High Strength, Encapsulated, Commercially Useful Components and Particles Made from Coal Combustion Residuals

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Project Scope

- Protect both the environment and the health & safety of the public
- Reducing the volume of CCR disposed of in impoundments
- Increase beneficial use and advance the management of CCR

- Innovative technology and concepts that increase beneficial utilization
- Innovations that improve cost and performance of CCR beneficiation
Kynos™ Carbon Framework

Repurposing both undervalued and waste carbon feedstocks to create valuable, customized, sustainable products.

SUSTAINABILITY = Economically Sustainable + Environmentally Sustainable
Kynos™ Carbon Framework

CARBON FEEDSTOCKS
- Geologic/Produced Waters
- Spent Graphite from Lithium-ion Batteries
- CO₂ Gas
- Coal
- CCR

Material Processing

HIGH-VALUE PRODUCTS
- Engineered Aggregates
- DioQuest™ Carbon-Negative Building Materials
- X-MAT CCC CCR-Derived Building Materials
- High-Capacity Anode Materials
- High-Temperature 3D Printing Filaments
- High-Performance Plastic Fillers
Project Objectives

1. Demonstrate ability to encapsulate CCR particles with a tailorable coating to reduce leaching of toxic elements by at least 80% over uncoated particles
2. Utilize the encapsulated CCR as a large volume filler/reinforcement to produce 9”-diameter support column prototypes with compressive strength and flexural strength 5-10X that of current concrete
3. Develop and demonstrate CCR encapsulated in a tailored, reactive resin coating as a filler for polypropylene that will increase the modulus and strength by 30-50% while reducing toughness and elongation by only 20-30% compared to traditional fillers
4. Develop initial predictive models for the behavior of CCR that reasonably predicts the effects of CCR and encapsulant composition and microstructure on mechanical properties in columns and polypropylene components
Technology Overview

- X-MAT resins
  - tunable at the Atomic Level
  - Plastic or Polymer-Derived Ceramic
- Easily manufactured plastic and ceramic composites
- Variety of particles “as-is” - CCR
- Binder for particles – no sintering needed
- Resin binds to and fully encapsulates the particle
  - Prevents leaching of toxic elements from CCR
- Controllable coating thickness
- Low-cost and Scalable

Typical X-MAT Processing Cycle
Commercial Scope

• ~70 Million short tons of CCR produced in 2020
• ~41 Million tons beneficially used
• Global polyolefin (polypropylene, polyethylene, etc.) market expected to exceed 207 million tons by 2026.
  • With a 40% filler loading and 10% adoption, this could result in utilization of 8.3 million tons of CCR
• Filling with X-MAT-modified CCR results in a lower-cost, higher strength polypropylene
• X-MAT-modified CCR competitive with current plastic fillers (calcium carbonate, talc, and mica)
  • X-MAT coated CCR = $0.08-$0.16/lb
  • Commercial fillers = $0.20-$0.40/lb
• X-MAT CCR aggregates could provide significantly enhanced properties for concrete vs. current CCR use in concrete
R&D Progress and Accomplishments
CCR Survey

- 24 CCR sources
- Selected a ND Lignite Ash as the primary candidate in the encapsulation and leachate work due to the relatively high levels of toxic metals

Initial encapsulation trials using a “dry mixing” method. This method was used primarily for initial screening.
Leaching Results (Objective 1)

*All Materials are well below the allowable limits set by the EPA

*Leach Testing carried out by UND Energy & Environmental Research Center (EERC)
Support Columns (Objective 2)

• Deliverable: 9” diameter prototype

• Bulk process to generate aggregates of resin-coated CCR particles
• Press the coated CCR aggregate into a cylindrical mold
• Cure in air @ 150-180°C
• Pyrolyze in inert gas @ 1000°C or less to convert polymer to a ceramic
Support Columns - Accomplishments

Hollow Columns produced by Center for Applied Research and Technology (CART)

1st Solid Ceramic Aggregate Column - 3.5” X 7”

Hollow Column - 6” X 11”

Compressive Strength

<table>
<thead>
<tr>
<th>Material</th>
<th>MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Block</td>
<td>23</td>
</tr>
<tr>
<td>CCR aggregate composite</td>
<td>76</td>
</tr>
<tr>
<td>CCR ceramic composite</td>
<td>103</td>
</tr>
</tbody>
</table>
Composite Properties Comparison

**Flexural Strength**
- Bituminous CCR: 37 MPa
- Lignite CCR: 35 MPa
- Bituminous CCR: 46 MPa
- Lignite CCR: 21 MPa
- Concrete: 4 MPa

**Bulk Density**
- CCR aggregate: 1.77 g/cc
- Bituminous CCR: 1.99 g/cc
- Lignite CCR: 2.27 g/cc
- Bituminous CCR: 2.18 g/cc
- Lignite CCR: 2.17 g/cc
- Concrete: 2.30 g/cc

Legend:
- Blue: Ceramic-Phase Composite
- Green: Plastic-Phase Composite
Polypropylene Filler (Objective 3)

- Coat CCR in dilute solution – thin layer for minimal agglomeration
- Cure in inert gas @ 130-150°C
- Mix coated CCR with polypropylene powder/pellets
- Compounding extruder/chopper system to produce composite “pellets”
- Pellets used to produce components
  - extrusion
  - compression molding
  - injection molding
Polypropylene Filler - Accomplishments

• Coating is 2.5% to 5% by mass of total filler material
  • $\sim$ $.08 – $0.16/lb of coated particles

• Vacuum casting used to produce initial flexure test specimens and to determine the effect of varied filler percentages in the polypropylene

• Demonstrated good bonding of the coating to the CCR and to the polypropylene

• Coating improves both the modulus and strength of filled PP vs conventional PP
## Polypropylene Filler - Mechanical Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Flexural Strength (psi)</th>
<th>Flexural Modulus (1000 psi)</th>
<th>Density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene 4045</td>
<td>4045</td>
<td>250</td>
<td>0.93</td>
</tr>
<tr>
<td>50% X-MAT Coated CCR filled PP</td>
<td>4920</td>
<td>640</td>
<td>1.24</td>
</tr>
</tbody>
</table>
CCR-Filled Polypropylene Composites

50% Uncoated CCR in Polypropylene

50% X-MAT Coated CCR in Polypropylene

SEM imaging and materials characterization by Clemson University
Next Steps

• Scale up to 9” diameter hollow support column prototypes
• Develop interlocking column design
• Move from casting process to compression molding for polypropylene components
• Develop predictive model (Objective 4)
  • Clemson

• X-MAT CCR aggregates for concrete

3D-Printed Prototype of mold inserts for Interlocking Mechanism
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Thank You for Your Time

Questions / Discussion