Coal-based Bricks & Blocks (CBBs): Process Development to Prototype Fabrication Coupled with Techno-Economic Analysis and Market Survey

DE-FE0003197

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Penn State University

U.S. Department of Energy

National Energy Technology Laboratory

Resource Sustainability Project Review Meeting

October 25 - 27, 2022

Project Overview

Funding DOE: \$499,173 Cost Share: \$125,060

Overall Project Performance Dates†

January 1st, 2021 – March 2023

†Project awarded Feb. 2021, finalized May 2021, initiated Aug. 2021, kickoff Nov. 2021.

Team Members:

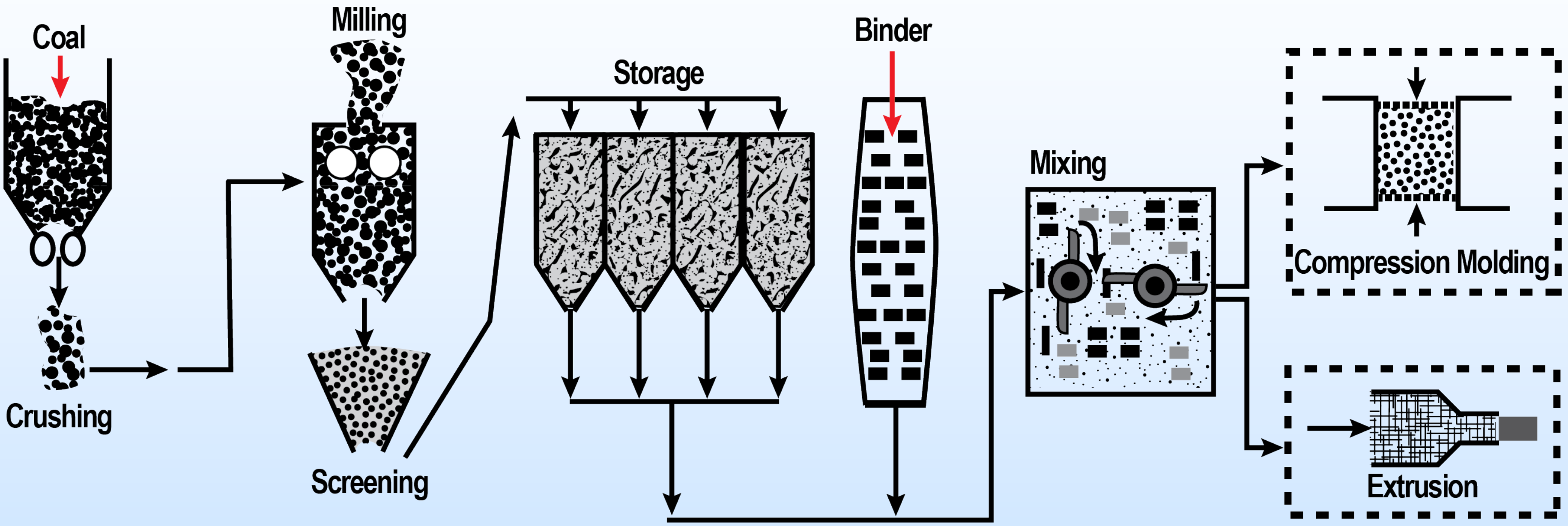
- Dr. Vander Wal is a Professor of Energy and Mineral Engineering, Materials Science and Engineering at Penn State.
- James Heim II is a PhD graduate student – Energy & Mineral Engineering at Penn State.
- Dr. Schobert is principal scientist at Schobert Intl. LLC, consultants.
- ADI Analytics is a consultancy firm specializing in coal, oil and gas and derivative industries reporting to the PI.
- Blaschak Coal Corp. is the largest Pennsylvania producer of anthracite coal.

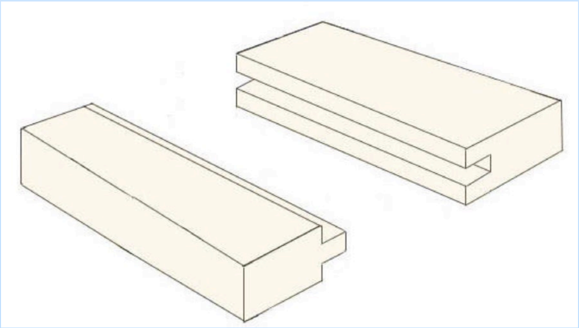
Project Overview

Objectives

1. Gather data via testing for an assessment of the technical feasibility of the concept, *and as input for…*
2. Conduct a techno-economic analysis to assess the readiness of the proposed technology
3. Provide a market analysis survey for the coal-derived products and all by-products created from the process, including a discussion of the required selling price, and
4. Complete a technology gap analysis showing what additional research and development is necessary to scale-up or commercialize the technology.

Technology Background





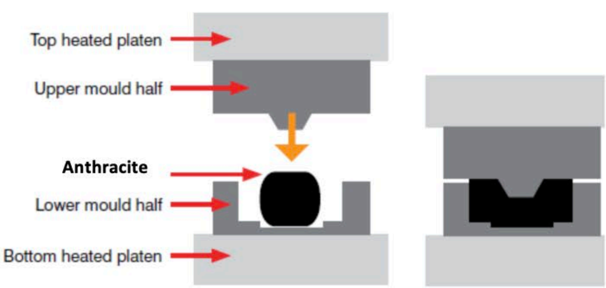
Variable form factor
by
extrusion

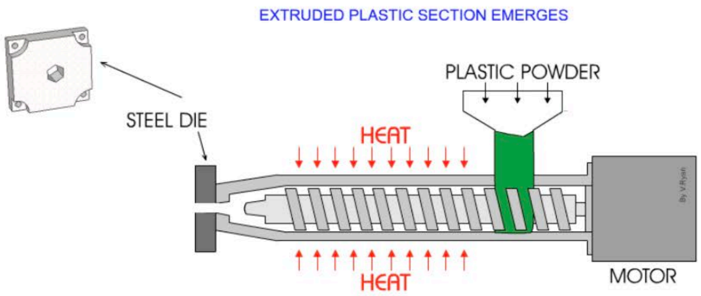
Technology Background

Anthracite

Anthracite fines → Binder → Mixing → Hot press molding/Extrusion → Bricks & Blocks → Engineering performance / Material Characterization

Plastic Waste





Technology Background

CBB Technical Advantages

- CBBs address many fire clay brick disadvantages at a comparable price
- Light weight
- Improved water resistance/frost protection
- No salt efflorescence
- Lower carbon intensity
- Potentially easier installation

Environmental and Economic Advantages

Clay bricks

- Require a skilled bricklayer for installation
- Impose environmental impact of kiln processing
- Result in deforestation and soil loss due to mining clay

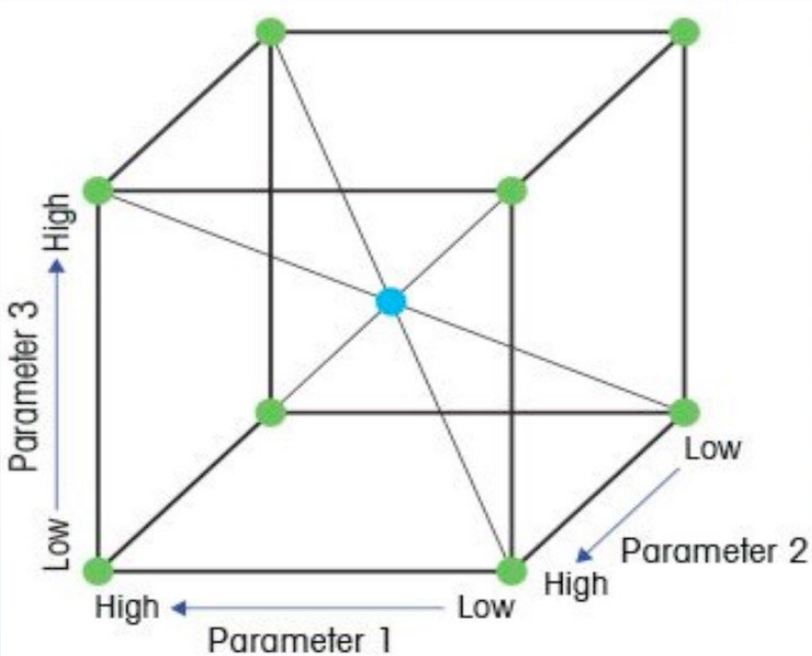
CBB Siting & Considerations

- Mining communities
- Resource proximity
- Modular & scalable manufacturing

CBB Technical Challenges

- Binder Costs
- At-scale extrusion
- Market Acceptance

Technical Approach/Project Scope



½ Fractional Factorial Design: Design Matrix

2^{3-1} Experiment

X_1	X_2	X_3	$X_1 X_2$	$X_1 X_3$	$X_2 X_3$	$X_1 X_2 X_3$
−	−	−	+	+	+	−
+	−	−	−	−	+	+
−	+	−	−	+	−	+
+	+	−	+	−	−	−
−	−	+	+	−	−	+
+	−	+	−	+	−	−
−	+	+	−	−	+	−
+	+	+	+	+	+	+

