Coal Plastic Composite Piping Infrastructure Components

DOE Cooperative Agreement No. DE-FE0031982

Project PI: Jason Trembly
Phone: (740) 566-7046
E-mail: trembly@ohio.edu

Project Period:
January 1, 2021 through December 31, 2022

Prepared by:

Yahya Al-Majali, Logan Veley, Damilola Daramola, Vick Dhanapal, Robert Statnick, Eric Shereda, and Jason Trembly

Submitted by:

Ohio University
1 Ohio University
Athens, OH 45701

Submitted to:
U.S. Department of Energy
Office of Fossil Energy and Carbon Management
National Energy Technology Laboratory

Disclaimer

Acknowledgment

This material is based upon work supported by the Department of Energy National Energy Technology Laboratory under award Number DE-FE0031982.

Abstract

This report examines the development and use of coal plastic composite materials for piping applications. Foam materials were developed at bench scale and evaluated according to ASTM specifications. Techno-economic analyses are also reported.

Table of Contents

1. Introduction

The primary goal of the National Energy Technology Laboratory's Carbon Ore Processing is to develop novel technologies for producing valuable products from coal and coal wastes. The objective of this project was to evaluate the development and application of coal-plastic composite (CPC) in building sector, with a specific focus on composite piping applications.

1.1. Project Objectives

The objective of this project is to develop coal plastic composite (CPC) formulation(s) containing at least 70 wt.% carbon and 51 wt.% coal that offer cost, performance, and environmental benefits in comparison to existing plastic pipe infrastructure materials. Project objectives include conducting bench-scale formulation and pipe manufacturing trials to generate data to validate CPC pipe technical feasibility, identifying and analyzing existing market applications for CPC piping, and conducting techno-economic and technology gap analyses to identify required selling price and resources necessary to scale-up and commercialize CPC-based piping materials.

2. Piping Formulations: Thermal, Physical, and Mechanical Properties

2.1. PVC Formulations

2.1.1. PVC Formulation Development

The impact of particle size distribution, coal type, coal content, and manufacturing process were investigated. Bituminous coal (high and low volatile matter) and semi-anthracite coal were used at different loading ratios ranging from 10-30 wt%. Note, PVC formulations containing up to 70 wt.% coal were investigated. Preliminary tensile properties for formulations containing greater than 30 wt.% coal indicated meeting ASTM D1784 requirements were unlikely. Table 1 below summarizes the formulations investigated. Note that the materials were processed using a vented twin to achieve optimum mixing and reduce porosity. Mechanical and physical properties for CPC materials were investigated with the goal of meeting ASTM D1784 requirements for 12454 cell classification [1]. This cell classification is required for PVC-based piping materials used for pressurized and non-pressure applications [2], [3]. Table 2 summarizes the required performance for 12454 cell classification.

Table 1. CPC piping formulations extruded using a vented twin extruder

Polymer	Filler	Volatile matter (%)	Type	Filler loading level (wt.%)	Mesh size
PVC	P8	33.8	Bituminous	10,20,25,30	500M
	P8				325X500M
	P8				120M
PVC	Keystone#325	18.0	Bituminous	10, 20, 25,30	325M
PVC	Keystone#121	10.0	Semi-anthracite		90% Minus 325

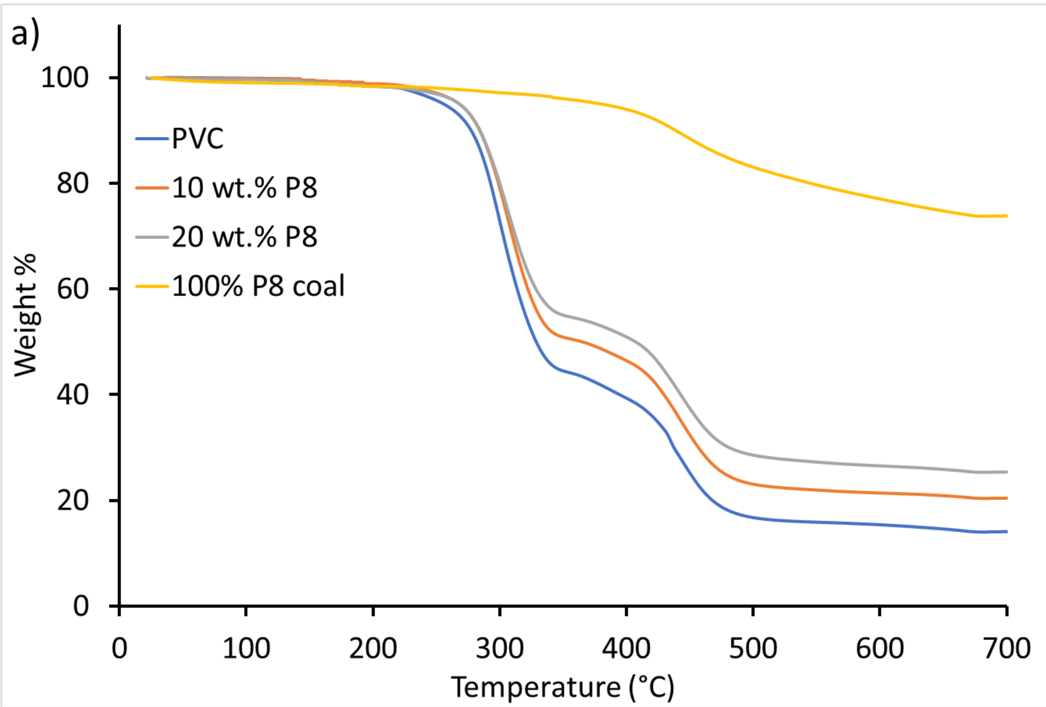
Table 2. Minimum requirements for Class 12454B rigid PVC compound (ASTM D1784)

Property and unit	**ASTM standard**	**Cell 12454**
Base resin	NA	PVC
Impact resistance (Izod), (J/m)	ASTM 256, Method A	34.7
Tensile strength, (MPa)	ASTM D638	48.3
Modulus of elasticity in tension (GPa)	ASTM D638	2.758
Deflection temperature under load (1.82 MPa), (°C)	ASTM D648	70
Flammability	ASTM D635	Burning extent <25mm; burning time< 10s

2.1.2. Thermogravimetric Analysis (TGA)

The main goals for conducting the thermogravimetric analysis (TGA) were to assess the thermal stability of CPC materials and determine the weight loss at the processing temperatures. This is important since volatiles released during processing are most likely to get trapped in the material's microstructure in the

form of porosity, leading to deteriorating the composite performance. As shown in Figure 1, TGA results revealed both P8 and Itmann coals decompose at higher temperatures and at a slower rate as compared to the CPC materials and unfilled PVC, suggesting higher thermal stability. Furthermore, the coals possessed single-step decomposition, while the composites and unfilled PVC had a two-step decomposition. Incorporating coal into PVC has minimal impact on the PVC decomposition behavior. However, residual weight increased with coal content.



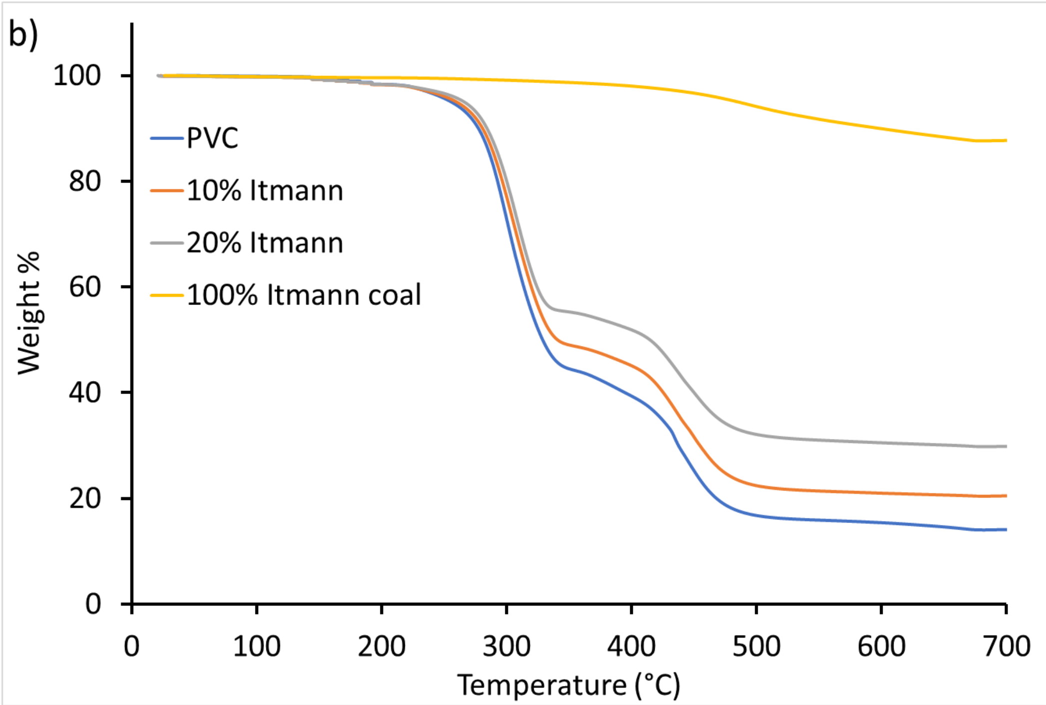


Figure 1. TGA plots for a) CPC with 10-20 wt.% in comparison to neat PVC and 100% P8 coal, and b) CPC with 10-20 wt.% in comparison to neat PVC and 100% Itmann coal

Figure 2 (a-b) shows the weight loss from CPC with 10-20 wt.% coal, P8 coal, Itmann coal, and unfilled PVC at six different processing temperatures ranging from 150 °C to 200 °C with 10 °C increments. Powdered specimens (10 ± 0.5mg) were tested under a nitrogen atmosphere. At first glance, it can be seen that processing the materials at lower temperatures will potentially generate less volatiles, while both the unfilled PVC and P8 coal had significant weight loss. For CPC/P8 (Figure 2a), PVC weight loss was higher than P8 coal at the higher temperatures (180-200 °C), and it was comparable to or less than P8 at the lower temperatures (180-200 °C). Furthermore, the weight loss for the composite mixtures increased with coal content increase from 10 wt.% to 20 wt.%. At all processing temperatures, Itmann coal possessed lower weight loss values as compared to unfilled PVC. Furthermore, increasing the Itmann coal content from 10 wt.% to 20 wt.% slightly increased the weight loss, as shown in Figure 2b. Comparing the composite mixtures, it can be seen that CPC with 10 wt.% P8 and 10 wt.% Itmann possessed comparable weight loss, while CPC with 20 wt.% P8 had higher weight loss as compared to CPC with 20 wt.% Itamnn. Based on the TGA results, it can be concluded the CPC materials need to be processed in a vented extruder to reduce the composite porosity. Therefore, the team has acquired a vented twin-screw extruder to process the materials.

