Direct Utilization of U.S. Coal as Feedstock for the Manufacture of High-Value Coal Plastic Composites

Final Technical Report

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Abstract

This report examines the development and use of coal-plastic composite (CPC) materials for use in building applications. CPC formulations were developed at bench scale and evaluated for decking applications. CPC decking boards were designed, manufactured, and evaluated. Techno-economic and lifecycle analyses for CPC decking are also reported.

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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 decking applications.

1.1. Composite Decking

The wood-plastic composite (WPC) market is significant, with a global value of $6.42 billion in 2021. The largest WPC market segments include building and construction (65%), automotive (18%), and electrical (8%) with the remainder associated with miscellaneous applications [1]. Tremendous growth in global WPC materials production is expected with an 11.5% compound annual growth rate (CAGR) through 2030. The growing demand and markets for WPCs provides an ideal opportunity for CPCs to enter and expand into this market without having to initially displace existing WPC production. Considering the significantly lower feedstock raw material costs and potential property advantages of CPCs in comparison to WPCs, it is reasonable to assume that CPC materials will be able to capture a portion, if not a substantial share, of new composite market growth.

The CPC manufacturing process consists of intimately mixing fine coal with high density polyethylene (HDPE) or other thermoplastic resins plus additional additives to enhance processing and product properties. A schematic of the CPC decking manufacturing process including energy and mass balances is provided in Figure 1. As received coal is pulverized and then fed along with HDPE and additives into a continuous extrusion process. This mixture is extruded into a substrate (or other profiles) along with a capstock to form the board product. The final product is cooled before being cut to various lengths (8 to 20 ft) and bundled for sale.

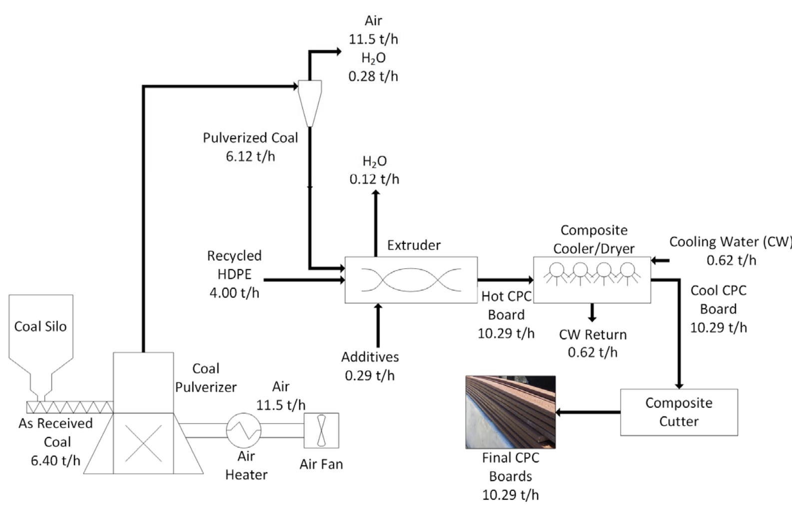

Figure 1: CPC manufacturing process flow diagram with mass balances.

Emphasis in this proposed project will focus on development of CPC extrusion including composite formulation and extrusion manufacturing. It is envisioned that integration of the CPC manufacturing

process into the coal value chain will be best suited at the mine mouth, as this will eliminate the need for coal transport, minimizing CPC manufacturing costs. Integration with a coal preparation plant is optimal. The fine coal product streams already produced at such preparation plants could serve as ideal feedstock, potentially yielding greater composite flexure strength than currently available in commercial composite decking boards. Otherwise, addition of a coal crushing step will allow CPC manufacturing at the mine mouth or at other coal handling facilities.

1.2. Project Objectives

The objective of this project is to develop a CPC decking product which possesses lower manufacturing costs than current commercial WPC decking and meets all applicable ASTM and International Building Code (IBC) performance specifications. The objectives for Phase 1 are to demonstrate that continuously manufactured CPC boards meet or exceed ASTM and IBC specifications for decking applications and possess lower manufacturing costs than existing composite materials, and to identify additional promising applications for CPC materials. Phase 2 objectives include demonstrating performance of CPC boards in the field, assessing CPC formulations for additional promising commercial applications, developing a marketing plan for CPC applications, and identifying installation methodologies to be used when installing CPC materials so that applicable environmental health and safety considerations are satisfied.

2. CPC Development

2.1. CPC Substrate Formulation

2.1.1. Coal Proximate/Ultimate Analyses

Both eastern bituminous and western sub-bituminous coal types were evaluated in this study. Pittsburgh No.8 (P8) and Powder River Basin (PRB) coals were used in the studies. Pulverized coal samples were obtained for each type of coal. Proximate and ultimate analyses for the coals are provided in Table 1.

Table 1. Proximate and ultimate analyses for P8 and PRB coals.

Component	P8	PRB
Heating Value [kJ/kg]	32,259	8,770
Proximate Analyses [wt.%]		
Moisture	6.30	23.4
Volatile Matter	37.30	33.8
Fixed Carbon	49.01	37.3
Ash	7.39	5.5
Ultimate Analyses [wt.%]		
C	76.46	67.5
H	5.16	4.7
N	1.53	1.2
Cl	0.09	0.0
S	2.55	0.3
Ash	7.89	7.2
O	6.32	19.1

2.1.2. Solid State Nuclear Magnetic Resonance (NMR) Spectroscopy of Coals

Cross polarization (CP)/Magic angle spinning (MAS) ^{13}C solid-state NMR measurements were performed on P8 high volatile bituminous coal and PRB sub-bituminous coal. ^{13}C solid state NMR spectra of P8 and PRB coals are shown in Figure 2 a b (solid red lines), respectively. The broad peaks at a peak position of ~250 ppm in both the spectra are called the spinning side bands (SSB) which arise due to incomplete averaging of anisotropic interactions during the magic spinning process - the intensity and position of the SSB is proportional to spinning rate of the sample[2]. The NMR spectra of both the coals exhibit two discernible broad peaks representing a distribution of various aromatic, aliphatic, and oxygenated carbon moieties. Quantitation of carbon moieties was performed by fitting a combination of Lorentzian-Gaussian (L/G = 0 to 1) peaks to the convoluted spectra. The fitting procedure involved a series of iterations based on peak picking, chemical shift position (see Table 2), and half width of each peak; a total of 12-13 peaks were fitted based on the coal sample to deconvolute the spectra. The curve fitting was validated by creating a simulated spectrum with the deconvoluted peaks; Figure 2a and b show superimposed simulated spectra (blue dot-dash lines) which are in good agreement with the measured spectra of P8 and PRB coals, respectively. The peak position of each of the deconvoluted peaks, barring the SSB, is representative of a carbon functional group type, whereas the peak area is proportional to the concentration of the carbon functional group type. The concentration of a carbon functional group is quantified by the ratio of peak area of a given carbon functional group type to the total area of the spectrum; Figure 3 represents and compares the concentrations of carbon functional group types in P8 and PRB coals in terms of percentages.