Fabrication Methods:

- Extrusion
- Hot-press molding

Thermoplastics tested:

- Virgin/PCR polyethylene and polypropylene
- Virgin polystyrene, polycarbonate, and polyamide 6/6

DoE Factors:

- wt.% plastic binder
- proportions of anthracite size fractions,
  e.g., fraction percentages 30/70 versus 70/30
- CB additive amount

DoE Response(s):

Compressive strength, permeability, density, hardness

Identifying optimal CBB composition

PennState

NATIONAL ENERGY TECHNOLOGY LABORATORY

Project Overview

Task/ Subtask	Milestone Title & Description	Planned Completion Date	Verification method†
1.0	Submit Phase II Application: Compilation of test results, TEA, R&D gap analysis and market survey	Sept. 30st, 2022	Submission of final report to NETL
2.0	Plastic Binder Evaluation: Identification of best CBB composition with HDPE, PP, PS and thermoset binders	March 31st, 2022	Compilation of composite fabrication and test results
3.0	Lab-scale Extrusion: Fabrication of test articles by extrusion for testing	July 31st, 2022	Comparative performance/property test results
4.0	Prototype Fabrication: fabrication of engineering-scale prototype coal-based bricks by commercial extrusion	Dec. 31st, 2022	Delivery of prototype brick, (or pictures) to NETL project manager
5.0	TEA Model: Development of the TEA model encompassing process stages and associated economics	Oct. 31st, 2022	TEA Report delivery to NETL project manager
6.0	Identification of Target Markets: Market survey identifying markets matching price and performance metrics of CBBs	Dec. 31st, 2022	Market Survey Analysis & Database delivery to NETL project manager
7.0	Technology Gap Analysis: Identification of R&D tests required for scale-up and or commercialization	March 31st, 2023	R&D Gap Assessment Report delivery to NETL project manager

Technical Approach/Project Scope

Success Criteria and Outcomes

1) Final prototype brick properties (at TRL 5) align with earlier results for smaller lab-scale studies and test articles (from a TRL 2 start).

2) Technical performance metrics of coal-based composite bricks using anthracite fines and varied plastics as binders – relative to current market equivalents.

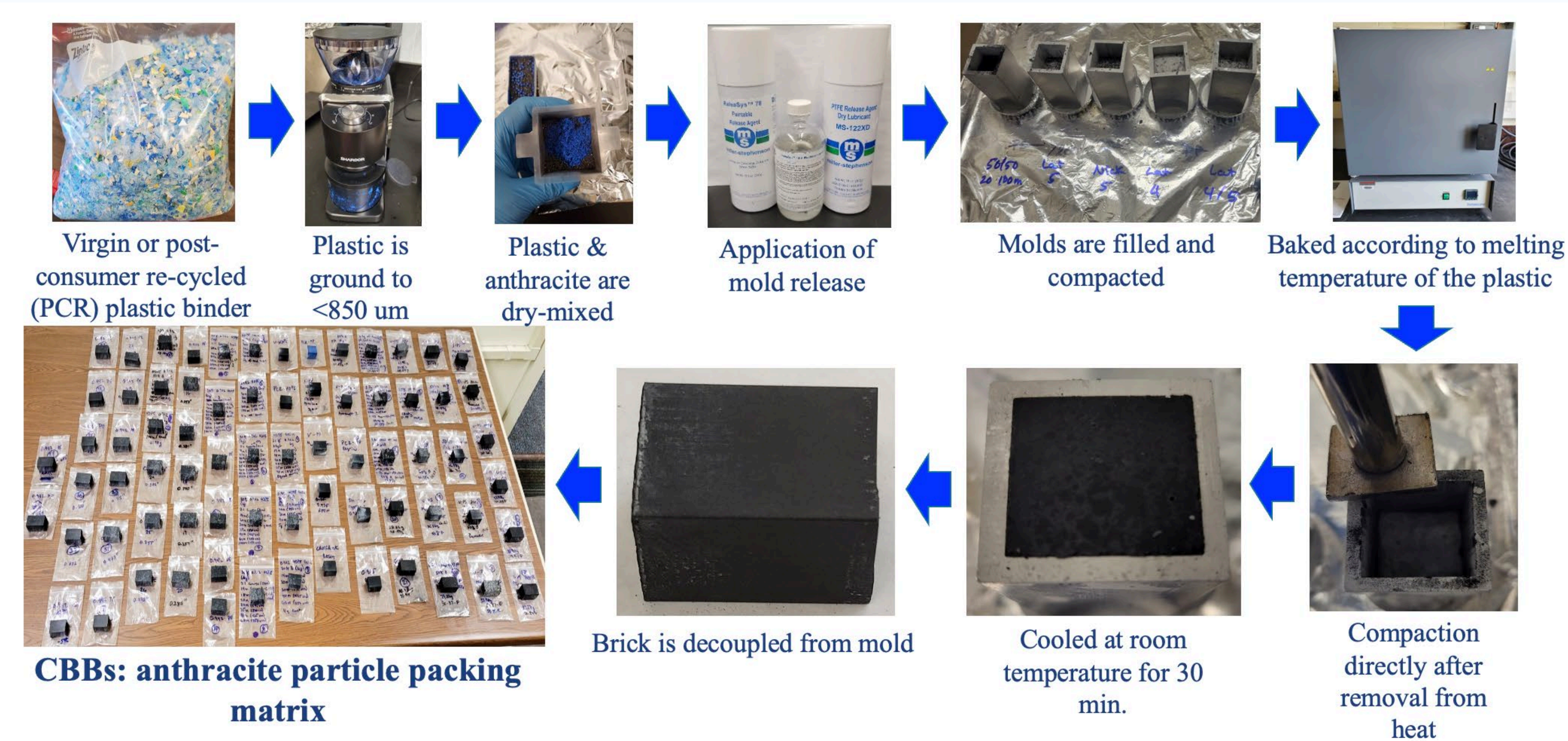
3) Techno-economic analyses showing the technical and economic viability of the proposed technology and providing quantitative information regarding the products and the market potential for such products. Additional features will include the following:
   - A target market survey analysis ranking potential markets by performance, price and scale.
   - A technology gap analysis identifying further technical development for commercialization.

