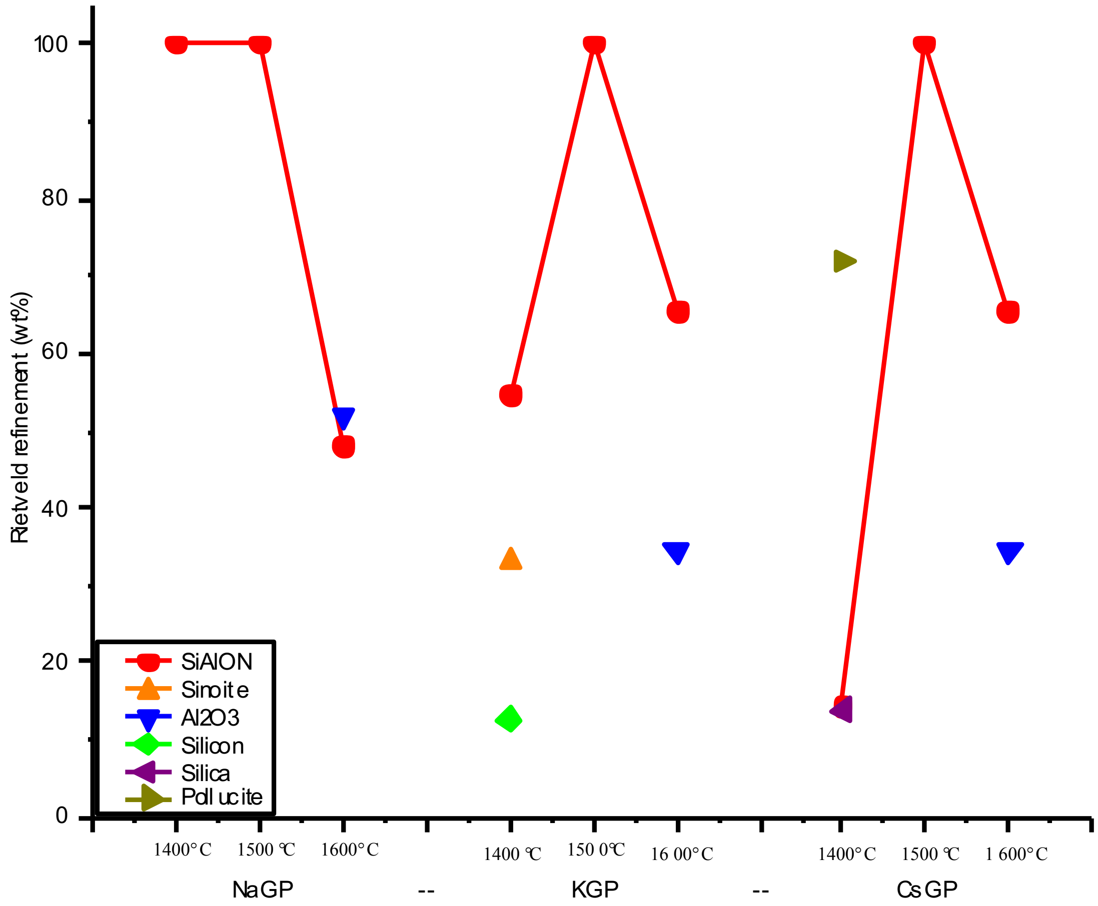


1600˚C



SEM micrographs of CsGP+9C precursor after being carbothermally reacted between the temperature range of 1400˚C-1600˚C in nitrogen.

3.4 Phase analysis and microstructural transformation of products made from GP+9C by carbothermal reduction under N_2



Rietveld refinement results of products from GP+9C after being nitrogen-fired in a tube furnace.

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CONCLUSIONS OF CARBOTHERMAL REDUCTION/NITRIDIZATION of GPs

- In this study, higher yield (over 95 %) of silicon carbide was synthesized from sodium precursor with 18C
- By carbothermal reduction, SiC, ($\alpha + \beta$) Si_3N_4 and SiAlON ceramic powders can be cost effectively synthesized from geopolymer precursors
- NaGP in both carbon compositions has an advantage over the KGP and CsGP in conversion of its carbide analogues as well as its low-cost
- By focusing on the NaGP and KGP precursors, useful structural ceramics and ceramic composites were made by an inexpensive geopolymer route

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Summary of Topics Covered

- Composition and starting materials
- Microstructure
- Processing route to ceramics
  - Oxides with tailorable CTE's
  - Non-oxides nanocrystalline (SiC, Si_3N_4, SiAlON's)

"Geopolymer-based Composites," W. M. Kriven, in Vol. 5, Ceramics and Carbon Matrix Composites, edited by Marina Ruggles-Wrenn. Part of an 8 volume set of books entitled Comprehensive Composite Materials II, Peter Beaumont and Carl Zweben, Co-editors-in-chief. Published by Elsevier, Oxford, UK, in press (2017)

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Potential Applications of Geopolymers

- Low CO_2 producing cements and concretes
- Fire resistant coatings
- Low level radioactive waste encapsulation
- 3D printed rapid-prototyping molds
- Porous water purification filters
- Corrosion resistant coatings
- Coatings on wood, steel, other metals
- Refractory adhesives
- Porous insulators and refractories
- Alternative processing routes to isochemical ceramics
- High temperature resistant airplane runways (1200 °C) for VLOs
- Fuel cells alternative to PEMS devices
- Solar panel substrates
- Bush fire breaker panels
- Acoustic meta-materials

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42nd International Conference and Expo on Advanced Ceramics and Composites (ICACC'18)

Symposium on Geopolymers
(17 conference proceedings to date)

January 21 – 26 (2018)
Daytona Beach, Fla. USA

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