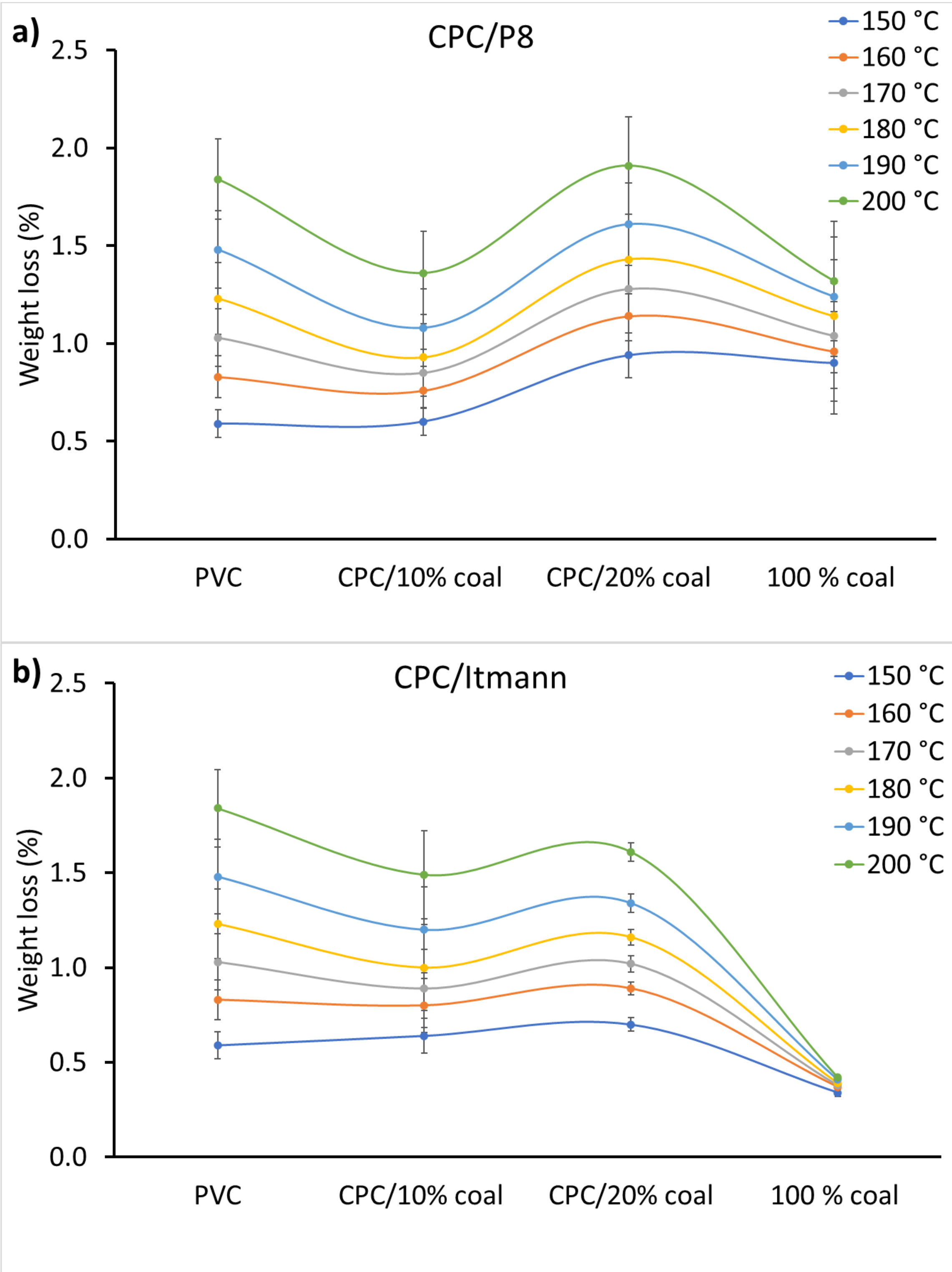


Figure 2. Weight loss for a) CPC with 10-20% P8, P8 coal, and PVC; b) CPC with 10-20% Itmann, 100 % Itmann coal, and PVC

To assess the impact of coal on thermal stability, an isoconversional analysis was performed to calculate the activation energy associated with the degradation of PVC and CPC materials. TGA tests for PVC and

CPC with 20 wt.% P8 coal were performed according to ICTAC committee recommendations [4], [5]. Materials were tested at three different heating rates (5, 15, and 30 °C/min), and the advanced isoconversional Method developed by Vyazovkin and Wight was used to determine the activation energy at different degrees of degradation (conversion) [6]–[8]. As shown in Figure 3, the unfilled PVC shows a steep decline in the activation energy until it reaches ~0.1 conversion, whereas PVC composites with P8 coal do not exhibit this behavior. The decrease in activation energy was associated with a free radical reaction scheme that begins once HCl and polyene segments (both products of PVC degradation) are present. The fact that this decrease is not seen in composites containing coal indicates that coal is acting as an antioxidant and preventing this free radical reaction scheme from occurring.

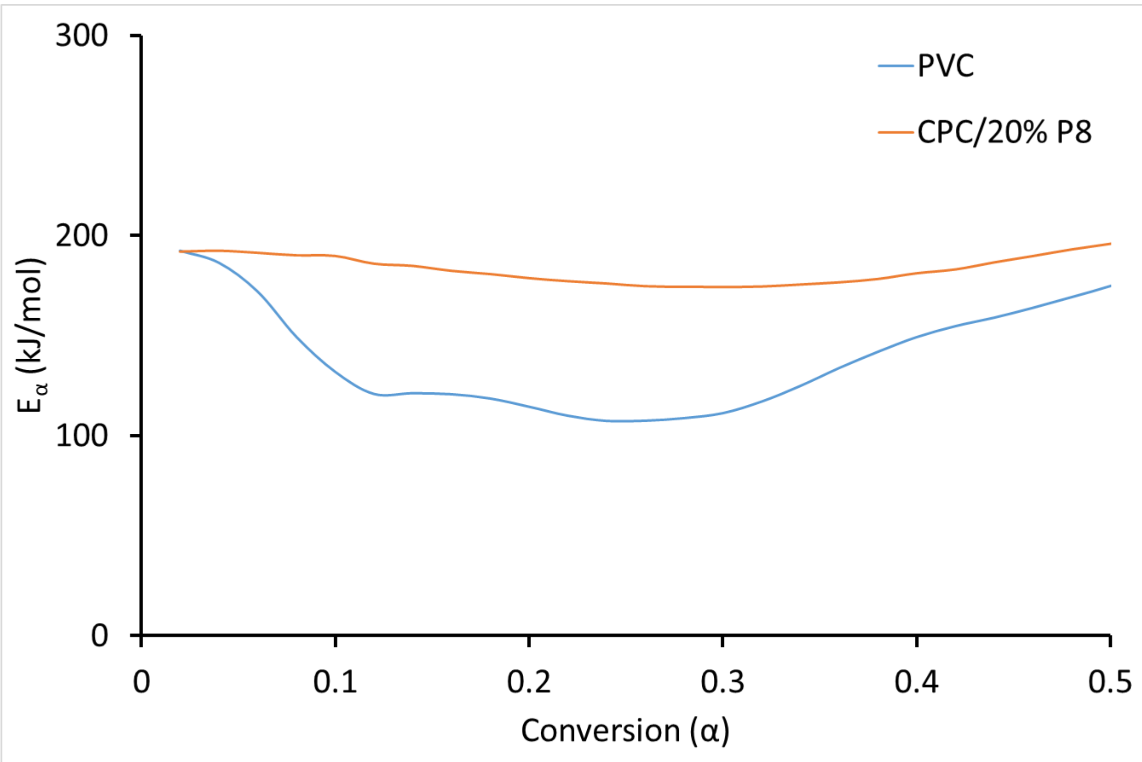


Figure 3. Activation energy at different degrees of degradation (conversion) for unfilled PVC in comparison to CPC filled with 20 wt.% P8 coal

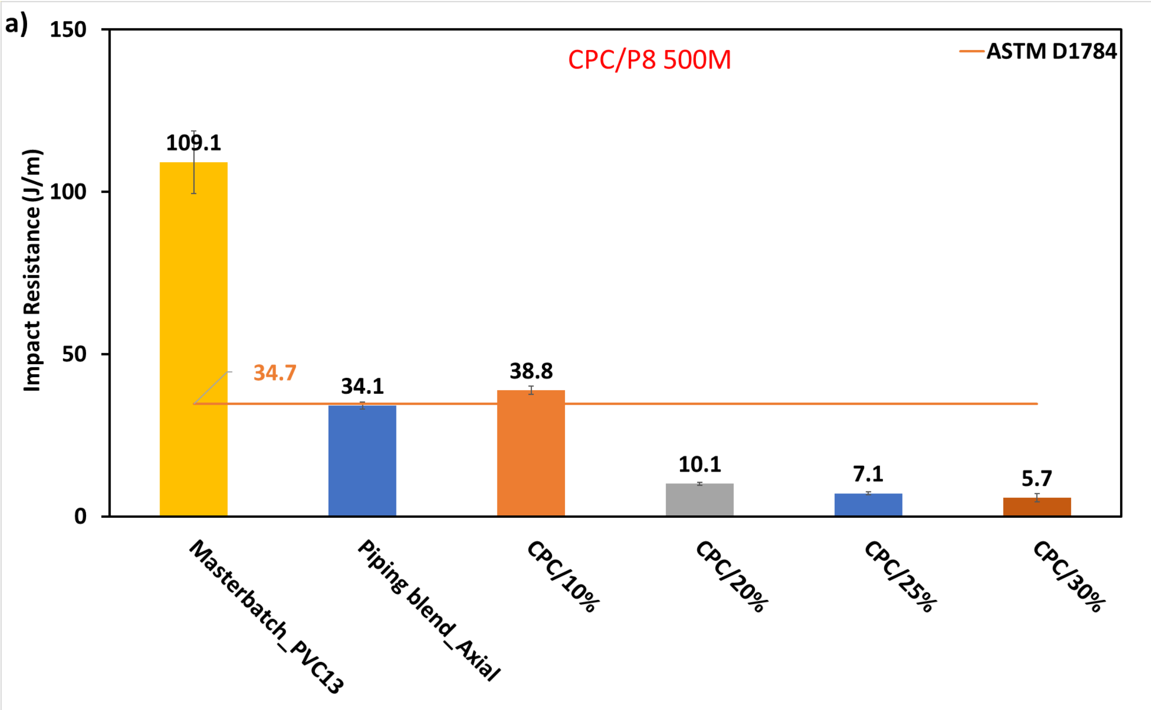
2.1.3. Impact Resistance

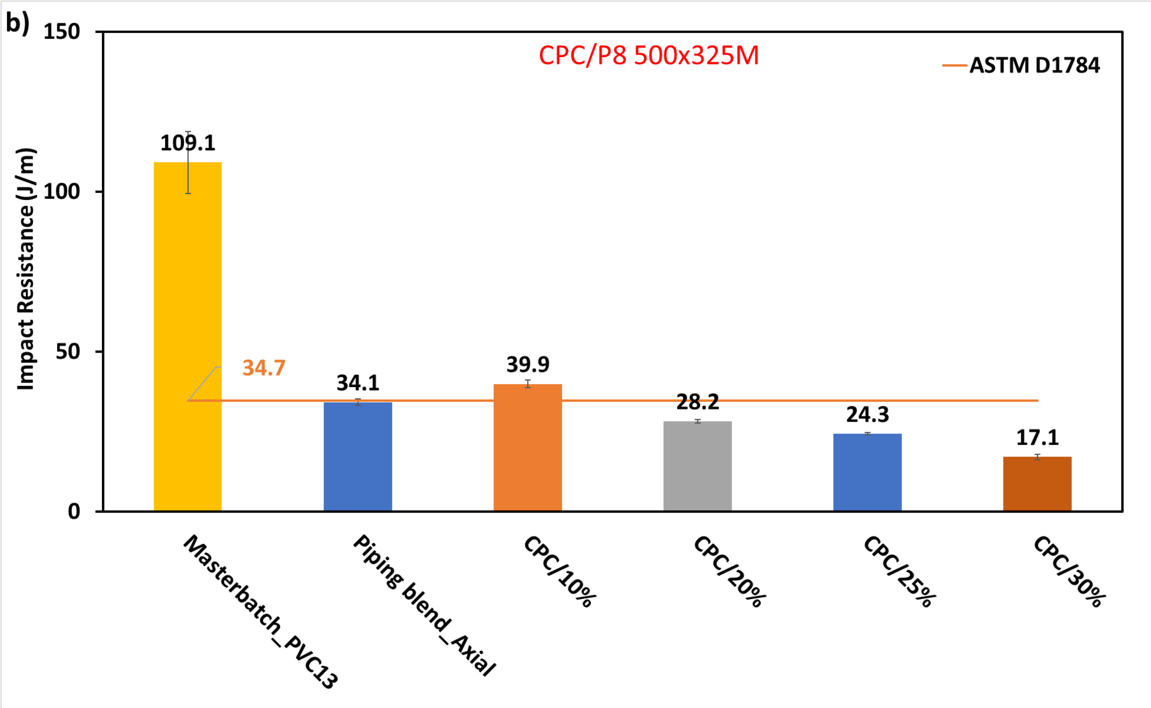
The impact resistance of CPC materials was investigated with the goal of meeting ASTM D1784 requirements for 12454 cell classification [1]. This cell classification is required for PVC-based piping materials used for pressurized and non-pressure applications [2], [3]. PVC masterbatch with impact modifiers, commercially available PVC piping blend, and CPC pipe formulations were tested as described in ASTM D256 to determine the impact resistance [9].