Technical Approach/Project Scope

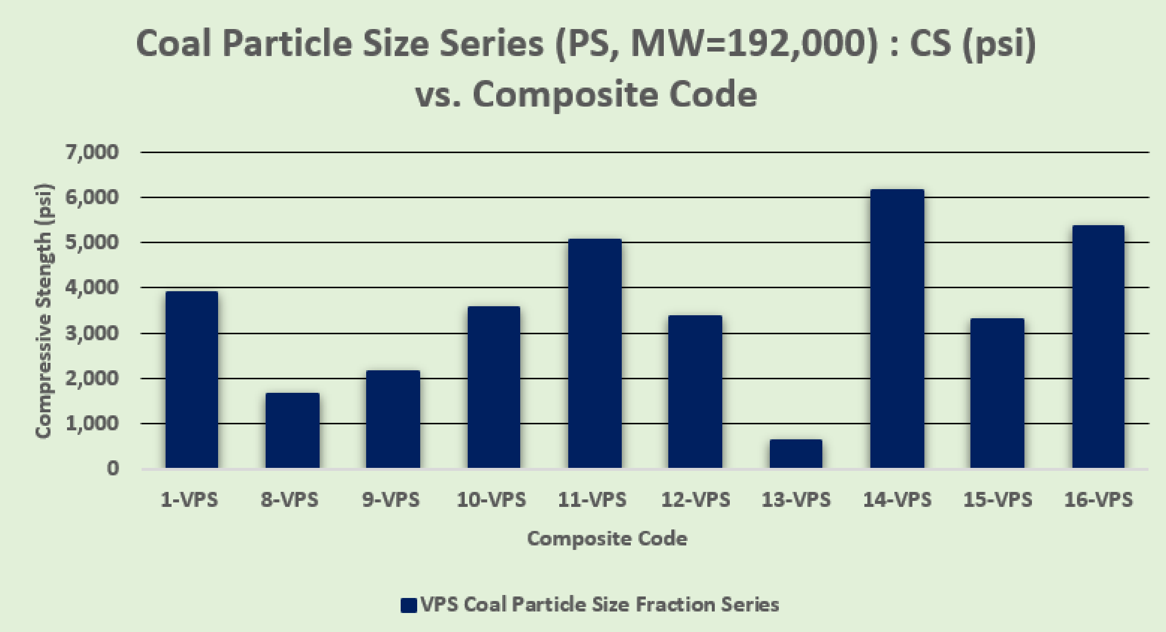
Perceived Risk	Risk Rating			Mitigation/Response Strategy
	Probability	Impact	Overall	
	(Low, Med, High)			
Financial Risks:				
Lab extruder failure	Low	Med	Low	Identify alternative academic or commercial extrusion services
A second Covid-19 wave and shutdown	Low	Med	Low	Place lab-work on-hold, start or accelerate TEA and market survey
Cost/Schedule Risks:				
Availability of supporting personnel (graduate student)	Low	High	Med	Complement the required work with technicians and wage payroll staff
Technical/Scope Risks:				
CBB performance metrics not meeting targets	Low	Med	Low	Reevaluate formulation parameters and fabrication process
CBB product consistency not meeting initial targets	Low	Low	Low	Perform parametric study on extrusion parameters.
Management, Planning, and Oversight Risks:				
Coordination between personnel	Low	Low	Low	All personnel report to PI
Time commitment of PI	Low	Low	Low	Rearrange priorities as needed
Availability of advisory team	Low	Low	Low	Readjust meeting schedules
ES&H Risks:				
Potential for generation of hazardous polynuclear aromatic hydrocarbons	Low	Med	Med	Include safety pre-assessment meetings before performing coal processing and CBB fabrication.
Unsafe handling of chemicals or high temperature equipment	Low	High	Med	Ensure proper training & follow Penn State EHS lab safety guide.
External Factor Risks:				
Personnel changeovers	Low	Low	Low	Project PI, Co-I have full expertise; fully debrief graduating personnel.
Change in U.S. coal production or envir. practices or restrictions	Low	Med	Low	Readjust coal source and/or pre-processing conditions.

Progress and Current Status of Project

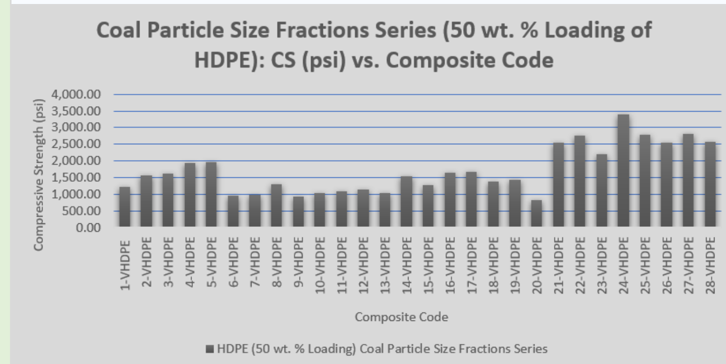
Thermoplastic CBBs: Hot-Press Molding Process



Progress and Current Status of Project



Thermoplastic CBBs Compressive Strength Results



Lab Extruder

Progress and Current Status of Project

Thermoplastic CBBs: Extrusion Process

Anthracite is placed in a pan and covered

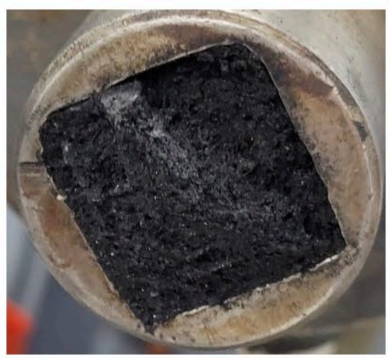
Pans are loaded into convection oven to remove moisture

Plastic & anthracite are dry-mixed

Barrel and nozzle are preheated according to transition temperatures

or

Mixture is loaded into hopper. Left image is PCR thermoplastic and right is virgin thermoplastic.