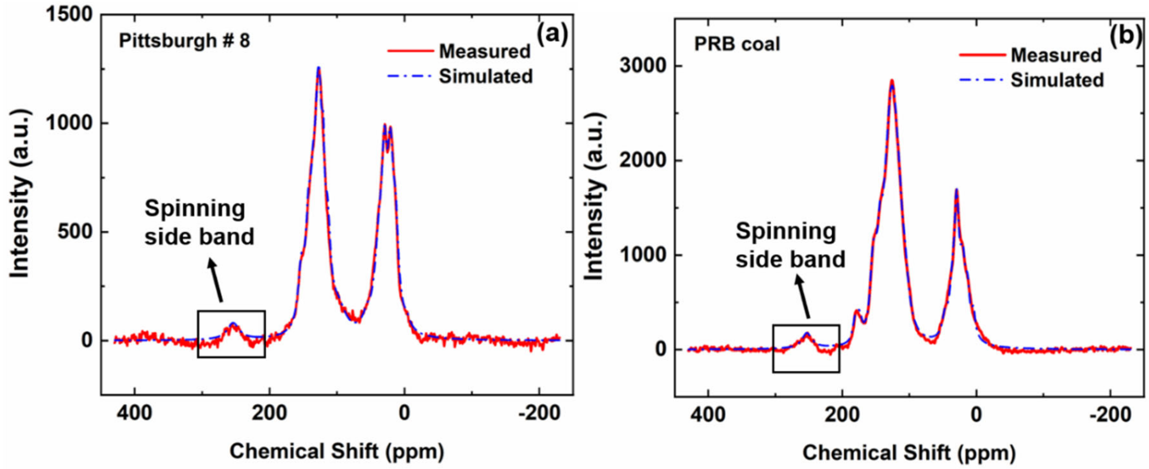

Figure 2. **^{13}C solid state NMR spectrum of (a) P8 and (b) PRB coal**

The major difference between the two types of coals is the abundance of aromatic bridge head type carbon in PRB coal when compared to P8. Aromatic bridge head carbons are atoms that are part of two or more rings in a polycyclic aromatic such as in naphthalene. In addition, PRB coal is significantly more aromatic than P8, and vice versa, in case of aliphatic carbon distributions. The percentage of aromatic bridge carbons in P8 coal from the present study (26 %) is also in good agreement with previous quantitation studies on P8 (27 %)[3]–[5]; however, the percentages of other carbon functional groups when compared differ slightly. Similar disagreements are also found in case of PRB coal, where the aromatic and aliphatic carbon percentages differ significantly from the values reported in a study on by Xu *et al.*[6]. The disagreement in the percentage carbon group distributions may be attributed to the difference in test and sample conditions.

Table 2. **Peak Assignments.**

	Chemical Shift* (ppm)	
Peak Type	**Pittsburgh #8**	**Powder River Basin Coal**
Carboxylic acids	NA	178
Oxygen bearing aromatic carbon	153	154
Alkylated aromatic carbons	143, 137	144, 137
Aromatic and bridge head carbons	128, 121,115	126, 118, 108
Oxygen bearing aliphatics	98	89
Methylene	57, 38, 30	48,36
Methyl carbons with aromatics	22	25
Terminal methyl carbons in longer side chains	14	14
Spinning side bands (SSB)	250, -3	251, -6.5

* reported chemical shifts are peak positions of deconvoluted peaks

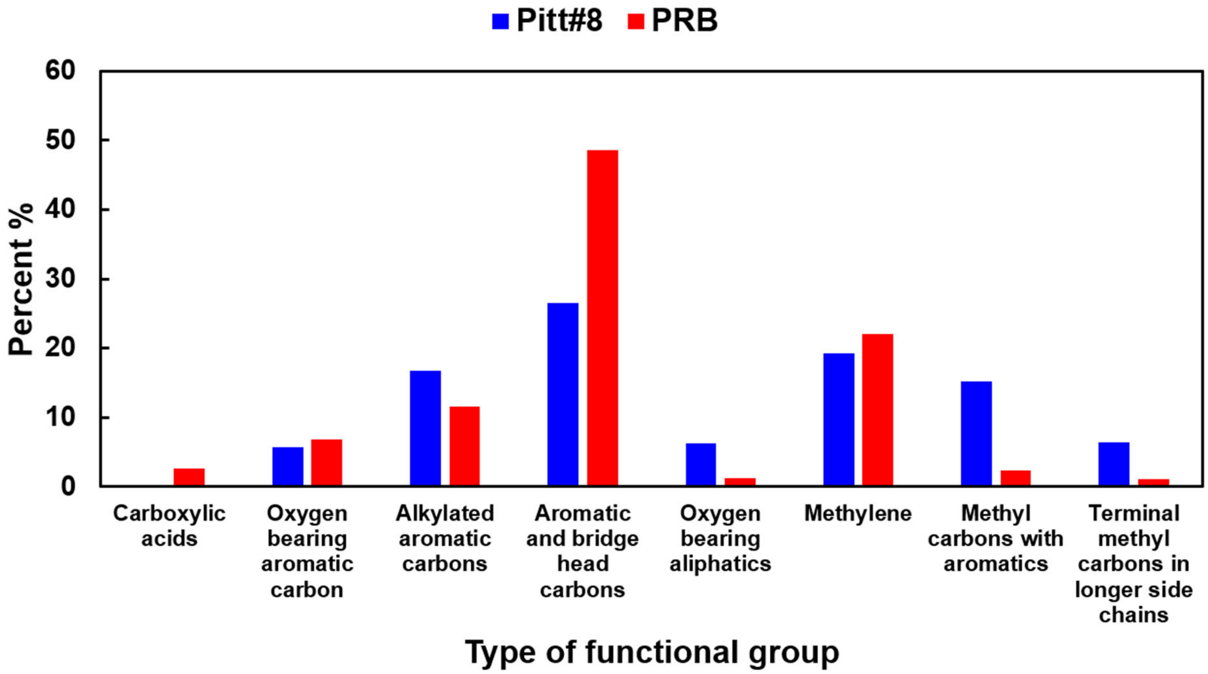

Figure 3. Carbon distributions of Pi8 and PRB coals.