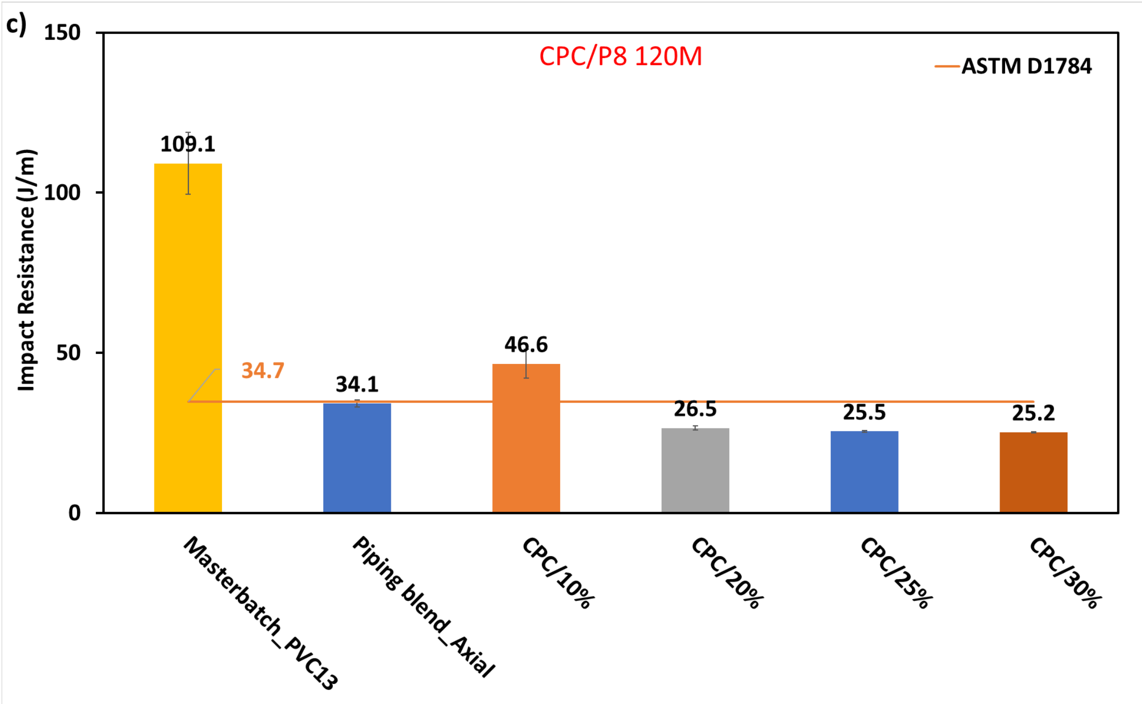
Figure 4(a-e) shows the impact resistance for all materials tested. Results indicated the unfilled masterbatch exceeded the ASTM requirement of 34.7 J/m impact resistance, while the commercial piping blend was not significantly higher from the ASTM requirement. Except for Keystone#325, all formulations with 10 wt.% coal have met the ASTM requirement with P8 120M possessing the highest impact resistance. At 20 wt.% coal loading, impact resistance values have shown to further decrease for

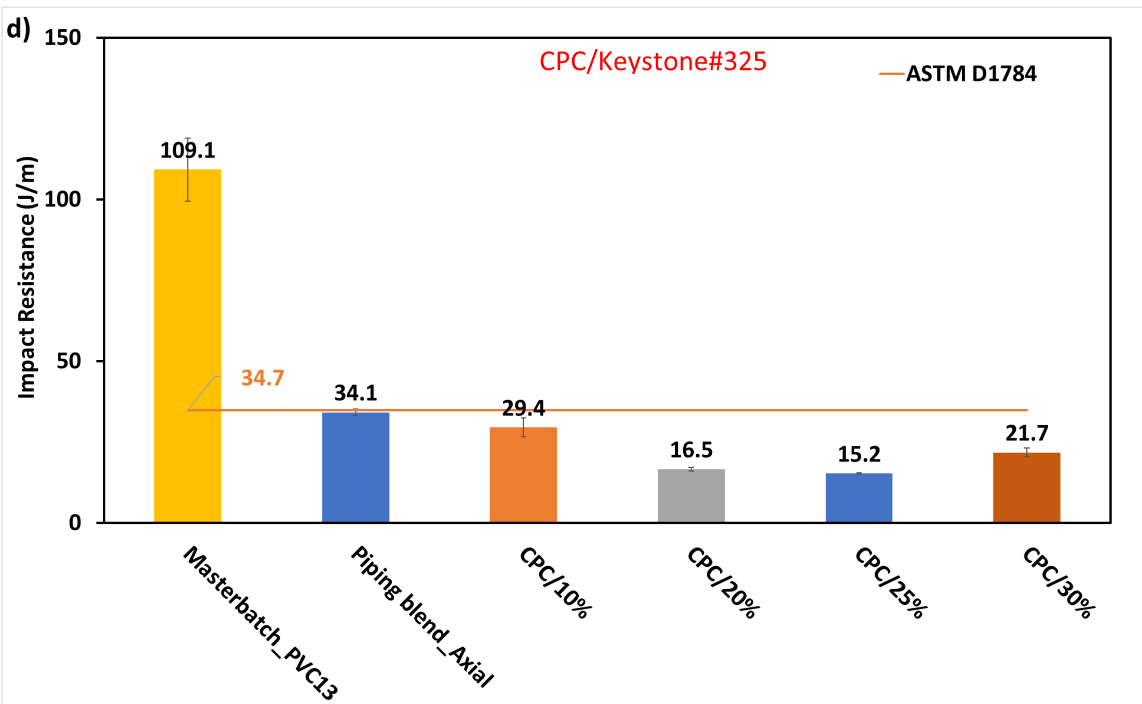
all formulations. At higher coal loading values (i.e., 25 wt.% and 30 wt.%), impact resistance dropped down more or remained comparable to the 20 wt.% formulations. The increase in the impact resistance for the CPC/30% Keystone#325 remains unexplained, but further examination of the material is needed. For most formulations from the different types of coal, increasing the particle size had shown to increase

the impact resistance of the resulting composite. A similar effect was reported in the literature for bio-based composite materials [10], [11].






c)
CPC/P8 120M
ASTM D1784
Impact Resistance (J/m)
150
100
50
0
109.1
34.7
34.1
46.6
26.5
25.5
25.2
Masterbatch_PVC13
Piping blend_Axial
CPC/10%
CPC/20%
CPC/25%
CPC/30%


d)
CPC/Keystone#325
ASTM D1784
Impact Resistance (J/m)
150
100
50
0
109.1
34.7
34.1
29.4
16.5
15.2
21.7
Masterbatch_PVC13
Piping blend_Axial
CPC/10%
CPC/20%
CPC/25%
CPC/30%

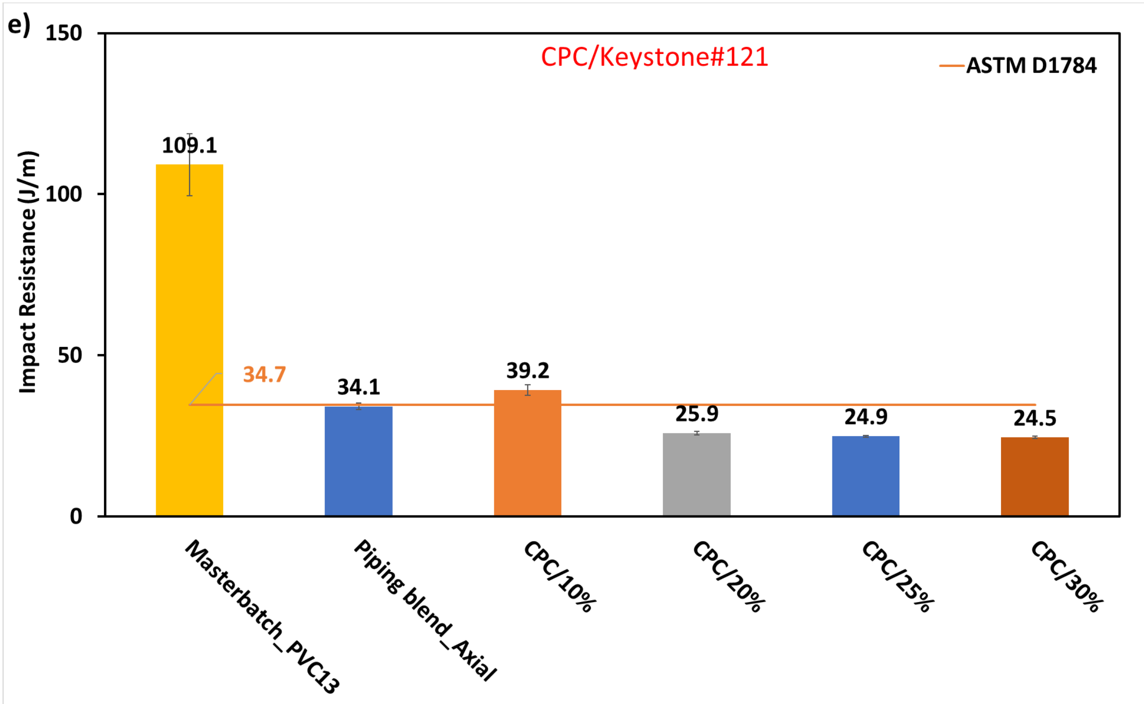
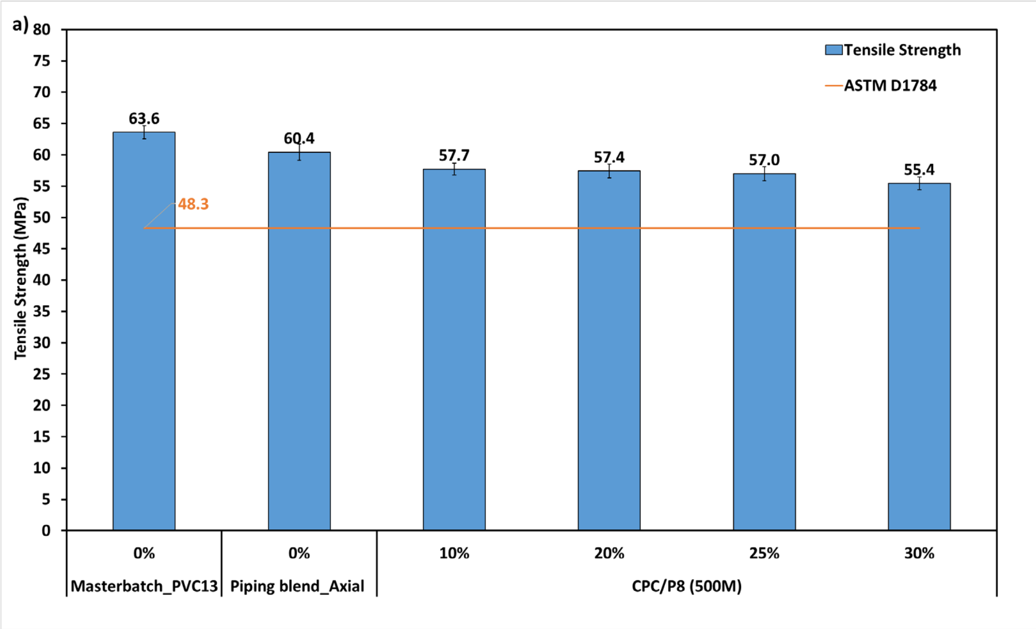