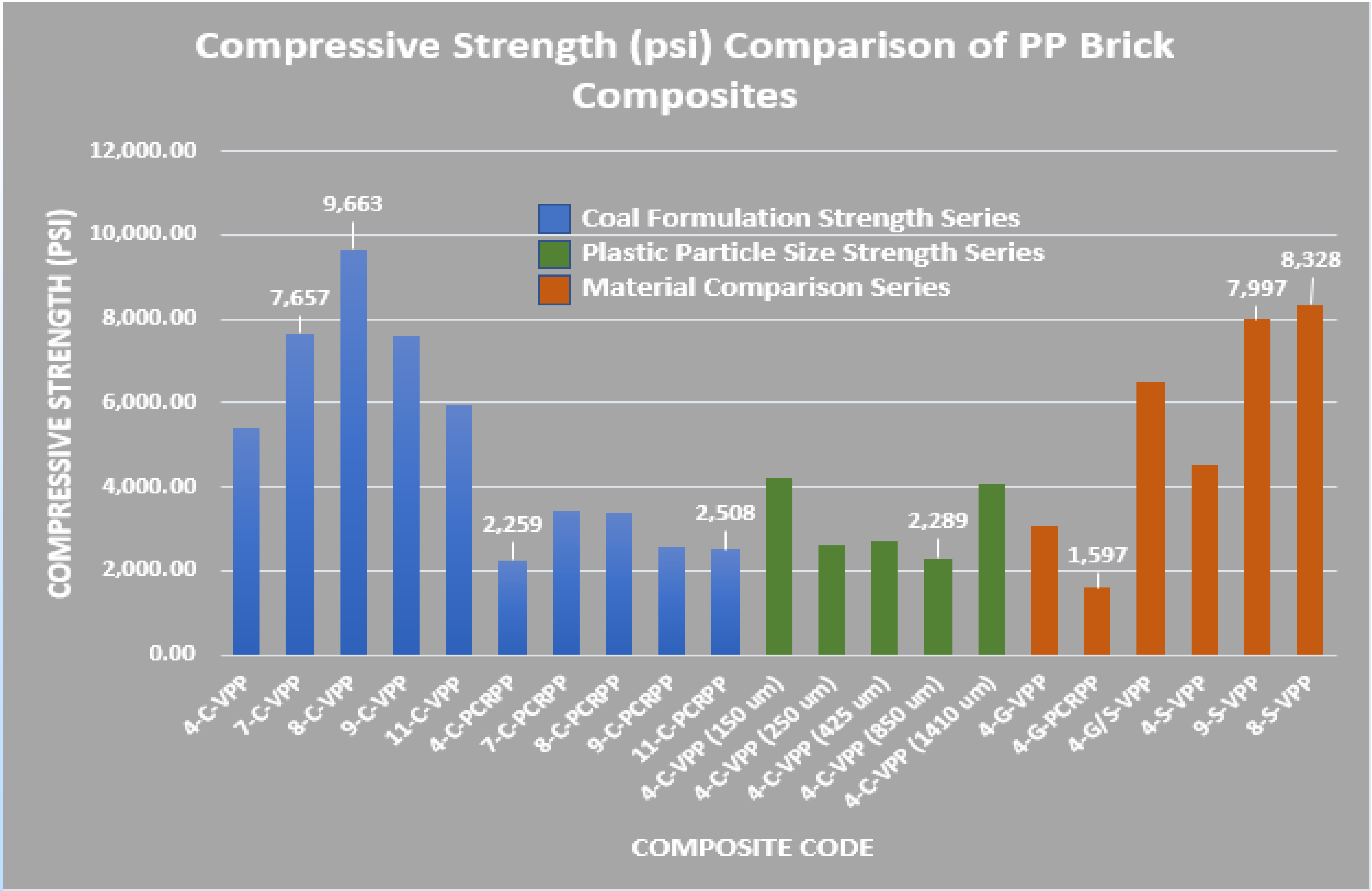


Homogeneous mixture is extruded, cut, and cooled

Thermoplastic CBBs

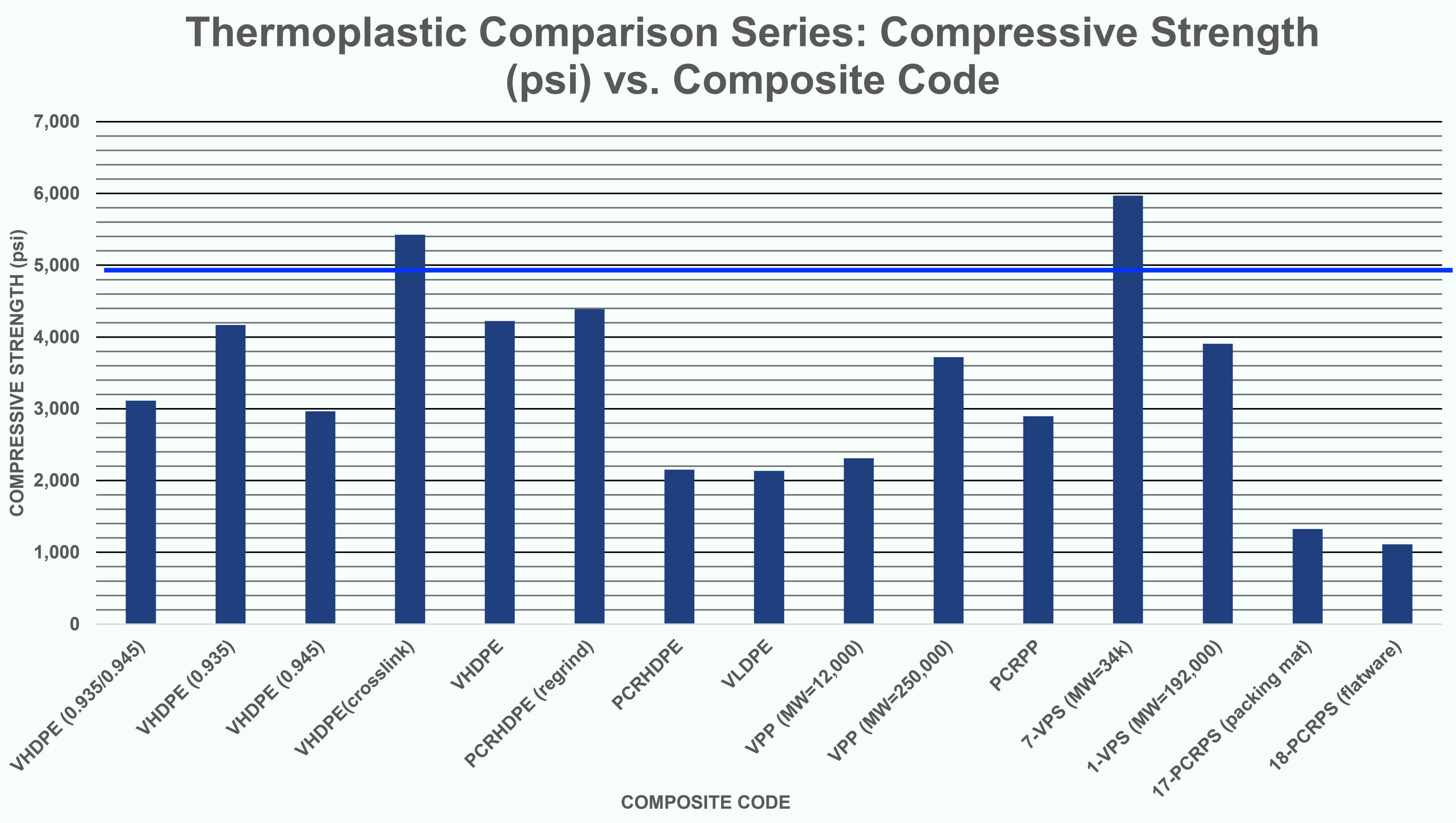
Progress and Current Status of Project

Thermoplastic CBBs Compressive Strength Results



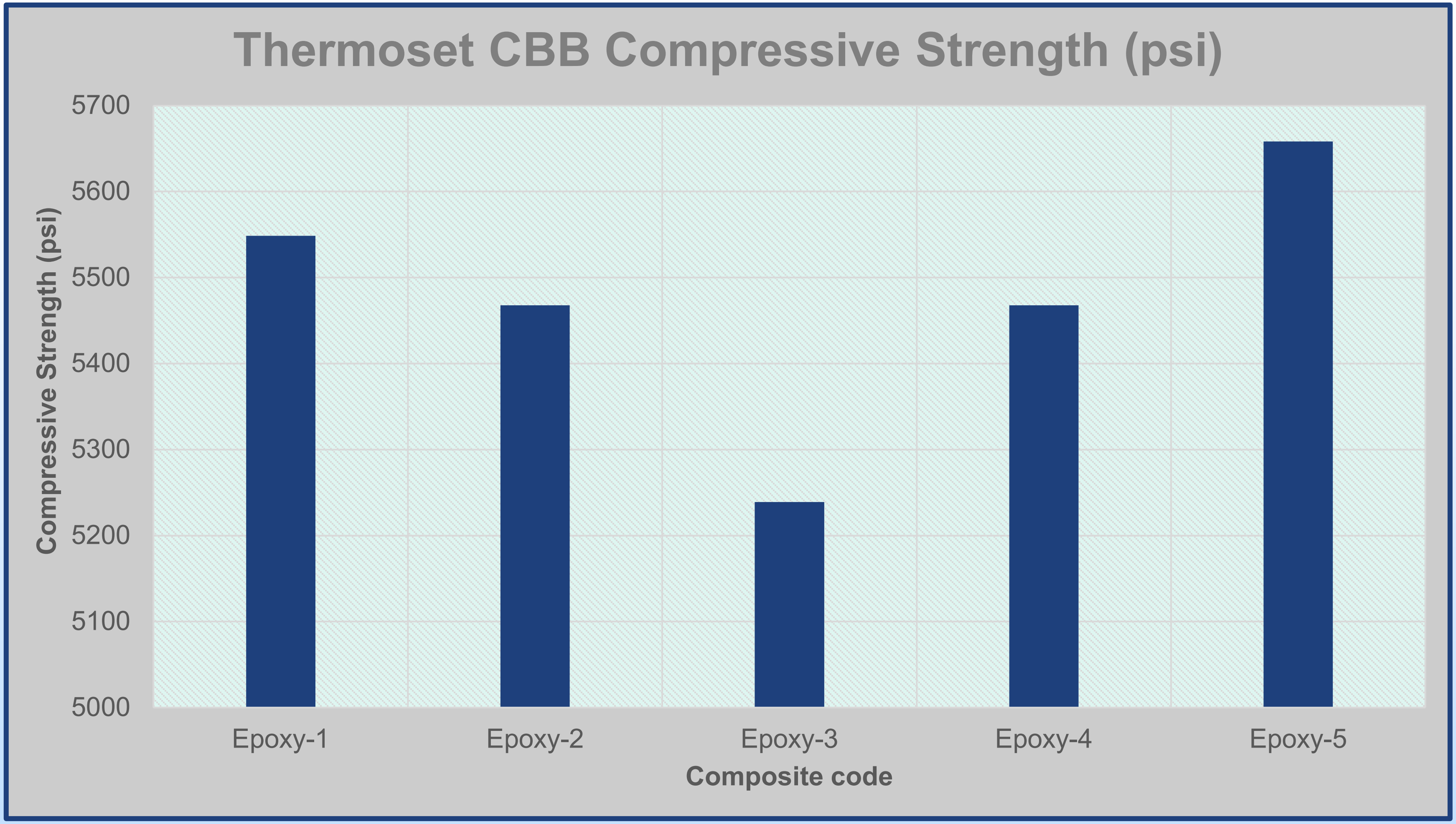
Progress and Current Status of Project

Thermoplastic CBBs Compressive Strength Results



Progress and Current Status of Project

Thermoset CBBs Compressive Strength Results

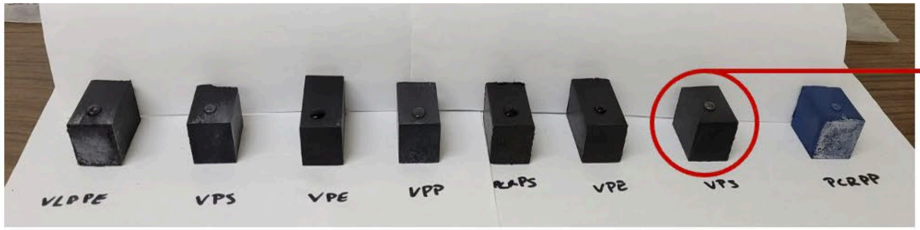


- ➢ Further testing of thermoset bricks needs to be conducted to find their ultimate strength.