2.1.3. Flexure Results

Flexural properties of CPC material and commercially available WPC products were determined at the lab-scale. CPC formulations with two types of coal including P8 and PRB coal and coal content ranging from 40-60 wt.% were investigated. Flexural testing was conducted as per ASTM D790. Figure 4 shows the flexural strength and flexural modulus of CPC in comparison to WPC products. Results indicated that increasing the coal content simultaneously increased both the flexural strength and flexural modulus, except for flexural strength of CPC/PRB with 60 wt.% coal. At high filler content (e.g. 60 wt.%), flexural strength of CPC/P8 was higher than CPC/PRB whereas the flexural modulus values of both formulations were comparable, 1.9 GPa for CPC/P8 versus 2.0 GPa for CPC/PRB. In comparison to WPC products, flexural strength of CPC/ P8 with 60 wt.% coal content was higher than all WPC products, while its flexural modulus was similar to TimberTech and Choicedeck WPCs and lower than Trex, Veranda, and FiberOn WPC products. Flexural properties were used to estimate load and deflections for a full-scale board with a width of 5.5 in. and 1 in. thickness. Table 3 shows that all CPC formulations with 40-60 wt.% P8 coal exceeds the International Building Code (IBC) requirements for deck board/stair tread.

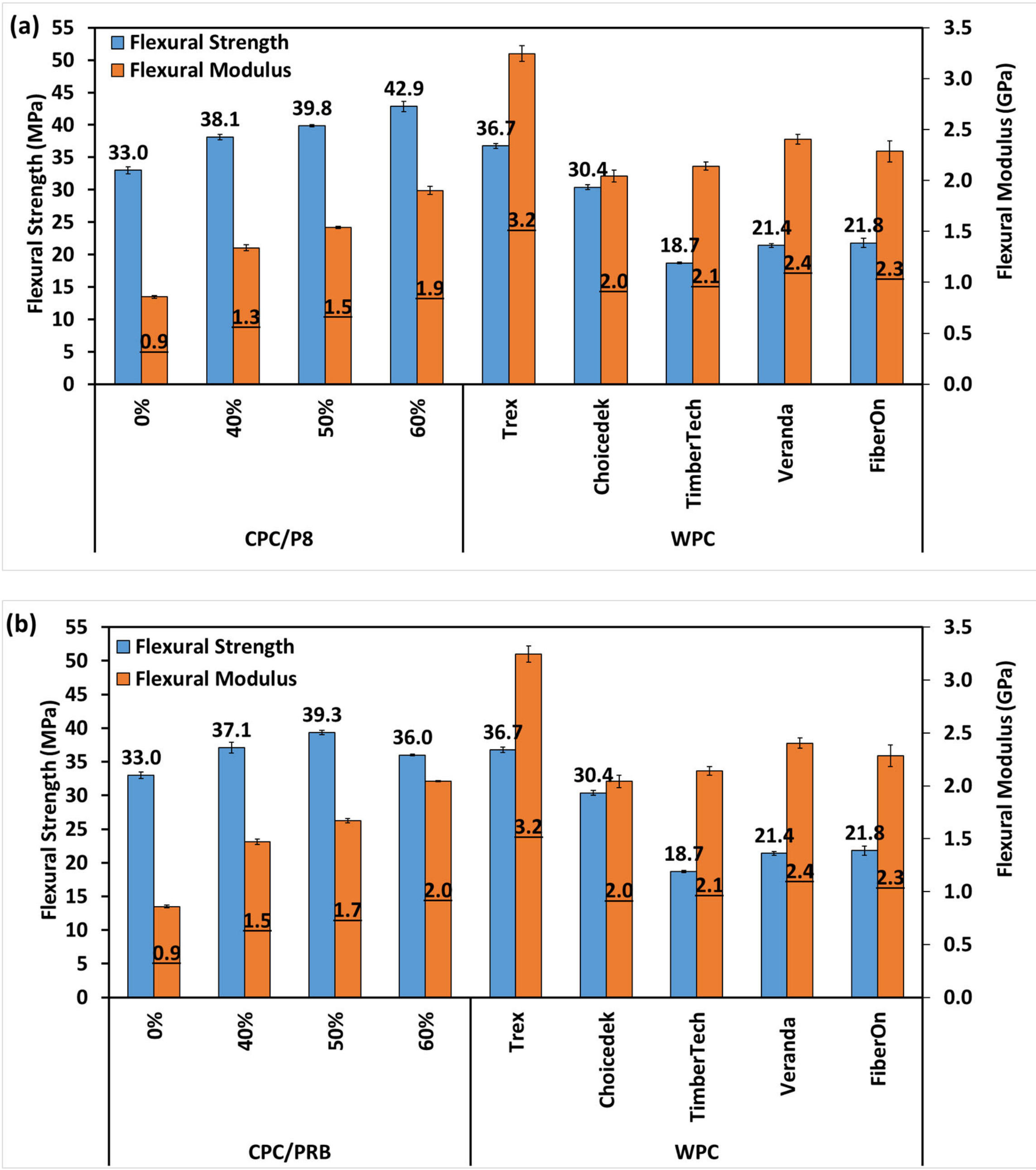

Figure 4:Flexural strength (blue) and flexural modulus (orange) for (a) CPC with 40-60 wt.% P8 coal and (b) CPC with 40-60 wt.% PRB coal in comparison to WPC products. Tests were conducted as per ASTM D790 and error bars are standard error.

Table 3: Decking (D_{Deck})/stair tread (D_{stair}) deflections and distributed load (W) for CPCs and commercial composite decking based upon IBC code.

Material	D_{Floor} (in)	D_{Stair} (in)	W (lbs/ft^2)
CPC/40 % P8	0.038	0.084	4144
CPC/50 % P8	0.033	0.073	4329
CPC/60 % P8	0.026	0.057	4677
Trex	0.015	0.034	3992
ChoiceDek	0.025	0.054	3307
TimberTech	0.023	0.052	2034
Veranda	0.02	0.045	2328
Fiberon	0.021	0.047	2371
IBC Spec	0.044	0.125	250

Board Dimensions: Width: 5.5 in; Height: 1 in
Deck/Stair Joist Spacing: 16 in/10.5 in

2.1.4. OIT

Thermo-oxidative stability of CPC material was assessed using differential scanning calorimetry (DSC). Oxidation induction time (OIT) determined by DSC is a relative measure of material resistance to thermo-oxidative degradation and higher OIT values indicate better degradation resistivity. Hence, longer service life. Figure 5 shows the OIT values of CPC material and WPC products determined in accordance with ASTM D3895. Results showed that OIT values of all CPC formulations were higher than the neat HDPE and OIT values increased proportionally with increasing the coal content from 40-60 wt.%. OIT values of CPC/P8 were much higher than CPC/PRB. Also, OIT value for CPC/P8 with 60 wt.% was higher than all WPC products, but lower than Trex. Note that the high OIT values of Trex WPC might be attributed to the presence of antioxidants in its composition. Activation energies of CPC and WPC were estimated based on Arrhenius model by running multiple OIT tests over a wide range of temperatures (170-200 °C). The activation energies of CPC/P8, CPC/PRB, and WPCs were found to be ranging from 94-112 kJ/mol, 52-135 kJ/mol, and 33-114 kJ/mol, respectively. High OIT values for CPC/P8 with 60 wt.% suggest that this formulation is less likely to degrade under thermoplastic processing conditions, and it will potentially have extended service life.