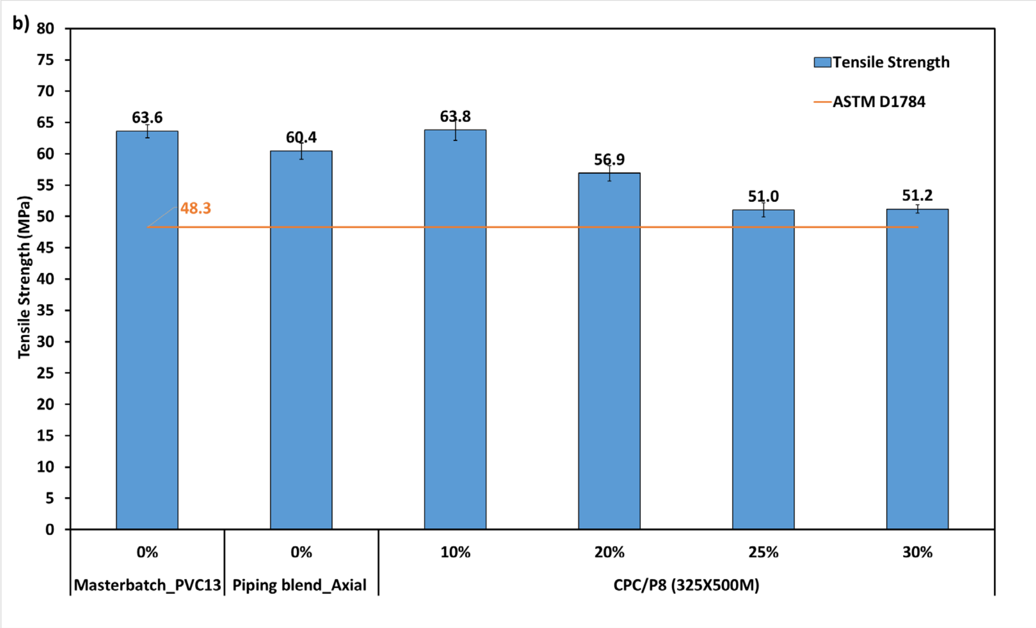
Figure 4: Impact resistance of CPC formulations with 10-30 % P8 and keystone coals. Tests were conducted per ASTM D256.

2.1.4. Tensile Properties

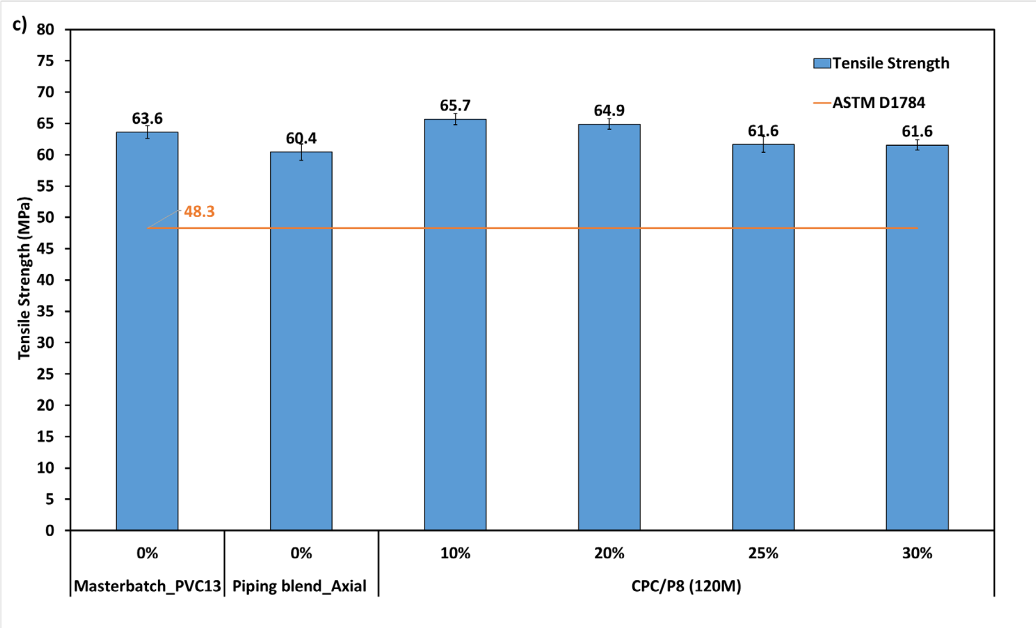
Tensile testing was conducted as per ASTM D638. Type-5 tensile samples were injection molded and tested at 1 mm/min speed. Figure 5(a-e) shows the tensile strength for PVC masterbatch, the commercial piping blend, and composite formulations (CPC/10-30 wt.% coal). Both the PVC masterbatch and piping blend exceeded the ASTM requirements for tensile strength with masterbatch being higher. All CPC materials have met or exceeded the ASTM requirements, except for the 30 wt.% Keystone#325 formulation. Compared to unfilled PVC masterbatch and piping blend, P8 500M formulations have shown a decrease in the tensile strength at 10 wt.%, while further increasing of coal content had minimal impact on the strength (Figure 5a). As for the P8 325X500M formulations, the 10 wt.% material possessed higher tensile strength compared to the 10 wt.% P8 500M and piping blend. However, bigger reductions in the tensile strength values were observed for the higher filler content (i.e., 25-30 wt.%). Unexpectedly, all CPC formulations with P8 120M possessed higher tensile strength values as compared to the smaller particle distributions. These formulations need to be further investigated. The tensile strength for keystone#325 at 10 wt.% was higher than the commercial piping blend and the unfilled PVC. However, tensile strength was substantially decreased with filler content, and the 30 wt.% was lower than the ASTM requirement. Except for the 10 wt.% formulation, tensile strength values of keystone#121 materials were higher than keystone#325. The reduction in the tensile strength might be attributed to several factors such as weak interfacial bonding, porosity, large particle size, and filler agglomeration [12].

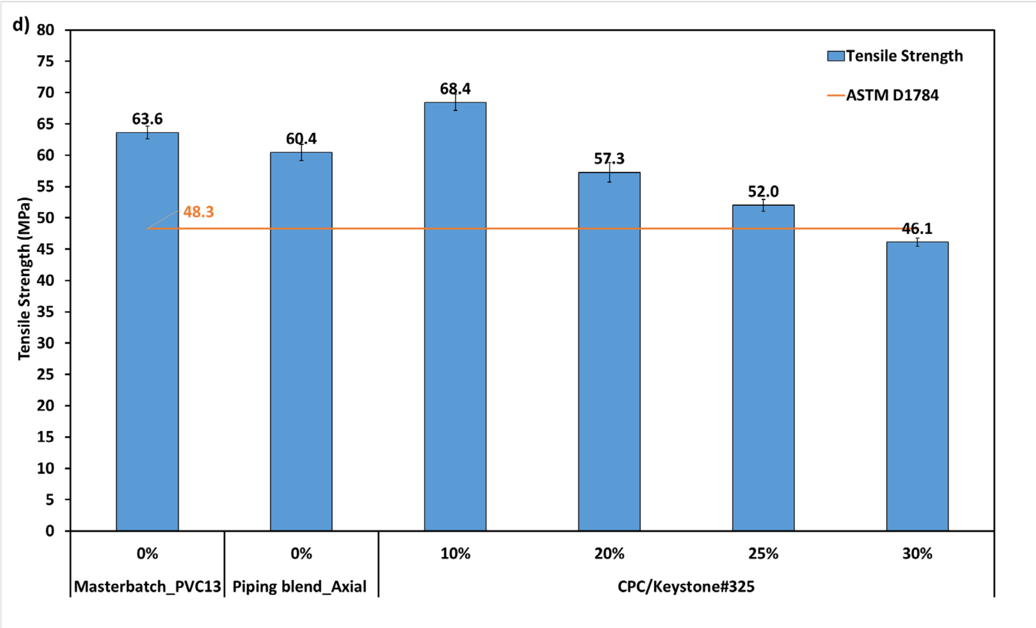


a)
Tensile Strength
ASTM D1784
Tensile Strength (MPa)
63.6
60.4
57.7
57.4
57.0
55.4
48.3
0%
0%
10%
20%
25%
30%
Masterbatch_PVC13
Piping blend_Axial
CPC/P8 (500M)



b)
Tensile Strength
ASTM D1784
Tensile Strength (MPa)
63.6
60.4
63.8
56.9
51.0
51.2
48.3
0%
0%
10%
20%
25%
30%
Masterbatch_PVC13
Piping blend_Axial
CPC/P8 (325X500M)


c)
Tensile Strength (MPa)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Tensile Strength
ASTM D1784
63.6
60.4
65.7
64.9
61.6
61.6
48.3
0%
0%
10%
20%
25%
30%
Masterbatch_PVC13
Piping blend_Axial
CPC/P8 (120M)


d)
Tensile Strength (MPa)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Tensile Strength
ASTM D1784
63.6
60.4
68.4
57.3
52.0
46.1
48.3
0%
0%
10%
20%
25%
30%
Masterbatch_PVC13
Piping blend_Axial
CPC/Keystone#325