- ➢ Only one of the five CBB composites fractured before the upper limit of the testing equipment (49.5 KN) was reached.

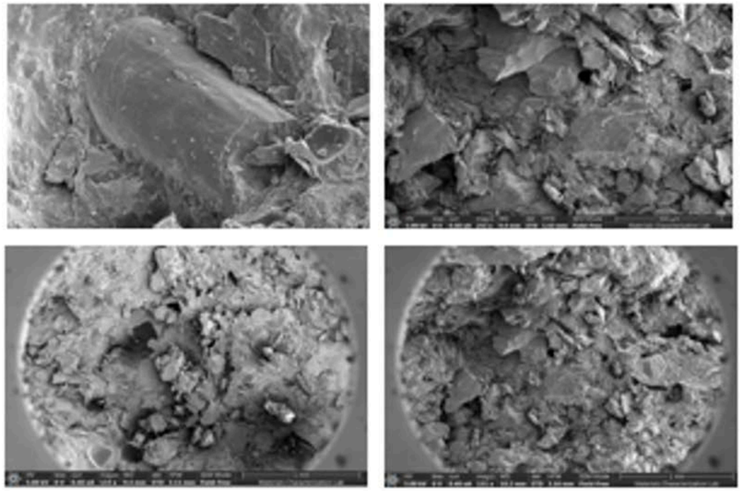
Progress and Current Status of Project

Material characterization (density, porosity, permeability, microscopic structure)

Contact Angle



Contact angle showing hydrophobicity of various virgin/PCR thermoplastics and anthracite composites



SEM to investigate surface interactions between coal and thermoplastic particles and dispersion homogeneity