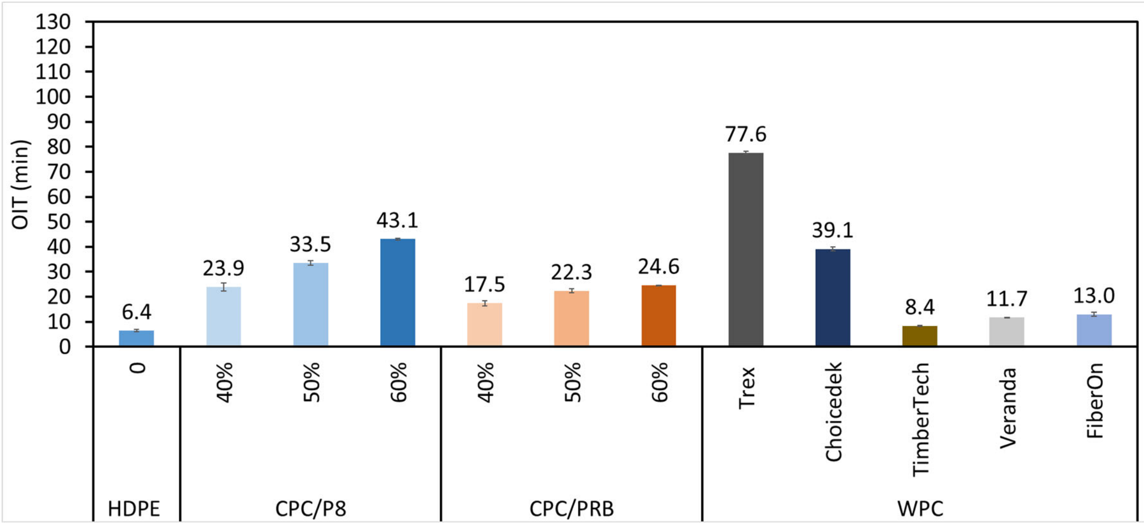

Figure 5: Oxidation induction time of CPC with P8 and PRB coal in comparison to WPC products. Tests were conducted as per ASTM D3895.

2.1.5. SBR

Rate of burning of CPC materials was determined and compared to commercially available WPC products. Tests were conducted as per ASTM D635. In this test, specimens (3.0 mm thick × 13 mm wide × 125 mm long) were ignited from one end while they are supported horizontally, and time and extent of burning were recorded. Rate of burning results (Figure 6) indicated that increasing coal content from 40-60 wt.% has the effect of slowing burning of CPC/P8 and CPC/PRB by 19.9% and 27.6 %, respectively. Results also showed that burning of CPC/P8 with coal content ranging from 40-60 wt.% were slower than all CPC/PRB formulations. Furthermore, burning rates of WPC products were ranging from 30-40 mm/min which was much higher than all CPC formulations investigated.

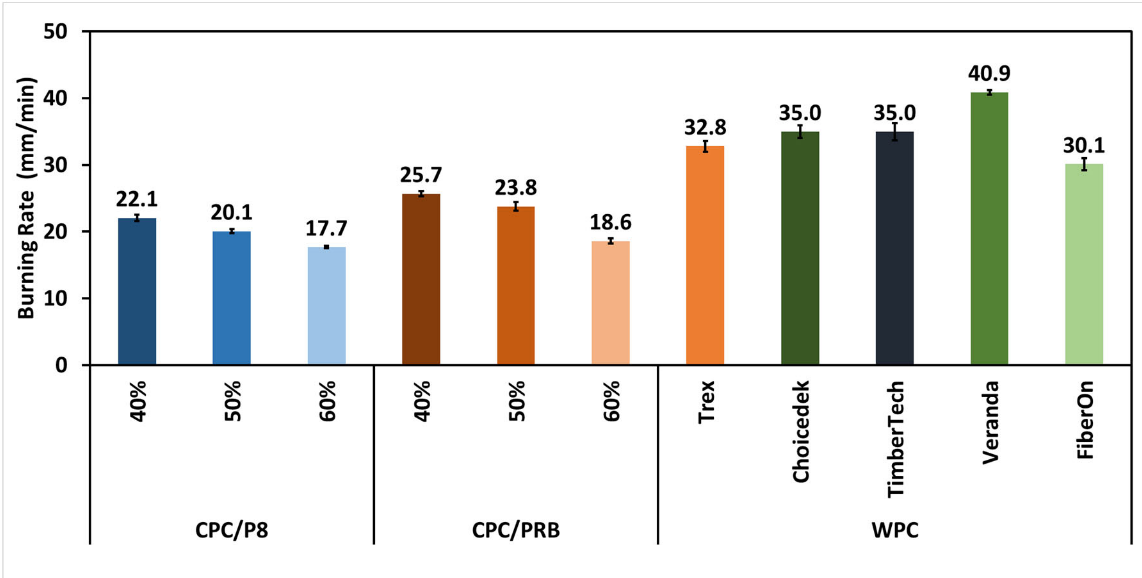

Figure 6: Burning rate of CPCs and WPC products. Tests were conducted as per ASTM D635. Error bars are standard errors.

2.1.6. FIT/SIT

Flash ignition temperature (FIT) is the minimum temperature at which flammable volatiles released from the material ignites with the presence of a pilot flame whereas self-ignition temperature (SIT) is the minimum temperature at which flammable volatiles released from a material ignites without the existence of a pilot flame. Note that materials with higher FIT/SIT will potentially have improved fire resistance and less flame spread. FIT/SIT values of CPC material and WPC products were determined as per ASTM D1929. Figure 7 shows the FIT/SIT values of CPC with 40-60 wt.% coal content in comparison to neat HDPE and WPC products. In comparison to neat HDPE, all CPC formulation possess higher FIT/SIT values, which suggests that the presence of coal improved the fire resistance of the resulting composite. FIT values of CPC/P8 with 40-60 wt.% were the same (390 °C) while the SIT values were ranging from 390-400 °C. On the other hand, FIT/SIT values of CPC/PRB were identical and comparable with CPC/P8. FIT values of WPC products were lower than CPC and ranging from 320-350 °C while SIT values were ranging from 380-410 °C. Current results indicate that CPC material in the presence of flame source is less susceptible to catching fire while at a higher temperature environment both CPC material and WPC products could self-ignite around the same temperature. The delay in the CPC FIT values suggests that coal starts to decompose at higher temperature values in comparison to wood flour in WPCs. Results also indicated that increasing coal content from 40-60 wt.% has minimal impact on both the FIT and the SIT values.