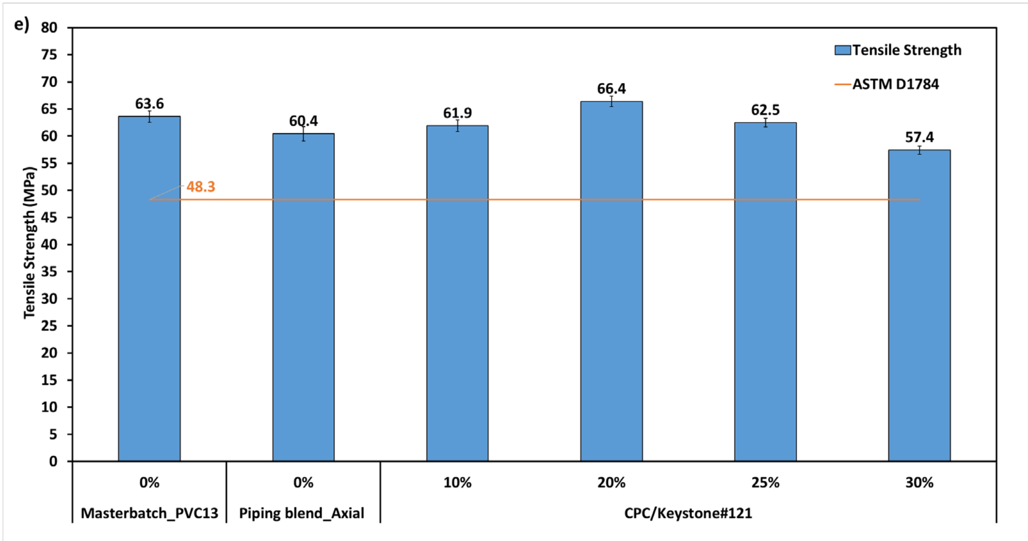
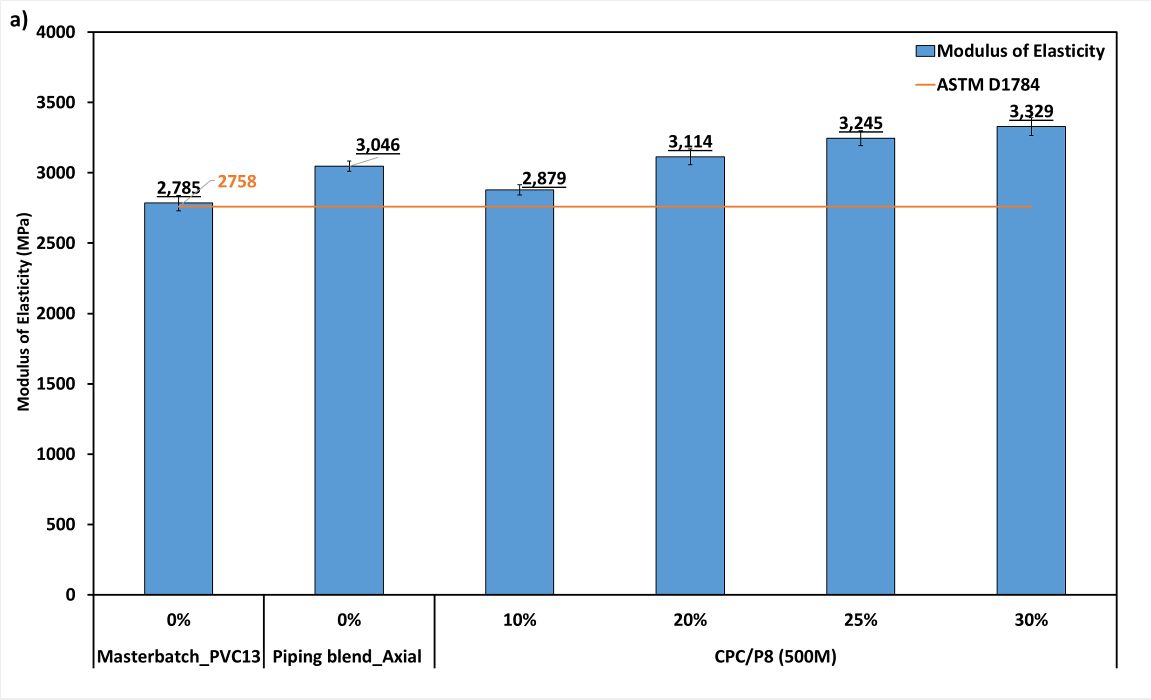
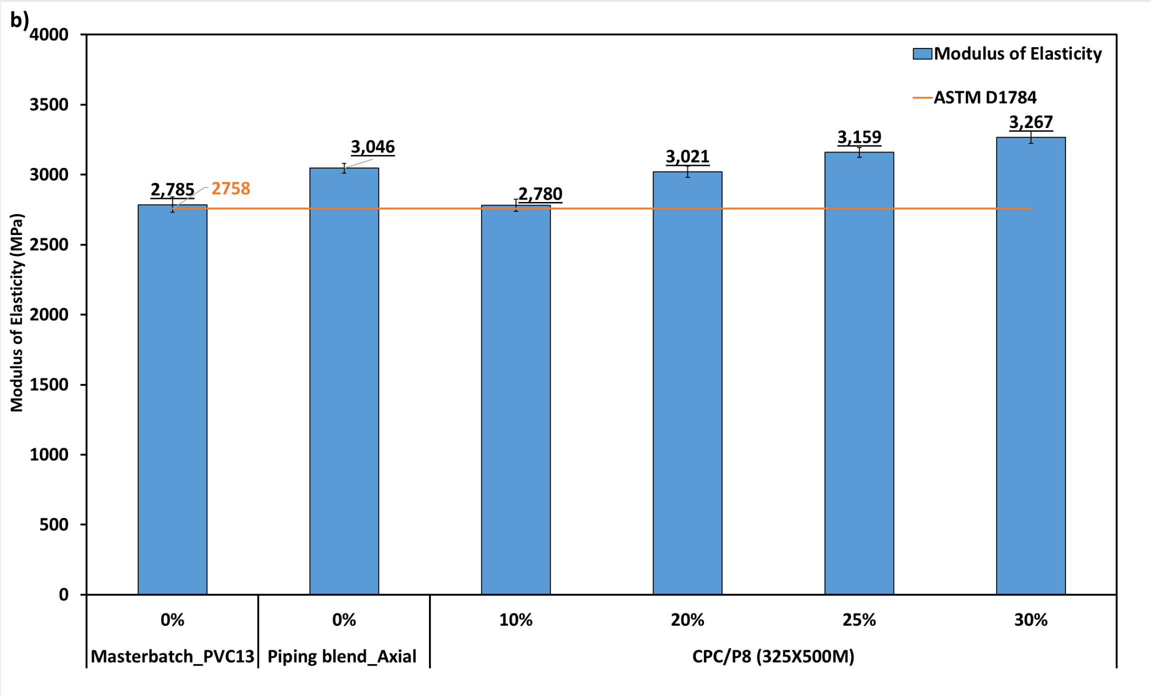
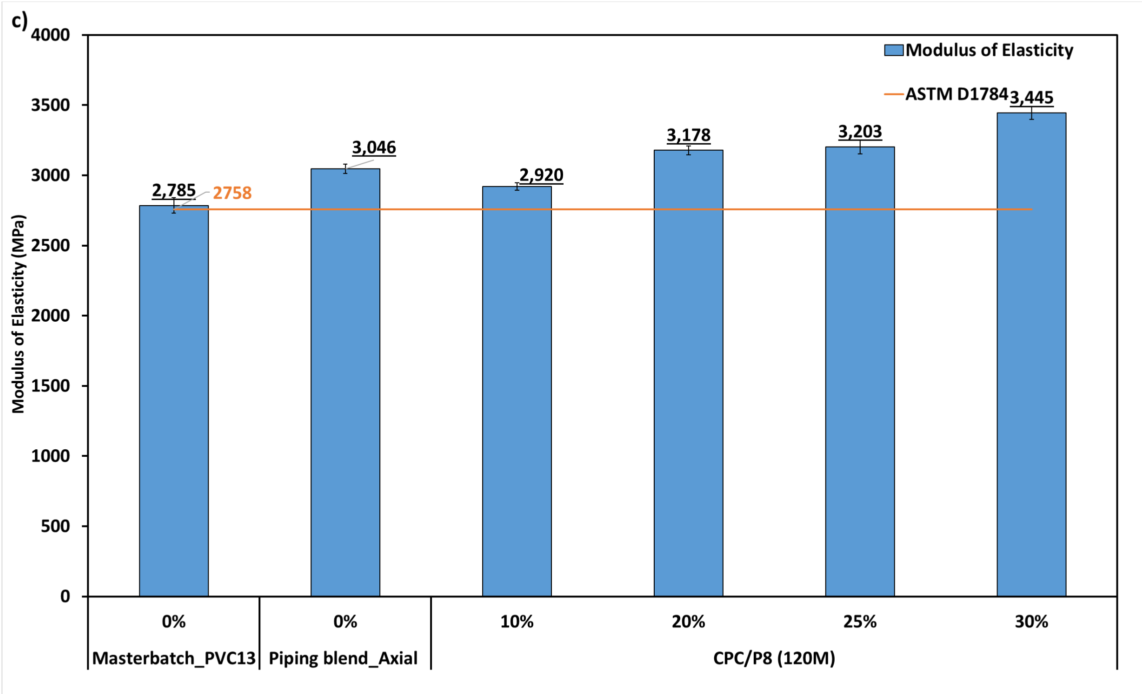


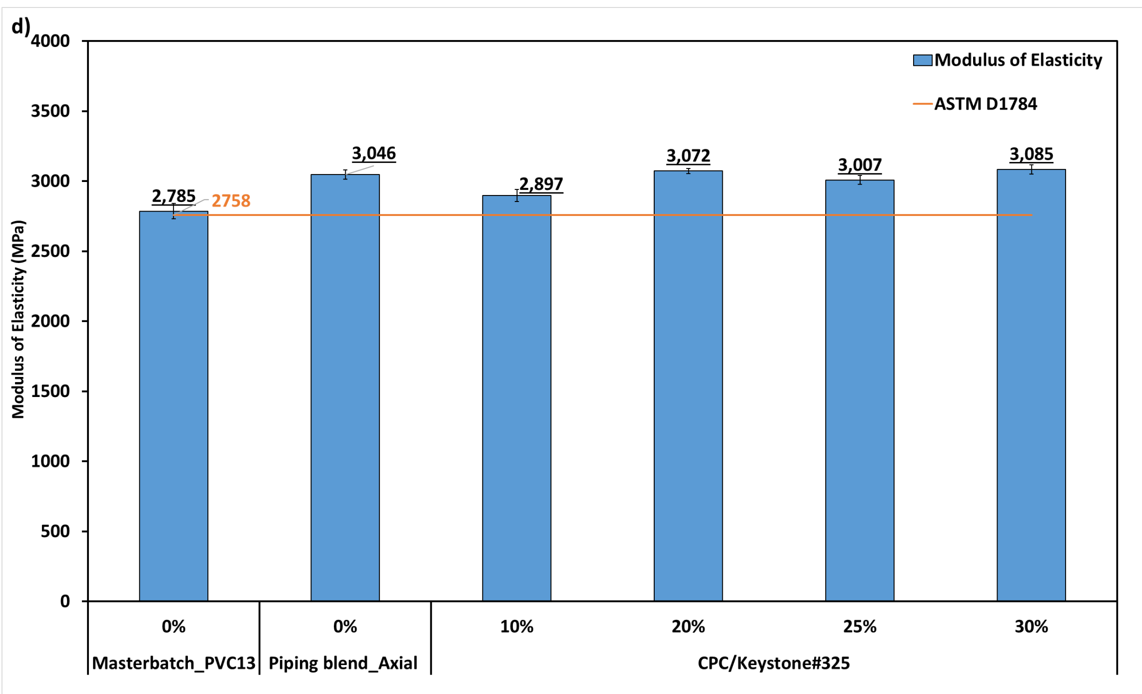
Figure 5: Tensile strength of CPC formulations with 10-30 wt.% coal content a) P8 500M, b) P8 500x325M, c) P8 120M, d) Kestone#325, e)Keystone#121. Tests were conducted per ASTM D638

Figure 6(a-e) shows the modulus of elasticity (MOE) for the different pipe formulations. Both the unfilled PVC masterbatch and the commercial piping blend have met the ASTM requirements with the piping blend being stiffer. Furthermore, all CPC formulations have met or exceeded the ASTM requirements. For P8 formulations (Figure 6 a-c), the MOE values for the 10 wt.% were comparable and in some cases higher than the unfilled PVC masterbatch, but lower than the commercial piping blend. In addition, results indicated MOE to have direct proportionality with the coal content. The results also indicated that P8 particle size had minimal impact on MOE. Unlike P8 formulations, Keystone formulations (Figure 6 d-e) have shown MOE to be affected by the particle size with Keystone#121 possessing higher values at 10, 20, and 25 wt.%. The MOE for the 20 wt.% Keystone#325 increased by 10 % compared to the unfilled plastic but remained comparable to the higher filler content (i.e., 25 wt.% and 30 wt.%). For Keystone#121 formulations, MOE values increase to a maximum value at the 20 wt.% and then decreased with coal content. In conclusion, processing the materials with a vented twin screw improved the tensile properties of the piping formulations. It also allowed for processing higher coal content formulations (i.e., 30 wt.%). Based on the preliminary results, P8 120M formulations possessed better overall properties. The increase in elastic moduli with coal content can be attributed to the limited mobility of the polymer chain and the higher stiffness of coal particles [12]–[15].