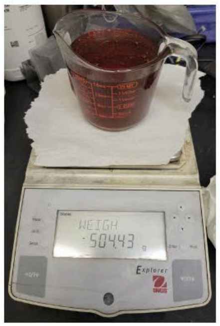
Particle-Matrix Interface

Apparent density calculated by Archimedes Method

Density

Progress and Current Status of Project

Thermoset CBB Fabrication Process



Components are weighed

Weighed anthracite, hardener & resin/modifier

Hardener is added to premixed resin/modifier

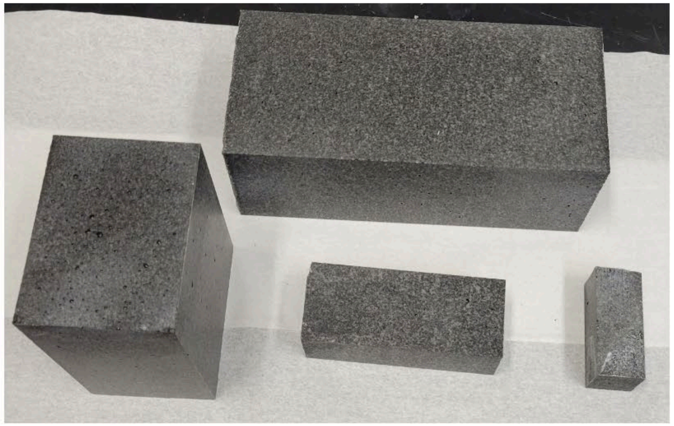
Anthracite is added to epoxy system

CBB mixture

Mixture is poured into molds and vibrated to remove bubbles

Push stamp is used to decoupled CBB after 24 h of curing

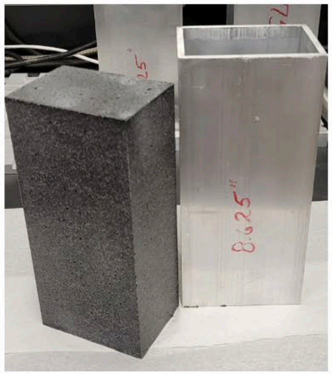
CBBs are cured at 100° C for 1 h

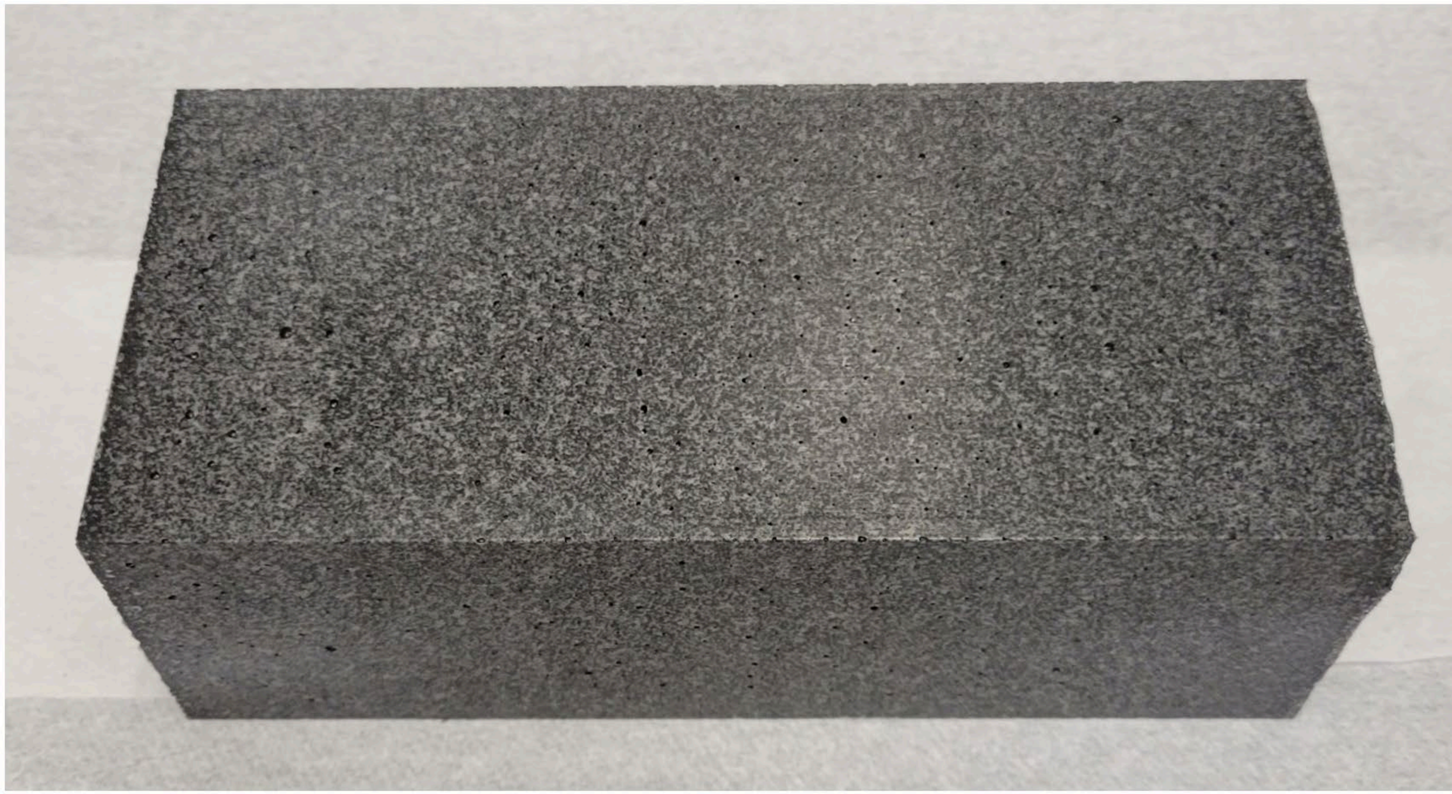


Various CBB sizes awaiting testing

Progress and Current Status of Project

Full-Scale CBB Images

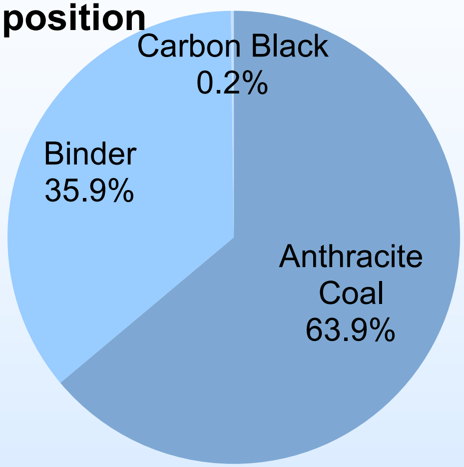




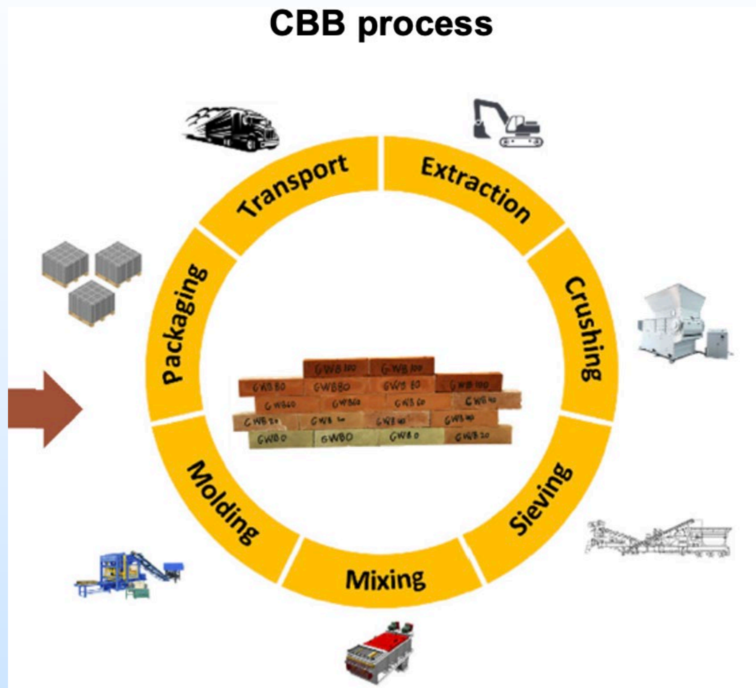
Actual full-scale CBB dimensions (l x w x h): 7-7/8" x 3-9/16" x 2-5/8"

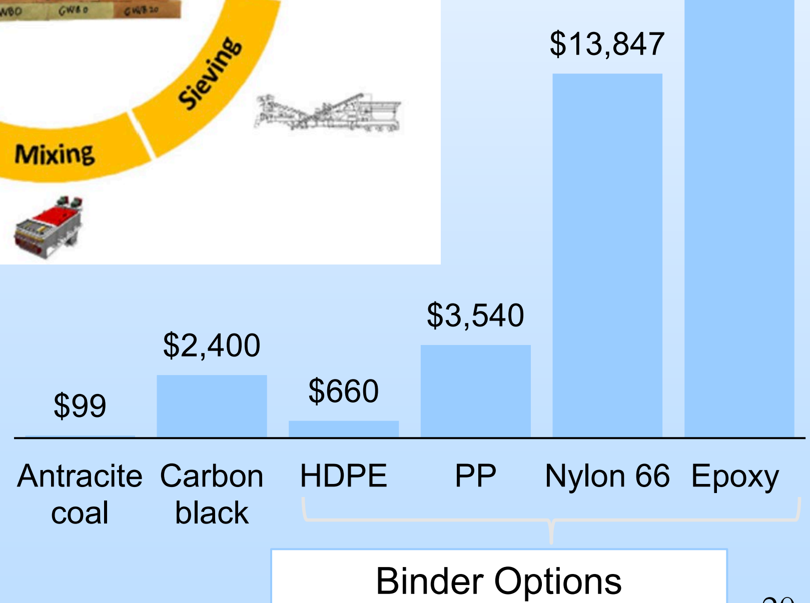
Progress and Current Status of Project TEA

CBB Composition



CBB process





CAPEX

- Procedure
- Storage of raw materials
- Crushing & screening
- Mixing & forming
- Cutting & coating
- Storage of product

OPEX – Feedstocks:

Anthracite coal

Binder material:

- HDPE
- PP
- Nylon 66
- Epoxy 862/3140

Progress and Current Status of Project
Market Survey

Usage and features of different clay brick types

Common red

- 2nd class brick
- Structural applications
- Used internally or covered with a veneer
- Not weatherproof
- No consistency in size, shape, or color

Face (including thin brick)

- 1st class brick
- Structural applications (except thin brick)
- Used in exposed brick structures or exterior applications
- Weatherproof
- Texture and color are key characteristics
- Thin brick is simply a veneer and may be made of cement, fiberglass, or other material

Engineered (includes fire / refractory bricks)

- Multiple uses
  - Foundations
  - Reinforced walls
  - Civil projects(e.g., sewers and tunnels)
- Fire pits and fireplaces
- Resistant to water and heat damage
- Fire bricks may offer highest heat protection and may be made from ceramic

Glazed (can be clay or concrete)

- Similar to face bricks
- Have ceramic coating
- Used in structural walls, partition walls, or veneers
- Decorative
- Resists graffiti, stains, impacts, and fire
- Long lasting
- Heavier than most clay bricks
- More labor-intensive installation