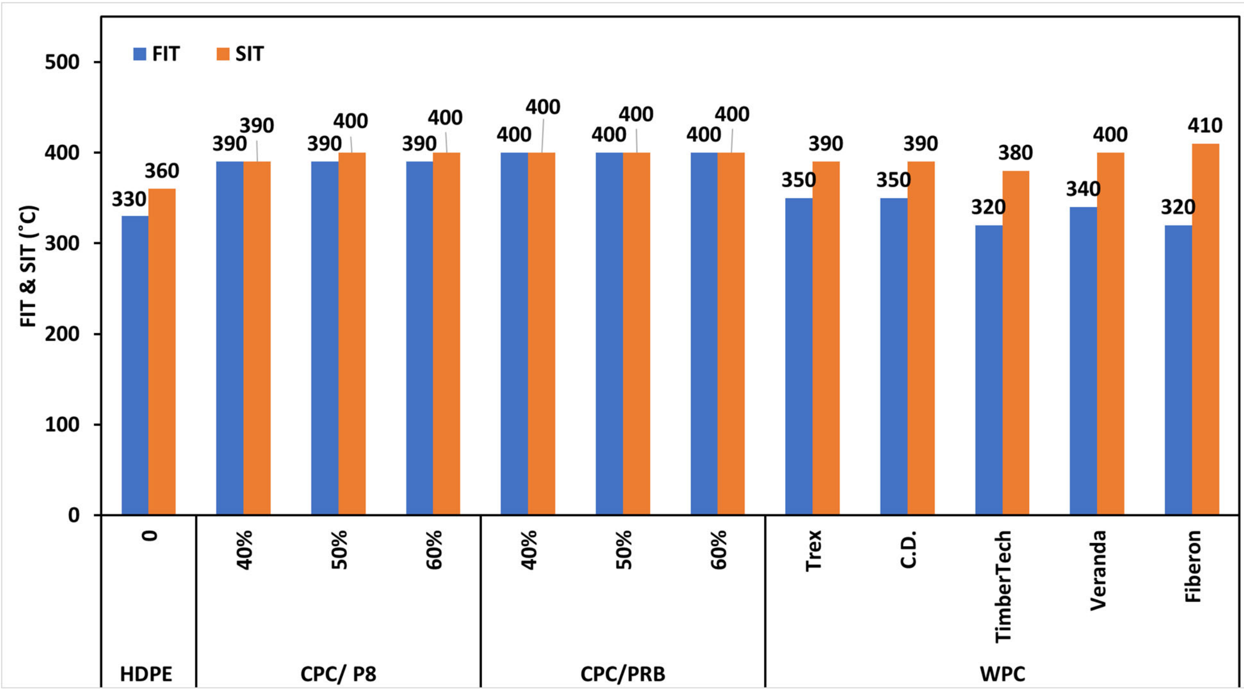

Figure 7: Flash ignition temperature (FIT) and self-ignition temperature (SIT) of CPC and WPC products. Tests were conducted as per ASTM D1929.

2.1.7. Cone Calorimeter Study

Fire properties determined using cone calorimetry provide a comprehensive understanding of material combustibility and indicate material burning behavior in an actual fire [7], [8]. Figure 8 shows a representative heat release rate (HRR) and smoke production rate (SPR) for CPC/40 wt.%, CPC/60 wt.%, Trex WPC product, TimberTech WPC product, and Red Oak. Images of charred samples are shown in Figure 9. Heat release from composite samples (CPC and WPC products) is longer in duration (Figure 8a) in comparison to Red Oak. In addition, the overall HRR for CPC material was lower than WPC products. CPC HRR decrease may be attributed to a more impervious char layer. Trex and TimberTech WPC possessed a wide second HRR peak followed by a big reduction in HRR toward the end of the burning. For CPC formulations, the increase in the HRR after 2000 s might be attributed to delamination of the top layers as evident in char pictures (Figure 9 a-b). The double peak associated with the Red Oak can be attributed to char cracking evident in the post-testing sample pictures (Figure 9e). The double peak HRR for wood was also reported in the literature [8], [9]. Similar to HRR, SPR for wood samples has a double peak, showing most of the smoke was released at the beginning and toward the end of the trials. Lower overall SPR values were recorded for CPC/60 wt.% in comparison to CPC/40 wt.%. It was noted all CPC samples foamed during combustion and rose into the cone area. During burning, CPC's top layer starts to delaminate and form short vertical fibers as shown in Figure 9a. The intumescence behavior of CPC material indicates the flame retardancy role coal plays in the composite material. The thickness of Trex WPC specimens decreased and the final char (Figure 9c) was soft grey powder. For TimberTech WPC, the thickness of the specimens slightly increased while the final char was grey ash on the upper half (Figure 9d). Red Oak wood samples smolder after completion of the test (flameout), and the final char formed black and grey chunks (Figure 9e).