a)
Modulus of Elasticity
ASTM D1784
Modulus of Elasticity (MPa)
4000
3500
3000
2500
2000
1500
1000
500
0
2,785
2758
3,046
2,879
3,114
3,245
3,329
0%
0%
10%
20%
25%
30%
Masterbatch_PVC13
Piping blend_Axial
CPC/P8 (500M)


b)
Modulus of Elasticity
ASTM D1784
Modulus of Elasticity (MPa)
4000
3500
3000
2500
2000
1500
1000
500
0
2,785
2758
3,046
2,780
3,021
3,159
3,267
0%
0%
10%
20%
25%
30%
Masterbatch_PVC13
Piping blend_Axial
CPC/P8 (325X500M)


c)
Modulus of Elasticity
ASTM D1784
Modulus of Elasticity (MPa)
4000
3500
3000
2500
2000
1500
1000
500
0
2,785
2758
3,046
2,920
3,178
3,203
3,445
0%
0%
10%
20%
25%
30%
Masterbatch_PVC13
Piping blend_Axial
CPC/P8 (120M)


d)
Modulus of Elasticity
ASTM D1784
Modulus of Elasticity (MPa)
4000
3500
3000
2500
2000
1500
1000
500
0
2,785
2758
3,046
2,897
3,072
3,007
3,085
0%
0%
10%
20%
25%
30%
Masterbatch_PVC13
Piping blend_Axial
CPC/Keystone#325

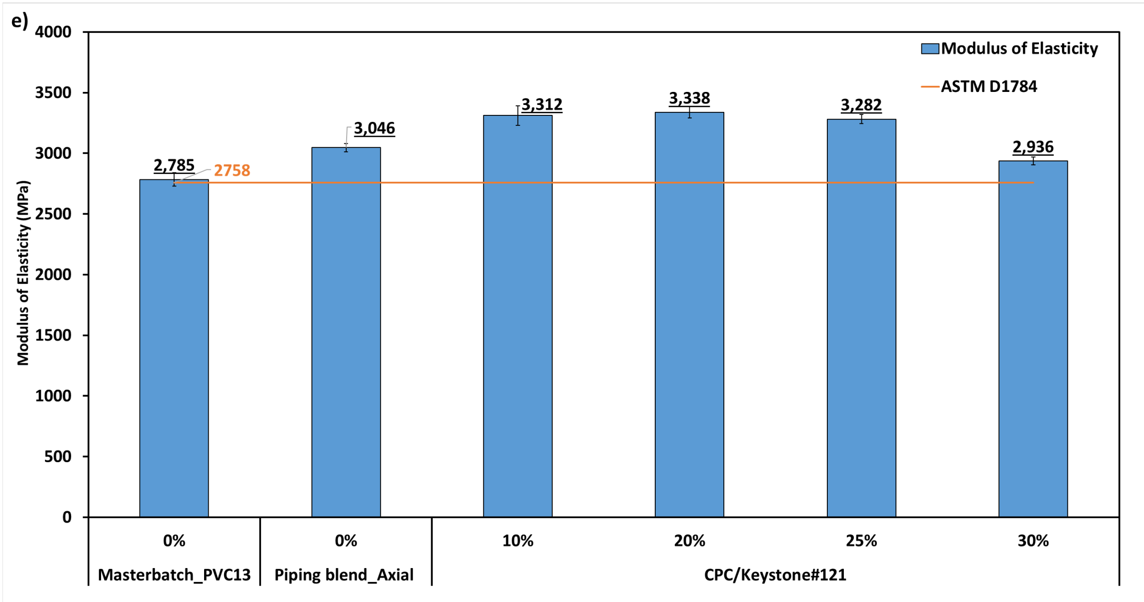


Figure 6: Elastic modulus of CPC formulations with 10-30 wt.% coal content a) P8 500M, b) P8 500x325M, c) P8 120M, d) Kestone#325, e)Keystone#121. Tests were conducted per ASTM D638

2.1.5. Deflection Temperature

Deflection temperature (DT) under flexural load was determined for unfilled PVC and CPC piping formulations as per ASTM D648 [16]. Test specimens were compression molded and sent for testing at Applied Testing & Geosciences, LLC. Figure 7 shows all PVC-based CPC pipe formulations exceed ASTM D1784 requirements for cell classification 12454. Results also indicated that increasing the coal content slightly increases the deflection temperature.

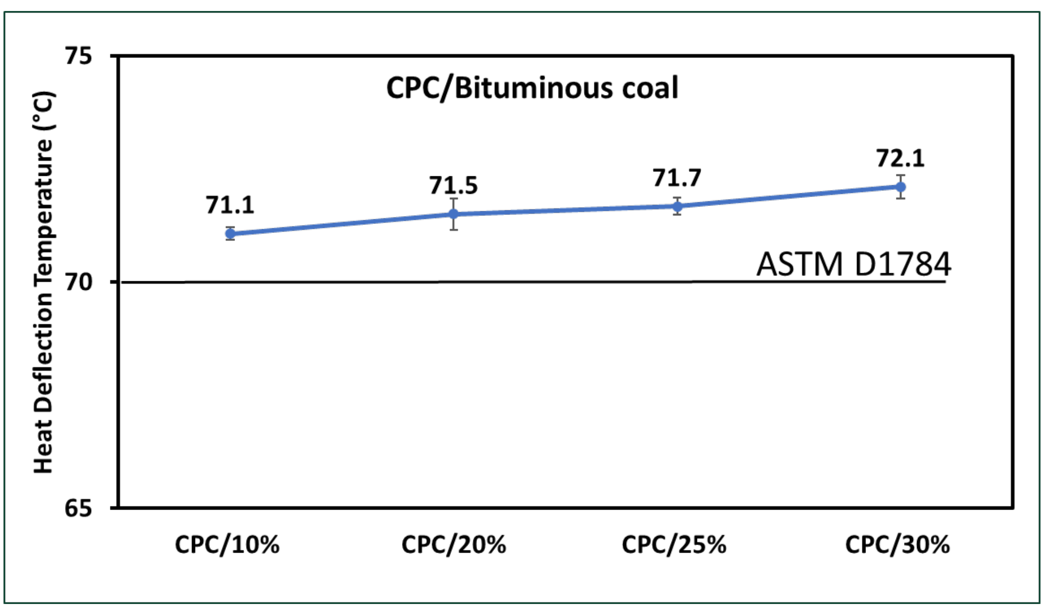


Figure 7: Deflection temperature of CPC pipe formulations determined in accordance with ASTM D648

2.1.6. Flammability

Flammability of PVC-based CPC formulations were investigated via rate of burning analyses according to ASTM D635. Burning extent values for all formulations were below 25 mm and burning times less than 10 sec. All CPC formulations meeting class 12454 requirements per ASTM D1784.

3. Continuous CPC Pipe Manufacturing

Preliminary pipe extrusion trials were conducted at Engineered Profiles. Four different pipe formulations were successfully extruded (see Table 3) and initial ASTM testing was conducted. Sch.40 1.25" CPC and Charlotte PVC pipes were tested for pressurized and non-pressurized applications in accordance with ASTM D1785 and ASTM D2665, respectively. Table 4 summarizes the key requirements for PVC piping used in pressurized and non-pressurized applications.

Table 3: Schedule 40 1.25" CPC pipes extruded at Engineered Profiles. Note error values for coal content of scaled formulations are ±2 wt.%.

Pipe	Filler type	Coal Content (wt.%)
CPC 8020 P8	Pittsburgh No.8 (P8)	20
CPC 5050 P8		50
CPC 8020 Key	Keystone	20
CPC 5050 Key		50

Table 4: Summary of PVC pipe performance requirements for pressurized and non-pressurized applications

Property	ASTM test method	Requirement
Non-Pressurized Pipe (ASTM D2665)		
TUP (Falling Weight)	D2444	81 Joule
Pipe Stiffness[A]	D2412	9650 kPa
Pressurized Pipe (ASTM D1785)		
Pipe Flattening	D1785	No splitting, cracking, or braking when a pipe is deflected 60% of the outside diameters
Burst Pressure	D1599	8.14 MPa minimum

[A] Measured at 5% deflection

Pipe impact resistance (Tup/ Falling weight) testing was conducted using 12 lb Tup C and holder A. The length of the pipe specimens was 152.4 mm, and twenty specimens were tested from each pipe type. Preliminary results indicated both the CPC and Charlotte PVC pipes failed to meet the 81 Joule impact resistance when tested as per ASTM D2444. Pipe stiffness for the pipe specimens was determined as per ASTM D2412. Specimens were 152.4 mm long and tests were conducted at a constant rate of 12.5 mm/min. The pipe stiffness values (Figure 8) for the 20 wt.% CPC pipes were in the same range and lower than both the ASTM requirements and commercial PVC pipes. Furthermore, increasing the coal content to 50 wt.% have shown to substantially decrease the pipe stiffness, while the 50% keystone possessed slightly higher stiffness values. Flattening tests were conducted on 76.2 mm long pipe samples and samples were pressed until the gap between parallel plates is 40 % of the outside diameter of the pipe. Preliminary results showed CPC pipes failed to meet the pipe flattening requirement and cracked before being deflected by 60 wt.% of the outside diameter. On the other hand, the Charlotte PVC pipe passed the flattening test.

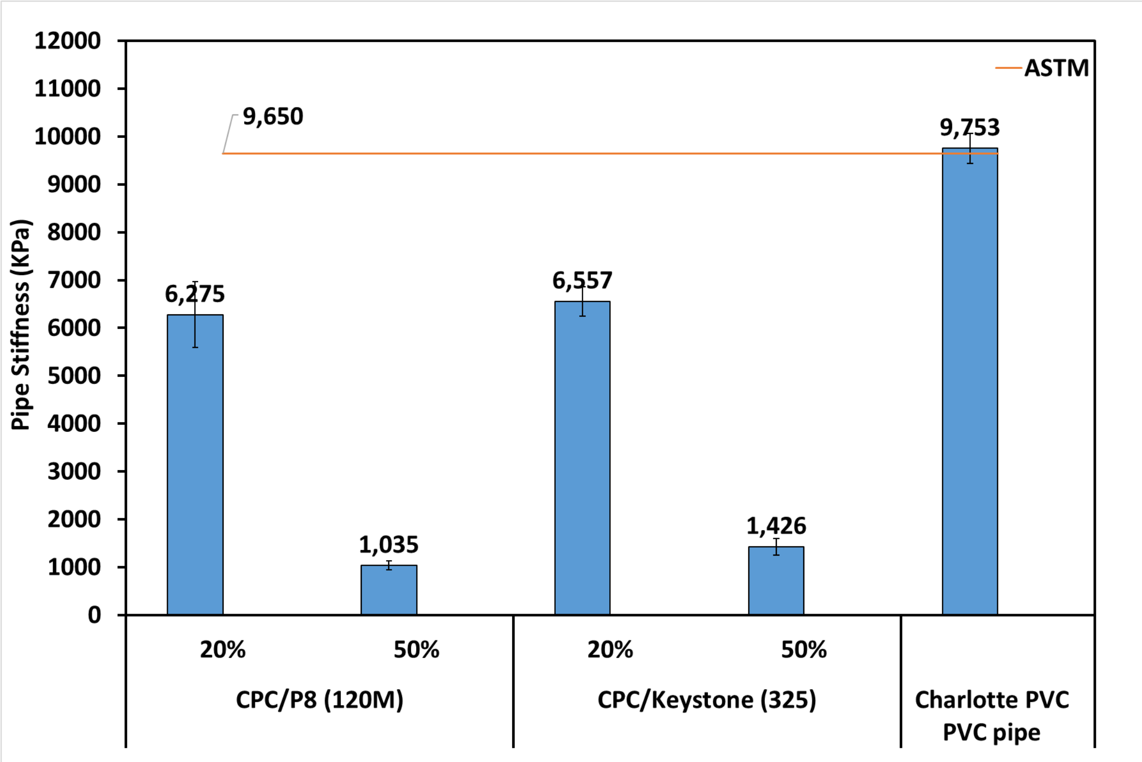


Figure 8: Pipe stiffness values for CPC pipes in comparison to Charlotte PVC pipe and ASTM requirement.