Progress and Current Status of Project Market Survey

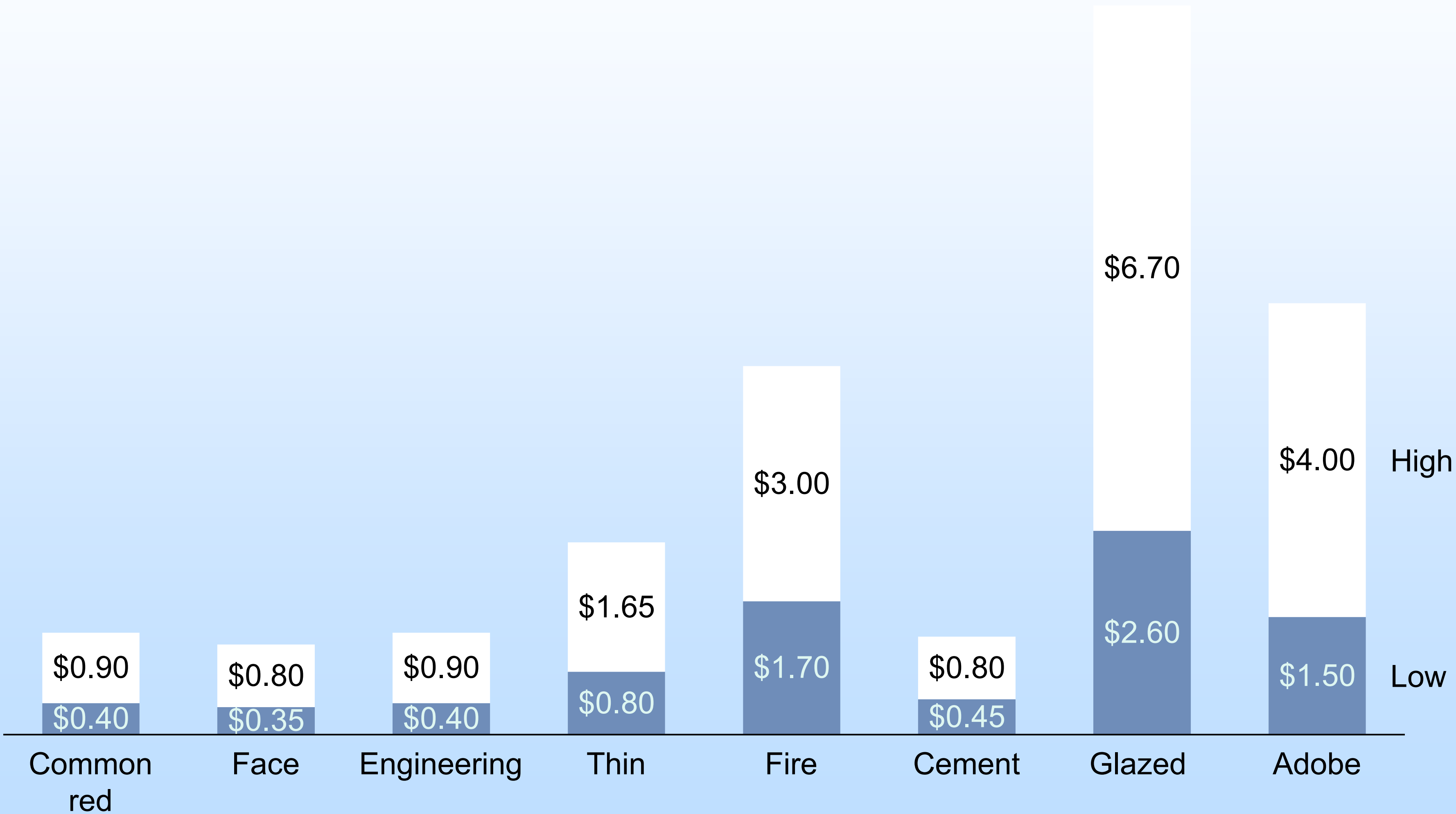
Brick type	Manufacturing process	Benefits	Primary use
Cement / concrete bricks	• Made using cement, sand, coarse aggregates, and water • Can be made on site	• Easily pigmented during production • Superior strength • Block heat, noise, and resist water	• Internal brickwork • Retaining walls • Load-bearing structures (except below grade)
Fly ash bricks	• Made using fly ash and cement (most similar to concrete blocks) • May contain clay, sand, or lime	• Resistant to weather. • Superior frost prevention, fire insulation, and resistance to water.	• Alternative to normal clay bricks. • Used in masonry structures
Sand lime bricks	• Mixing sand, fly ash, and lime • Bonded together by chemical process rather than kiln dried	• Strong and durable • Resists water, wind and heat • Easily pigmented • Requires less mortar during construction	• Structural foundations • Exposed brick and pillars, • Ornamental uses (when pigmented)
Sun-dried bricks (includes adobe)	• Also referred to as unburnt clay bricks. • Made by drying clay bricks to sun exposure.	• Soft • Generally, less expensive bricks	• Temporary structures • Adobe popular in SW USA – requires stucco coating

Source: The Spruce; Waterproof Caulking, The American Ceramic Society

Progress and Current Status of Project Technology Gap Analysis

	Technology gap
1	The extrusion process requires modification to allow adequate cooling and solidification of the CBB mixture.
2	CBBs made from the two viable binder options need to be evaluated to see if they meet the technical standards to compete with other bricks.
3	Glazed and thin bricks sell for premium prices; can the manufacturing process be modified to create these specialty bricks?
4	A more in-depth market/consumer analysis is required to determine if end users are open to CBBs.
5	ASTM Standards testing for intended uses.
6	Field testing

Progress and Current Status of Project Technology Gap Analysis



Source: Homeguide, 2022

Plans for future testing/development/ commercialization

Current Project

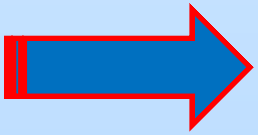
a. Perform pilot scale extrusion at commercial facility
b. Finish fabrication of half- and full-scale bricks by molding.
c. Conclude property testing for compressive strength, density, and permeability.
d. Finalize the TEA, Market Survey and Technology Gap analysis

Next Project

Scale-up potential exists. TEA is favorable with suitable binder. A phase II effort is required to reach TRL of 6 or higher.

Plans for future testing/development/ commercialization

	TEA Findings
1	The main differences are different feedstocks and the absence of the energy intensive curing process.
	Market Survey
2	Beyond fire clay bricks, there are multiple other brick types that the CBBs would compete with including: concrete bricks, fly ash bricks, and sand lime bricks.
	Technology Gap Analysis
3	The extrusion process requires modification to allow adequate cooling and solidification of the CBB mixture.



ASTM designation
C 62
C 216
C 652
C 1088
C 902
C 1272
C 126
C 1405
C 1261
C 279
C 32
C 410

Plans for future testing/development/ commercialization – in a Phase II effort

Brick type	ASTM designation
Building brick	C 62
Facing brick	C 216
Hollow brick	C 652
Thin veneer brick	C 1088
Pedestrian and light traffic paving brick	C 902
Heavy vehicle paving brick	C 1272
Ceramic glazed structural clay facing tile, facing brick, and solid masonry units	C 126
Glazed brick, single fired	C 1405
Residential firebox brick	C 1261
Chemical-resistant masonry units	C 279
Sewer and manhole brick	C 32
Industrial floor brick	C 410

Potential for Workforce Development

Improving the Value Chain for Coal Production in the U.S. and Projected Scale

- In 2019 the US share of world brick production was 0.53%, or 8 billion bricks [1].

- CBB carbon content targets are >51 wt.% from coal and >70 C wt.% overall.

- *Estimating anthracite density as 1,800 kg/m^3 and CBB anthracite content as 0.9 yields an estimate of ~16,000 U.S. short tons of coal to realize 0.1% of the current brick production.*

- For concrete blocks, annual U.S. production is roughly split between building versus paving (block) markets, each well over 4 billion units [2].

- *Based on a standard CMU (410 x 200 x 200 mm) size, anthracite density as above, at 1% of the current market requires 118,000 short tons of coal.*

1,2 IBIS World Industry Research Report. Bricks, Cement

Outreach and Workforce Development Efforts or Achievements

Outreach/Dissemination

- Technical presentations (TechConnect ‘22), Pittsburgh Coal Conference (‘22), Penn State Research Showcases (April, Oct. ‘22), Materials Days (Oct. ‘22).

Small business support

- Blaschak Coal Corp.
- Citizens Scientific and ADI Analytics

Workforce Development

- Graduate student training and professional development: Laboratory experience, instrumental characterization techniques, project presentations.
- Post-doctoral training: ADI Analytics personnel conducting techno-economic analysis, market survey and technology gap assessment.
- Project provided support for Penn State staff in characterization instrumentation.

Summary Slide

Key Findings

- Validated hot press molding and extrusion feasibility for fabrication quarter- and half-scale bricks.
- Can achieve 70 wt.% coal loading within thermoplastic and thermoset binders as matrices.
- Compressive strengths comparable to clay-based bricks.
- ~ ½ the weight of clay-based bricks, impermeable and not subject to corrosive environments.
- TEA – CBBs can be price competitive for some applications.
- Market Survey– favorable array of brick types and uses to enable market entry
- Gap Analysis – process optimization, scaling and ASTM tests required prior to market entry.