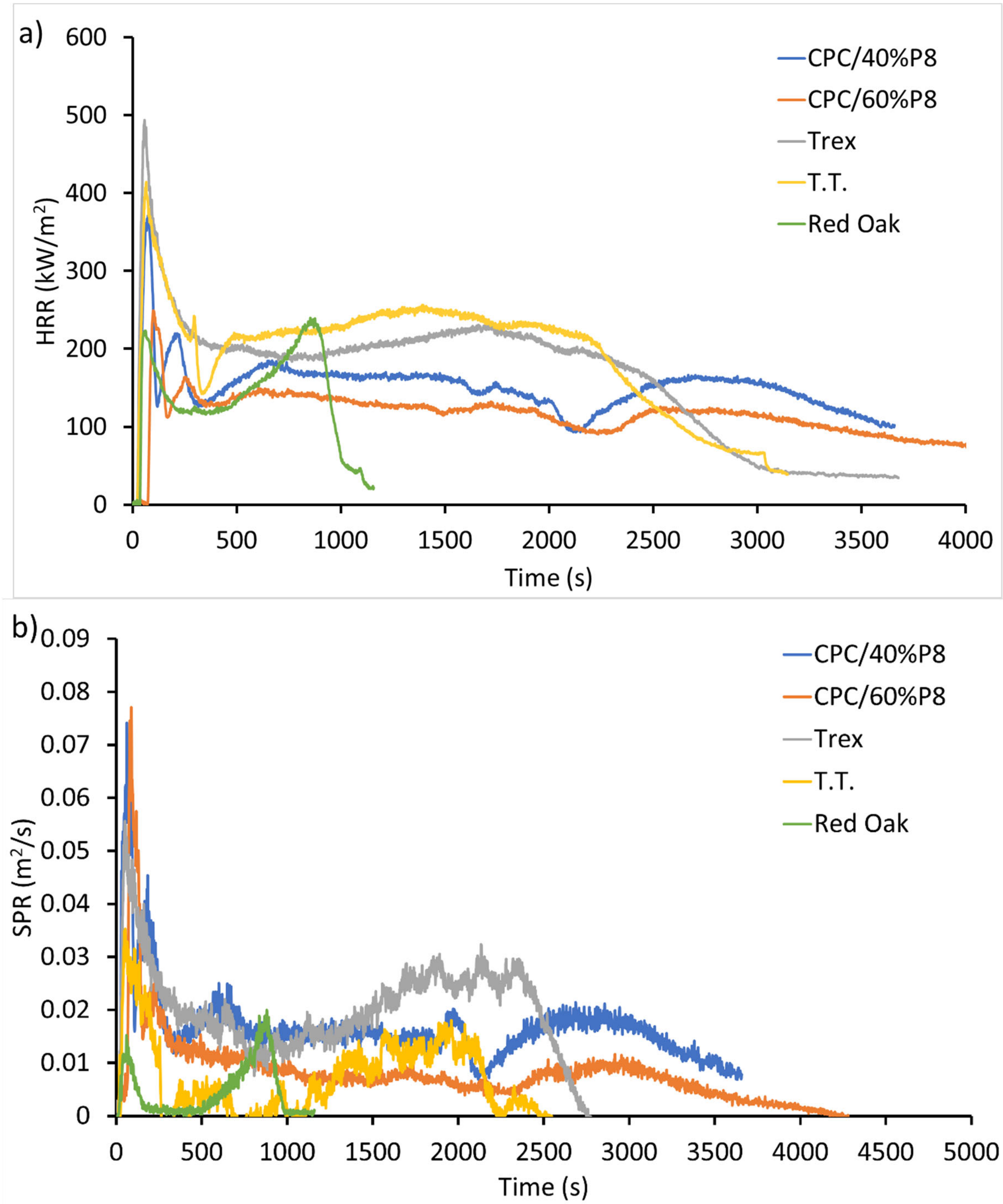

Figure 8. a) representative Heat Release Rate (HRR) and b) representative smoke production rate data for CPC with 40 & 60 wt.% P8 coal, Trex and TimberTech (T.T.) commercial WPC products, and Red Oak. Tests were conducted per ASTM E1354.

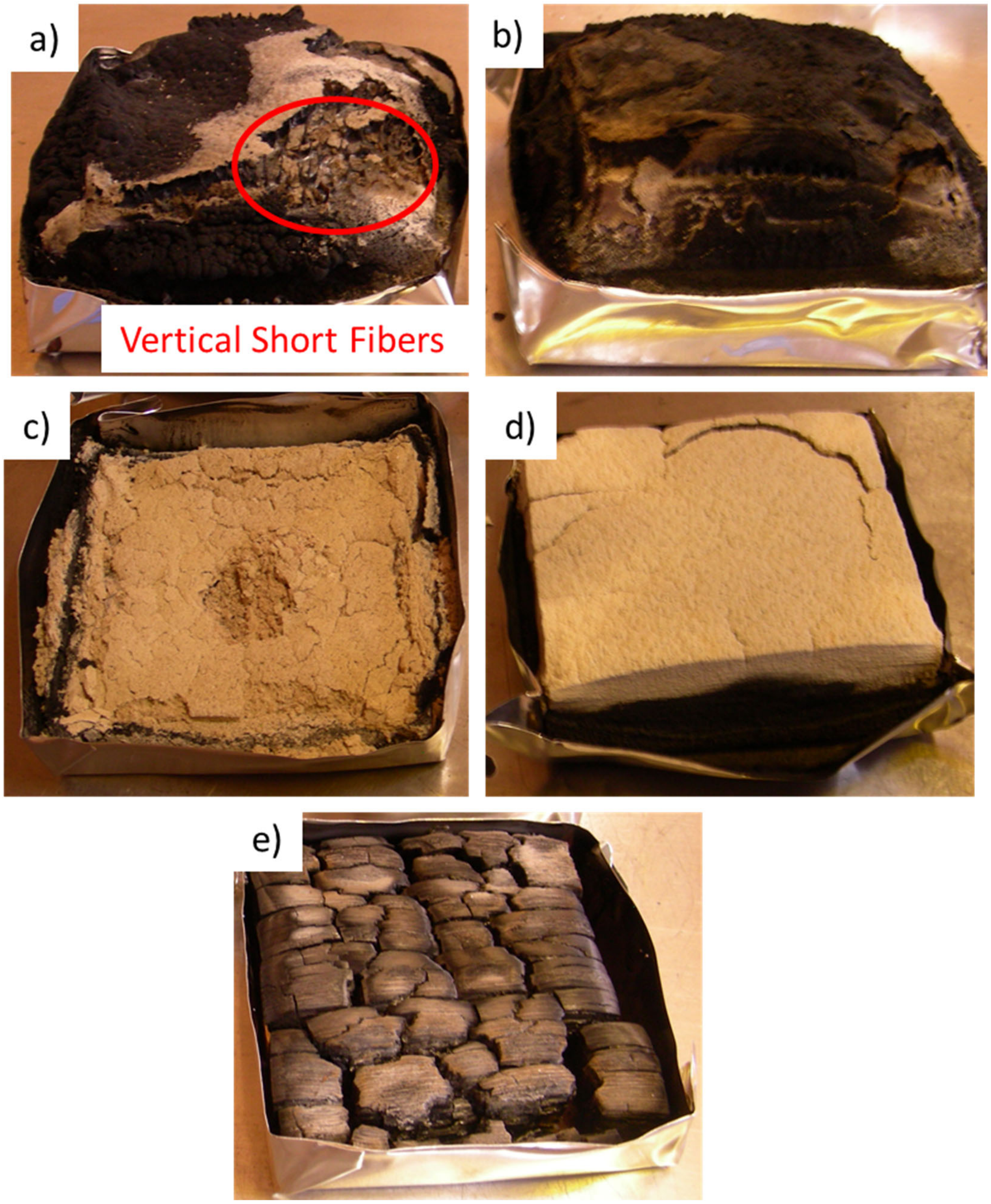

Figure 9. Final char pictures after cone calorimeter testing at 50 kW/m^2 for a) CPC/40 wt.%, b) CPC/60 wt.%, c) Trex WPC product, d) TimberTech WPC product, and (e) Red Oak.