As for the burst pressure testing, the test setup was built, and CPC and PVC pipe were tested in accordance with ASTM D1599. According to ASTM D1785, the minimum burst pressure for Sch.40 1.25" pipe is 8.14 MPa. Results indicated the commercial PVC pipe (Sch.40 1.25" Charlotte) passed the ASTM requirement, whereas all types of CPC pipes failed below the minimum burst pressure. CPC pipe with 20 wt.% and 50 wt.% P8 failed at 6.35 MPa and 1.74 MPa, respectively. As for keystone pipe formulations, the 20 wt.% pipe failed at 5.76 MPa, while the 50 wt.% failed at 2.38 MPa. Figure 9 shows representative CPC pipe samples after burst pressure testing.

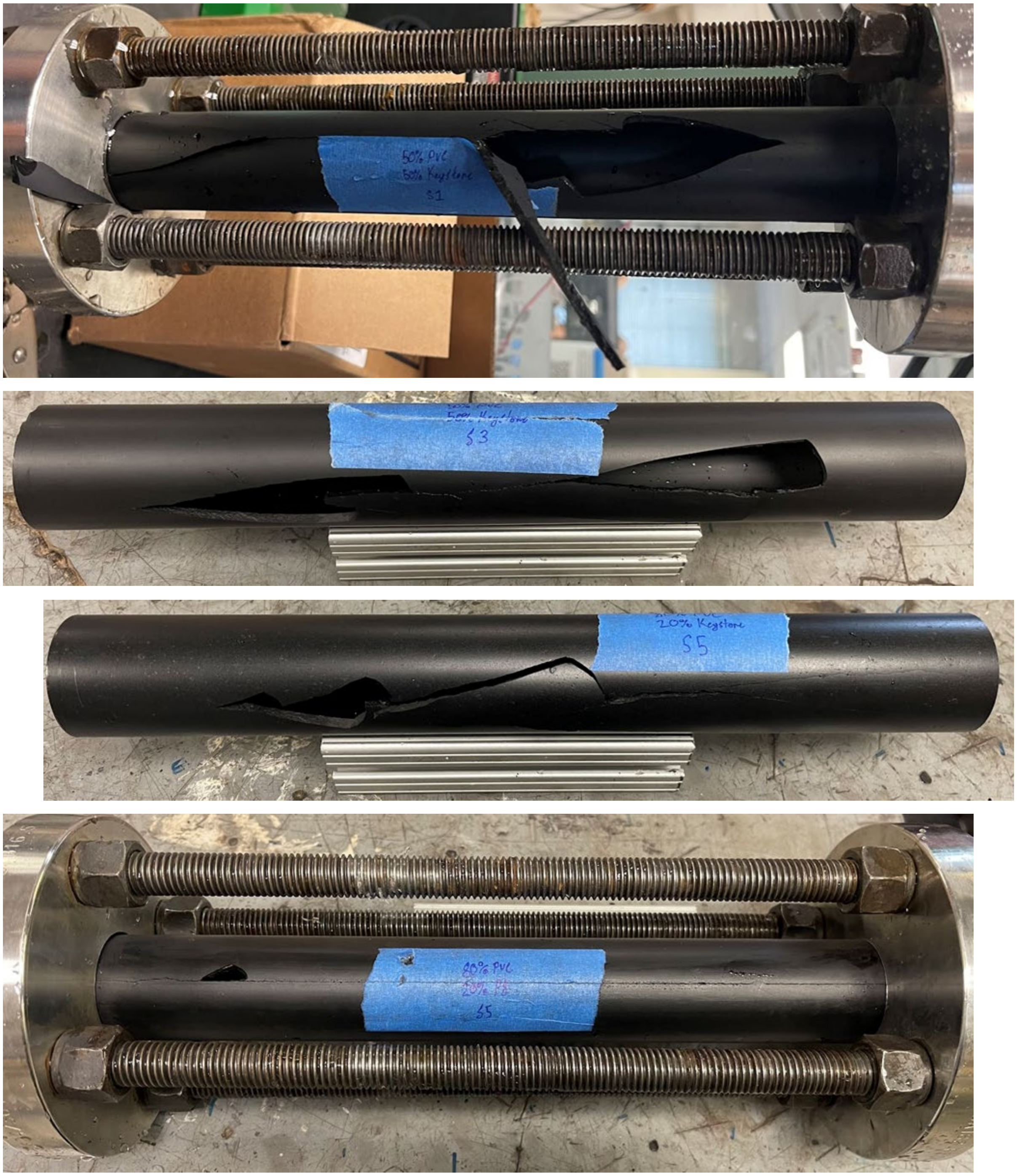


Figure 9: CPC pipe samples after burst pressure testing

Coal plastic composite (CPC) pipe extruded by Engineered Profiles during Phase I of the project was evaluated for compliance with commercial pipe fittings and glues. The CPC pipes were polyvinyl chloride (PVC) based, and the pipes were extruded as 1.25-inch schedule 40 pipes. The CPC pipes were compared to the commercially available 1.25-inch schedule 40 Charlotte Pipe [17]. All pipes were glued to Homewerks PVC elbows and couplers [18].

The CPC and commercial pipes were cut into six-inch sections before being deburred and wiped clean. Oatey purple primer was applied to the fittings and pipes [19]. Next, Oatey RAIN-R-SHINE PVC glue was applied to the fittings and pipes, and the fittings were pressed onto the pipe sections [19]. The PVC glue was allowed to dry, and the pipe sections were visually inspected.

Figure 10 shows the CPC and Charlotte pipes glued to a 90° elbow, and Figure 11 shows the CPC and Charlotte pipes glued together with a coupler. Throughout the cutting and gluing process, the CPC pipe exhibited the same behavior as the commercial PVC pipe. The PVC glue created an adequate bond between the commercial fittings and the CPC pipes, and the CPC pipes exhibited tight fitment with the commercial fittings. After drying, the glued joints showed qualitative torsional and bending strength comparable to that of the glued joint with the commercial pipe.

Figure 10: Commercial PVC elbows were glued onto the CPC pipes.

Figure 11: The CPC pipes glued together with a commercial coupler.

3.1. PE-based Pipe Formulations: Physical and Mechanical Properties

Polyethylene (PE) based piping is utilized in numerous commercial and industrial applications including water and natural gas distribution lines, chemical transport, sewer lines, and drainage applications [20], [21]. The PE-based pipes exhibit high toughness, feasible installation, and excellent chemical stability. For pipe and fitting applications, PE materials must adhere to the PE cell classification of 233424B from

ASTM D3350 which specifies the acceptable density, melt index, flexural modulus, tensile strength at yield, and the slow crack growth resistance of the material [22].

High-density polyethylene (HDPE) material was compounded with Pittsburgh No. 8 (P8 120M) coal sieved below 125 microns. The pipe composite material was processed under vacuum via a vented twin screw extruder. The composite pellets were compression molded into sheets of material that were water jet cut into ASTM D790 flexural samples and ASTM D638 tensile samples [23], [24]. Figure 12 shows the tensile strengths at yield for the HDPE-coal composites. The composite formulations meet the minimum bound for the tensile strength of the cell classification of 21.0 MPa. The tensile strengths of the composites remain relatively constant with the increase in coal content after the initial reduction in strength from the neat plastic. The composite pipe compounds meet the ASTM requirements for tensile strength.

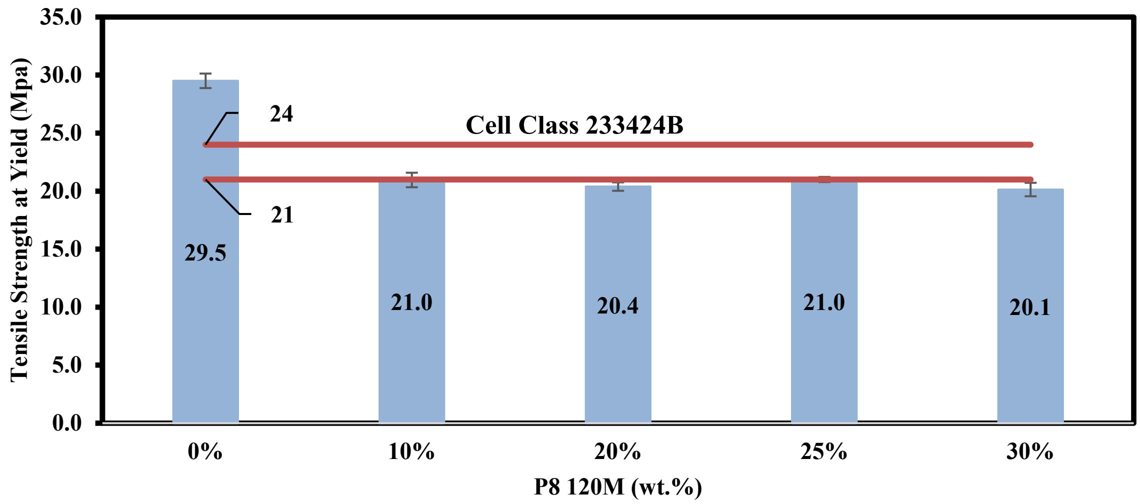


Figure 12: The tensile strength at yield of the HDPE pipe composites.

Figure 13 shows the flexural moduli of the HDPE composites. The flexural moduli of the material increase with an increase in coal content. All flexural moduli of the materials exceed the allowable limit of the ASTM cell classification. A base HDPE resin with lower stiffness would be needed to develop coal-plastic composites with flexural moduli between the allowable bounds of 276 MPa to 552 MPa.

The melt flow rate (MFR) for the HDPE-based formulations was determined using Dynisco Melt Indexer as per ASTM D1238. Average MFR for 10 wt.%, 20 wt.%, 25 wt.%, and 30 wt.% CPC formulations were 1.66, 1.07, 1.17, and 0.931 g/10 min, respectively. These values were higher than the cell classification requirement for MFR of 0.4-0.15 g/10 min.

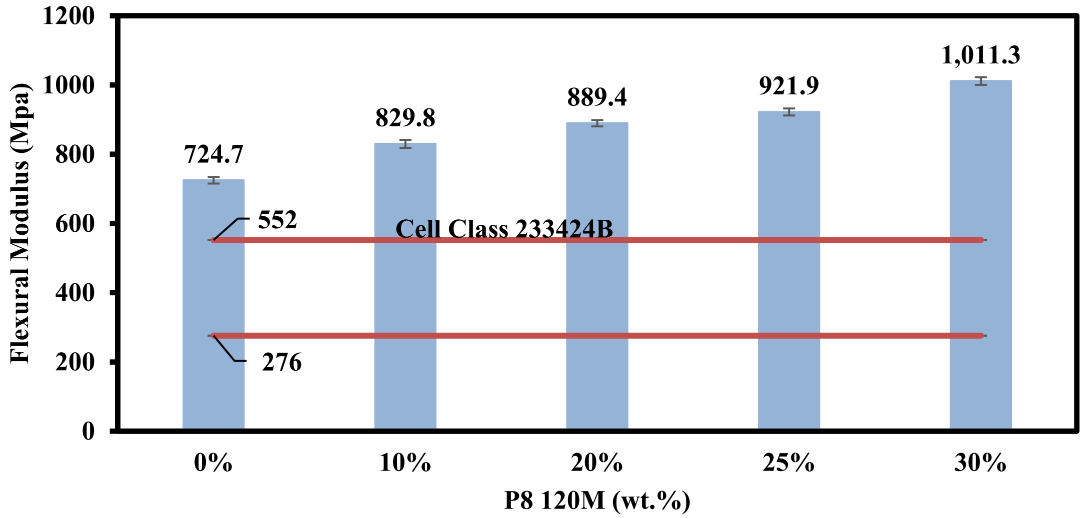


Figure 13: The flexural moduli of the HDPE pipe composites.

4. Techno-economic Analyses

4.1. Overview

Techno-economic analyses were conducted based on an nth plant comparison between a coal piping composite plant and a PVC pipe plant using the base assumptions listed below for the plant:

1. 25,000 lb/hr of composite product generated based on the formulations in Table 5.
2. Plant operates for 24 hours per day for 50 weeks per year, with an assumed uptime of 85%
3. Taxes and Insurance are both calculated at 2% of the Capital Cost.
4. The formulations below provide a CPC and PVC densities of 85.5 and 89.3 lb/ft^3, respectively with a cross-sectional area of 0.0219 ft^2 as calculated for a 4-inch nominal internal diameter pipe.
5. The composite manufacturers selling price yields an internal rate of return (IRR) of 30%, based on a capital cost spread over two years and profits recovered over 20 years.