Lessons Learned

- DoE matrix: particle size, loading and plastic
- Processing temperatures

Take-away

- ***CBBs' compressive strengths are comparable to those of standard clay bricks.***

Technology Summary

Features of coal bricks	Discussion
Equivalent strength	▪ **Strength comparable** to the lower range of traditional clay bricks (although not as brittle)
More impermeable to water	▪ Although clay bricks are moisture resistant, they still are a porous medium ▪ **Reduced porosity and permeability of coal bricks** provides greater moisture resistance and protection against degradation due to freeze-thaw cycles ▪ **Reduced permeability and lack of salts** in feedstocks prevents efflorescence that can ultimately reduce the integrity of bricks
Weigh less	▪ **Coal bricks can be up to 70% lighter** than regular brick ▪ Reduced weight can lower building and transportation costs
More sustainable	▪ **Manufacturing coal bricks does not require natural gas fired kiln drying, greatly reducing energy usage** ▪ Clay mining process is not environmentally friendly and results in deforestation and topsoil erosion

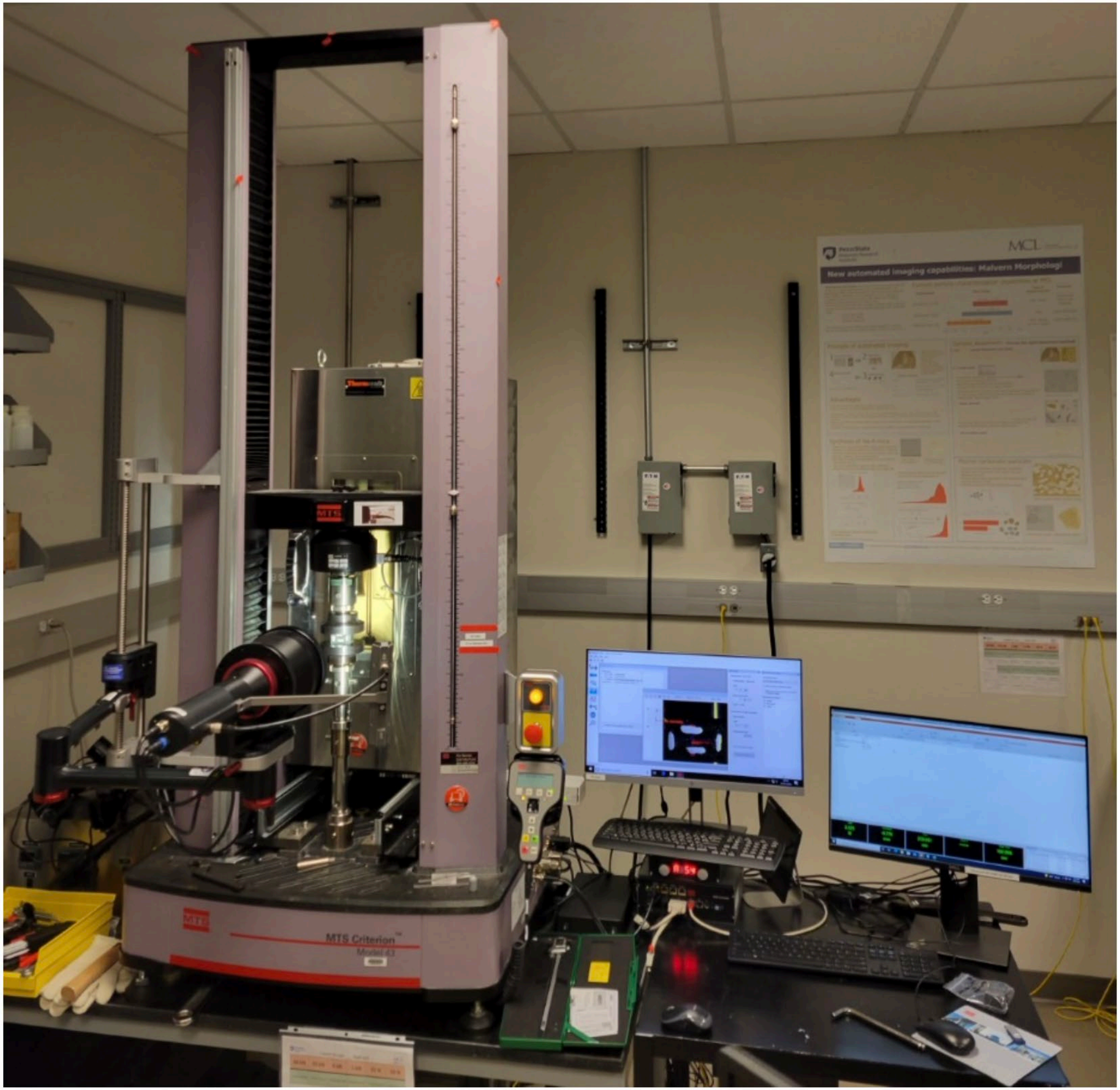


Figure 15: 50 KN MTS Criterion Load Frame

Appendix I

Organization Chart

Roles and Responsibilities of Participants:

- Scientific and technical direction of this proposal will be managed by Dr. Randy Vander Wal as Principal Investigator (PI).
- **Dr. Vander Wal** – responsible for the project scope, managing costs, and meeting schedules.
- **James Heim II** – fabricating bricks & blocks; testing process and composite performance.
- **Schobert International LLC** –science advisor for coal properties.
- **ADI Analytics** – commercial organization will assess the market potential of the resulting products, develop the TEA model and conduct the gap analysis.
- **Blaschak Coal Corp**. – industrial advisor for technical input to the TEA model developed by ADI Analytics and is also providing anthracite coals.

Gantt Chart

Project Timeline: Task & Milestones†	Assigned	Year 1 – 2021			Year 2 – 2022				Year - 2023	
Task Name	Personnel	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Task 1.0 –Project Management Planning	PI, Co-I's	△								
Task 2.0 Plastic Binder Evaluation	GS, PI, & HS									
Milestone 1					△					
Task 2.0 Plastic Binder Evaluation										
Milestone 2					△					
Task 2.0 Plastic Binder Evaluation										
Milestone 3					△					
Task 3.0 – Lab-scale Extrusion										
Milestone 4							△			
Task 4.0 Prototype Brick Fabrication										
Milestone 5							△			
Task 5.0 Techno-economic analysis	ADI & GS & PI									
Milestone 6								△		
Task 6.0 Market survey summary										
Milestone 7								△		
Task 7.0 Technology gap assessment										
Milestone 8									△	
Task 1.0– Final Report	PI,ADI,HS									

Project Timeline: Task & Milestones†	**Assigned**	**Year 1 – 2021**			**Year 2 – 2022**				**Year - 2023**	
Task Name	**Personnel**	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Task 1.0 –Project Management Planning	PI, Co-I's	■ ▲	■	■	■	■	■	■	■	■
Task 2.0 Plastic Binder Evaluation	GS, PI, & HS	■	■	■	■					
Milestone 1					▲					
Task 2.0 Plastic Binder Evaluation			■	■	■	■				
Milestone 2					▲					
Task 2.0 Plastic Binder Evaluation				■	■	■				
Milestone 3					▲					
Task 3.0 – Lab-scale Extrusion			■	■	■	■	■			
Milestone 4							▲			
Task 4.0 Prototype Brick Fabrication					■	■	■	■		
Milestone 5							▲			
Task 5.0 Techno-economic analysis	ADI & GS & PI					■	■	■		
Milestone 6								▲		
Task 6.0 Market survey summary								■	■	
Milestone 7								▲		
Task 7.0 Technology gap assessment								■	■	
Milestone 8									▲	
Task 1.0– Final Report	PI,ADI,HS									■

Personnel: PI – Dr. Vander Wal, GS – grad. student, HS – Dr. Schobert, ADI (Analytics) – Dr. Turaga