Time to ignition (TTI), time to peak HRR, peak HRR, average HRR, total heat release (THR), weight loss, total smoke release (TSR), and average effective heat of combustion (EHC) for CPC materials, WPC products, and Red Oak specimens are shown in Figure 10. Higher TTI and lower HRR are favorable for better fire performance [9], [10]. Figure 10a shows the TTI for CPC/60 wt.% was higher than all formulations, indicating less tendency to ignite. This result is in good agreement with the FIT results where the CPC/60 wt.% material has shown to possess higher FIT values than WPC products. Time to peak HRR (Figure 10a) values for CPC/60 wt.% were higher than WPC products, indicating possible lower flame spread, which agrees with the rate of burning results. Peak HRR is defined as the maximum

value of HRR during burning, and higher peak HRR values indicate self-propagation of the flame and cause nearby objects to ignite. Peak HRR values (Figure 10b) for CPC/60 wt.% and Red Oak were comparable and lower than CPC/40 wt.% and WPC products. Average HRR over the entire combustion trial and THR represented by the area under the heat release curve are shown in Figure 10c-d, respectively. Average HRR for CPC/60 wt.% was lower than all materials tested. THR from CPC/60 wt.% was lower than CPC/40 wt.% and WPC products, indicating lower energy content of the material. It is worth noting THR for CPC/60 wt.% was considerably higher than Red Oak. Figure 10e shows weight loss (%) for CPC/60 wt.% was lower than all formulations, suggesting a higher char formation. These results are in good agreement with TGA char results. TSR is a very important parameter for the current application of CPC material in building/construction applications, and it is measured using a laser photometer beam. High TSR values are typically attributed to an incomplete burning or chemical structure of the material. TSR for CPC/60 wt.% was significantly lower than CPC/40 wt.% and Trex WPC product, but higher than TimberTech and Red Oak as shown in Figure 10f. It is expected for polymer composite with flame retardancy and no smoke suppression to have higher smoke values due to incomplete burning of combustible matters [7], [11].

EHC is another vital parameter that assesses the flammability of volatiles as it measures the ratio of heat released to mass loss [11], [12]. As indicated in Figure 10g, CPC materials have a higher average EHC than WPC products and Red Oak. Fire hazard parameters, maximum average rate of heat emission (MARHE), and fire growth rate (FIGRA), which are often disregarded in literature, provide critical information about flame spread and ignition of nearby objects [13]. MARHE (total heat release divided by time) and FIGRA (peak HRR divided by time to peak HRR) values for CPC/60 wt.% were lower than CPC/40 wt.% and WPC products, indicating less tendency for flame spread and ignition to nearby objects. MARHE value for CPC/60 wt.% was comparable with Red Oak while FIGRA for Red Oak was much lower than CPC/60 wt.%. Based on the above discussion, it can be concluded that flammability and smoke release for composite with higher coal content (CPC/60 wt.%) was lower than CPC/40 wt.%, indicating the role of coal as a natural intumescent flame retardant. Despite the limited research on fire performance of coal-based composite, it was reported in the literature that coal when mixed with APP flame retardant, has been shown to improve the fire performance of plastic composites [11]. In comparison to WPC products, CPC/60wt.% possessed a better overall fire performance. However, in some categories, the WPC products outperformed the CPC/60 wt.%. Compared to Red Oak, CPC/60 wt.% fire performance was comparable in some fire parameters (MARHE, Peak HRR), but much higher on other parameters such as THR and TSR. It is important to note that the average starting mass for CPC/60 wt.% was much higher than wood samples (229 grams versus 167 grams for Red Oak), indicating a greater amount of combustible fuel. It is worth noting previous studies have shown WPC and wood possess better fire performance as compared to neat polyethylene, PP, and PVC [7], [9], [14]. Further, char forming fillers combined with intumescent structure have been reported to achieve optimized flame retardancy [14]. Compared to other natural fillers such as wood flour, coal possesses favorable characteristics as char former and intumescent filler.