Table 5. Composition by mass percent for the CPCs and PVCs

Component	CPC	PVC
Coal Filler	20%	0%
PVC Masterbatch	80%	91%
Calcium Carbonate Filler	0%	9%

The block flow diagram below (Figure 14) was developed in conversations with Engineering Profiles and illustrates the components and unit operations required for the coal or PVC pipe plant. The coal filler material is received via truck and dried to 1% moisture prior to blending with the polymer masterbatch. On the other hand, the inorganic $CaCO_3$ requires only storage as a capital cost. The components are blended together and conveyed to the extruder. The extruder manufactures pipes which are cut to the desired length and then stored in the warehouse prior to sales. To reduce the environmental impact of the plant, the CPC or PVC dust from cutting the pipes to the desired length or off specification boards is reclaimed. Water is used to cool the warm decking boards and treated prior to recycle.

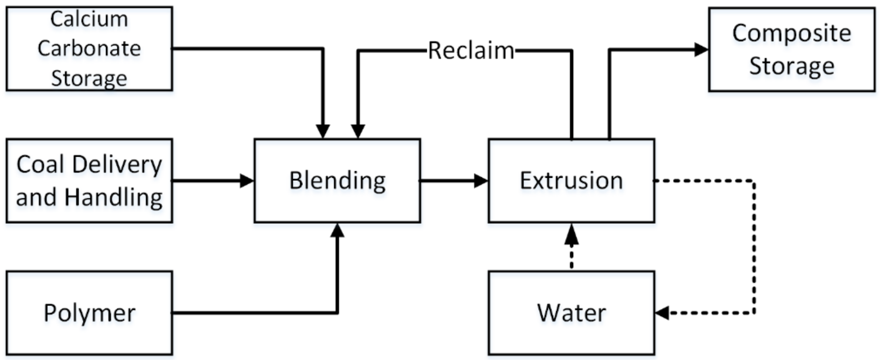


Figure 14. Block flow diagram for a proposed coal piping composite manufacturing plant including the block for calcium carbonate found in a typical piping plant.

Using the base assumptions, the overall capital (includes 15% contingency) and operational costs of the new CPC plant in comparison to a typical new PVC plant is provided in Table 6 and shows that the differences between the equipment costs (also reflected in the taxes and insurance) are mainly due to coal handling equipment. Conversely, the differences between the cost of chemicals is due to the comparative costs of fillers and the PVC polymer consumed in the processes. The calcium carbonate costs are expected to be and the price (~$200 per ton received) is not expected to change to compete with coal prices (~$60 per ton received).

Table 6. Comparative cost analyses for a proposed composite plant based on using either coal (CPC) or calcium carbonate (PVC) as filler and using the base assumptions previously listed.

Cost	Comments	CPC	PVC
Capital Cost	*Equipment*	$41,097,000	$33,407,000
	Building and Land	$11,434,803	
Fixed OPEX	*Labor*	$17,330,000	$17,050,000
	Maintenance and Warranty	$5,450,000	
	Taxes and Insurance	$2,101,272	$1,793,672
Variable OPEX	*Utilities*	$1,777,156	$1,710,240
	Chemicals	$172,505,455	$196,367,850
	Freight and Packaging	$3,844,531	
Production Cost ($/lb)	*Excludes Capital Cost and intermediary markup*	$1.14	$1.27
Production Cost ($/ft)		$2.13	$2.48

These production costs show a 10% (mass basis) and 14% (length basis) cost advantage for the CPC plant in comparison with the PVC plant based on fixed and variable costs alone.

For a comparison to current retail pricing, an IRR calculation was used to obtain an expected product sales price FOB manufacturing location. These values are provided in Table 7.

Table 7. Sales prices (in $/ft) expected for the CPC and the WPC at the manufacturer and the retailer

Price Basis	**Price ($/ft)**	
	CPC	**WPC**
30% IRR (FOB manufacturer site)	$2.32	$2.65

This base techno-economic analyses demonstrates the economic viability of the CPC based on a side-by-side comparison to a current market product. Further sensitivity analyses will be conducted to account for expected variability in process and market conditions including chemicals costs, changes in CPC or WPC formulation, transportation costs, labor costs, maintenance labor and materials cost, etc. Furthermore, comparisons will be made to actual market products to put the sales prices provided in Table 3 within context.

4.2. Technology Gap Analysis

The project-matured CPC piping to TRL 5 as the ability to manufacture pipe using a commercial extrusion system was demonstrated. CPC pipe made using commercial equipment was shown to tentatively meet AST D2729 requirements for sewer and drain pipe applications, indicating commercial viability of the material. Techno-economic analyses also indicate CPC piping potentially offer cost savings in comparison to current PVC piping.

This project provides an ideal foundation for further development of CPC pipe manufacturing. Further development of CPC piping will require optimization of compound formulations to better suit a wide variety of applications. The team recommends the next stage of development utilize a continuous manufacturing system that will allow the production of 4-inch schedule 40 piping. Extensive independent testing of continuously manufactured pipe is also recommended to validate the piping meets all ASTM specifications. In addition, additional tests to assess potential for leaching from the pipe under sewer and drainage applications should be investigated. Finally, existing techno-economic analyses should be updated with pilot-scale material and energy balances to further refine manufacturing costs and price competitiveness. The project team estimates the costs associated with the next stage of development will require an investment of $700 thousand. If successful, the next stage of development would mature the technology to TRL 8.

4.3. Summary

This project developed and studied CPC materials for piping applications. Results from the project were successful in demonstrating PVC-based CPC formulations were able to meet ASTM D1784 class 12454 requirements. CPC formulas containing 10 wt.% coal exceeded class 12454 specifications, while formulas containing 20 and 30 wt.% coal exceeded all 12454 specifications, except for impact resistance, further R&D is recommended to modify CPC formulations to increase impact resistance. TEA studies also indicate CPC-based piping materials may potentially offer consumers savings over existing PVC-based piping materials.

5. References

[1] "ASTM D1784 −20:Standard Classification System and Basis for Specification for Rigid Poly(Vinyl Chloride) (PVC) Compounds and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds." ASTM.

[2] "ASTM D2665: Standard Specification for Poly(Vinyl Chloride) (PVC) Plastic Drain, Waste, and Vent Pipe and Fittings." ASTM.

[3] "ASTM D1785−15: Standard Specification for Poly(VinylChloride) (PVC) Plastic Pipe, Schedules 40, 80, and 120." ASTM.

[4] S. Vyazovkin *et al.*, "ICTAC Kinetics Committee recommendations for analysis of multi-step kinetics," *Thermochimica Acta*, vol. 689, p. 178597, Jul. 2020, doi: 10.1016/j.tca.2020.178597.

[5] S. Vyazovkin *et al.*, "ICTAC Kinetics Committee recommendations for collecting experimental thermal analysis data for kinetic computations," *Thermochimica Acta*, vol. 590, pp. 1–23, Aug. 2014, doi: 10.1016/j.tca.2014.05.036.

[6] S. Vyazovkin and C. A. Wight, "Model-free and model-fitting approaches to kinetic analysis of isothermal and nonisothermal data," *Thermochimica Acta*, vol. 340, pp. 53–68, 1999.

[7] S. Vyazovkin and C. A. Wight, "Estimating Realistic Confidence Intervals for the Activation Energy Determined from Thermoanalytical Measurements," *Anal. Chem.*, vol. 72, no. 14, pp. 3171–3175, Jul. 2000, doi: 10.1021/ac000210u.

[8] P. Budrugeac, "Estimating errors in the determination of activation energy by advanced nonlinear isoconversional method applied for thermoanalytical measurements performed under arbitrary temperature programs," *Thermochimica Acta*, vol. 684, p. 178507, Feb. 2020, doi: 10.1016/j.tca.2019.178507.

[9] "ASTM D256-10: Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics." ASTM.

[10] N. Petchwattana and S. Covavisaruch, "Effects of rice hull particle size and content on the mechanical properties and visual appearance of wood plastic composites prepared from poly(vinyl chloride)," *J Bionic Eng*, vol. 10, no. 1, pp. 110–117, Mar. 2013, doi: 10.1016/S1672-6529(13)60205-X.

[11] A. Nourbakhsh, A. Karegarfard, A. Ashori, and A. Nourbakhsh, "Effects of Particle Size and Coupling Agent Concentration on Mechanical Properties of Particulate-filled Polymer Composites," *Journal of Thermoplastic Composite Materials*, vol. 23, no. 2, pp. 169–174, Mar. 2010, doi: 10.1177/0892705709340962.

[12] S.-Y. Fu, X.-Q. Feng, B. Lauke, and Y.-W. Mai, "Effects of particle size, particle/matrix interface adhesion and particle loading on mechanical properties of particulate–polymer composites," *Composites Part B: Engineering*, vol. 39, no. 6, pp. 933–961, Sep. 2008, doi: 10.1016/j.compositesb.2008.01.002.

[13] S. Rimdusit, N. Kampangsaeree, W. Tanthapanichakoon, T. Takeichi, and N. Suppakarn, "Development of wood-substituted composites from highly filled polybenzoxazine–phenolic novolac alloys," *Polym. Eng. Sci.*, vol. 47, no. 2, pp. 140–149, Feb. 2007, doi: 10.1002/pen.20683.

[14] T. Ratanawilai and K. Taneerat, "Alternative polymeric matrices for wood-plastic composites: Effects on mechanical properties and resistance to natural weathering," *Construction and Building Materials*, vol. 172, pp. 349–357, May 2018, doi: 10.1016/j.conbuildmat.2018.03.266.

[15] S. Sengupta, D. Ray, and A. Mukhopadhyay, "Sustainable Materials: Value-Added Composites from Recycled Polypropylene and Fly Ash Using a Green Coupling Agent," *ACS Sustainable Chemistry & Engineering*, vol. 1, no. 6, pp. 574–584, Jun. 2013, doi: 10.1021/sc3000948.

[16] "ASTM D648-16:Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position." ASTM.

[17] "Charlotte Pipe 1-1/4-in 5-ft 370 Psi Schedule 40 White PVC Pipe Lowes.com," *Lowe's*. https://www.lowes.com/pd/Charlotte-Pipe-1-1-4-in-dia-x-5-ft-L-370-PSI-PVC-Pipe/3133099 (accessed Dec. 19, 2022).

[18] "Homewerks 1-1/4-in x 1-1/4-in 480 Psi Coupling PVC Coupling Lowes.com," *Lowe's*. https://www.lowes.com/pd/Homewerks-1-1-4-in-SOLVENT-x-1-1-4-in-SOLVENT-Schedule-40-PVC-Coupling/5013090679 (accessed Dec. 19, 2022).
[19] "Oatey Handy Pack 8-fl oz Purple and Blue PVC Cement and Primer Lowes.com," *Lowe's*. https://www.lowes.com/pd/Oatey-Rain-R-Shine-8-fl-oz-PVC-Cement/1000422527 (accessed Dec. 19, 2022).
[20] "PE (Polyethylene) Plastic Pipe | PPFA." https://www.ppfahome.org/page/pe (accessed Jan. 18, 2023).
[21] "Industrial Applications." https://www.plasticpipe.org/MunicipalIndustrial/Municipal_Industrial/Applications/Industrial-Applications.aspx (accessed Jan. 18, 2023).
[22] ASTM, "ASTM D3350 Standard Specification for Polyethylene Plastics Pipe and Fittings Materials." 2014.
[23] ASTM, "ASTM D790 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials." ASTM, 2010.
[24] ASTM, "ASTM D638 Standard Test Method for Tensile Properties of Plastics." ASTM, 2014.