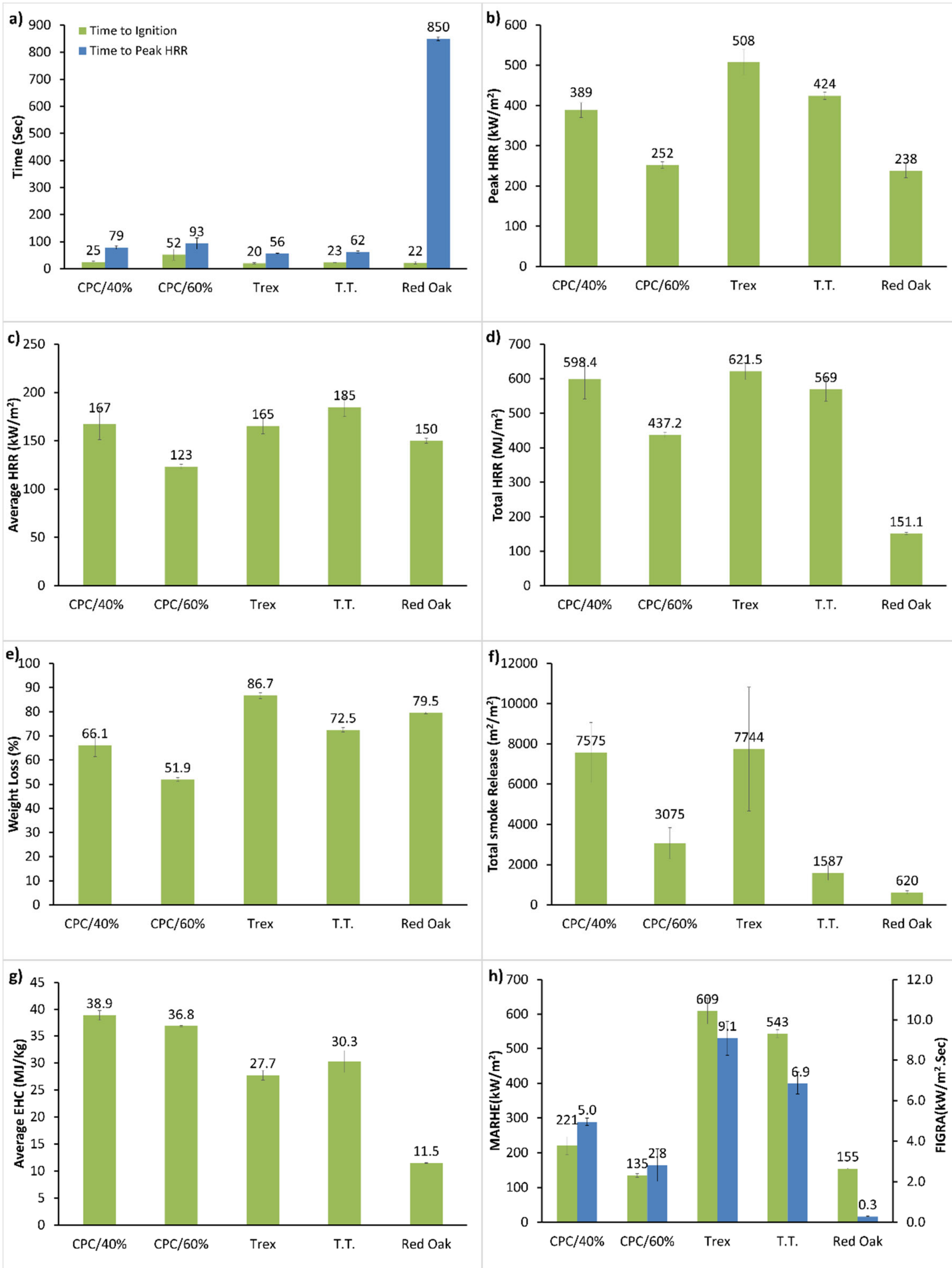

Figure 10. (a) Time to ignition (TTI) and time to peak HRR, (b) peak HRR, (c) average HRR, (d) total heat release (THR), (e) weight loss, (f) total smoke release (TSR), (g) Average effective heat of combustion (EHC), and (h) maximum average rate of heat emission (MARHE) and fire growth rate (FIGRA) for CPC/40%, CPC/60%, Trex, TimberTech (T.T.), and Red Oak.

3. CPC Decking Board Development

To support continuous CPC decking manufacturing trials, a dedicated material blending system was designed and installed. This system allows for the blending of three unique ingredients with the option to add an additional ingredient for future formulations. This system (Figure 11a) homogeneously blends coal with a polymer and adds additional processing aids. Extrusion tooling for continuous CPC decking manufacturing has also been designed and fabricated (Figure 11b).

a) b)

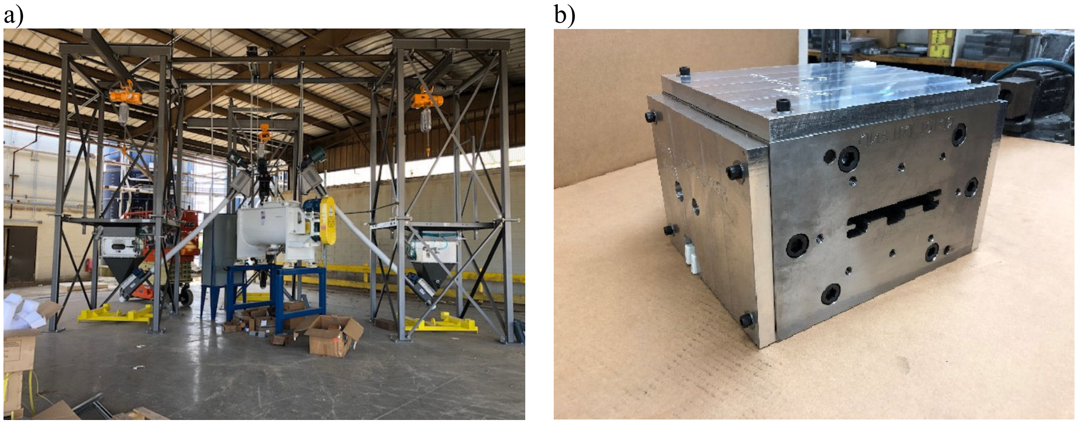

Figure 11. Engineered Profiles CPC manufacturing systems, a) ribbon blender system and b) tooling for continuous CPC decking manufacturing trials.

Commercial WPC extrusion equipment was utilized to manufacture CPC decking boards. Several thousand feet of CPC decking board were manufactured during development trials to establish processing parameters which yielded commercially aesthetic board products. CPC boards were provided to externally certified organizations to conduct testing according to ASTM D7032 specifications for composite decking applications. A summary of CPC decking results is provided in Table 4. Independent testing results indicate CPC decking materials meet or exceed ASTM and IBC requirements for decking applications.

Table 4. Summary of CPC Decking ASTM Testing Results

Property	Test Method	Status
Board Strength	ASTM D1609	Exceeds IBC[1] Specification
Board Deflection	ASTM D1609	Exceeds IBC Specification
Water Absorption	ASTM D570	Water absorption significantly lower than WPC[2]
Oxidation	ASTM D3895	Greater oxidation resistance than most WPCs
Flash Ignition Temperature	ASTM D1299	Higher than WPCs
Self Ignition Temperature	ASTM D1299	Higher than WPCs
Rate of burning	ASTM D635	Slower than WPCs
Smoke/Heat Release	ASTM E1354	Lower total heat/smoke release than WPCs
Surface Burning	ASTM E84	Passes, Class B rating
Leaching	SPLP/TCLP	Passes, BDT[3] or well below RCRA limit
Respirable Dust	NIOSH 600	Pass
Hail	Ice Cannon	Pass
Screw Fastening	ASTM D7032	Pass

1. IBC: International Building Code
2. WPC: Wood-Plastic Composite
3. BDT: Below Detection Limit

To evaluated CPC decking constructability, boards manufactured at Engineered Profiles were provided to a home building product testing organization. The objective of the activity was to obtain feedback from deck builders on the handling and installation of the CPC product. Five teams of two experienced deck builders were recruited to build a 10-ft by 20-ft deck. Figure 12 presents images of a CPC deck installation and completed deck. Valuable information was learned during the CPC deck installations. Key advantages noted by the builders were that the CPC material was easier to carry and install in comparison to existing decking materials. Results from the constructability study indicate CPC decking is a viable commercial product and demonstrates maturation of the technology to TRL8.

Figure 12. CPC Deck Installation and Finished Deck Installation.

4. Techno-Economic and Lifecycle Analyses

4.1.1. Techno-economic Analyses

Techno-economic analyses were conducted for a new CPC plant and compared to a new WPC 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 6.
2. Plant operates for 24 hours per day for 50 weeks per year, with an assumed capacity factor of 85%
3. Taxes and insurance are calculated at 2% each of the Capital Cost.
4. The composite density is 72.4 lb/ft^3 and a cross-sectional area of 0.0256 ft^2.
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 WPCs.

Component	CPC	WPC
Coal/Wood Flour	60%	50%
HDPE	29%	30%
Talc	10%	15%
Additive	1%	5%

The block flow diagram below (Figure 13) was developed based on information provided by Engineering Profiles who built and operates a WPC manufacturing facility. The block diagram illustrates the components and unit operations required to manufacture the coal or wood plastic composites. The filler material is received via truck and dried to 1% moisture prior to blending with the polymer, talc, and processing aid. The components are blended together and conveyed to the extruder. The extruder produces decking boards with the specified cross-sectional area which are then cut to the desired length (8, 10, or 16 foot) and then stored in the warehouse prior to sales. To reduce the environmental impact of the plant, the CPC or WPC dust due to cutting the decking boards is reclaimed. Water is used to cool the warm decking boards and is treated prior to being recycled.

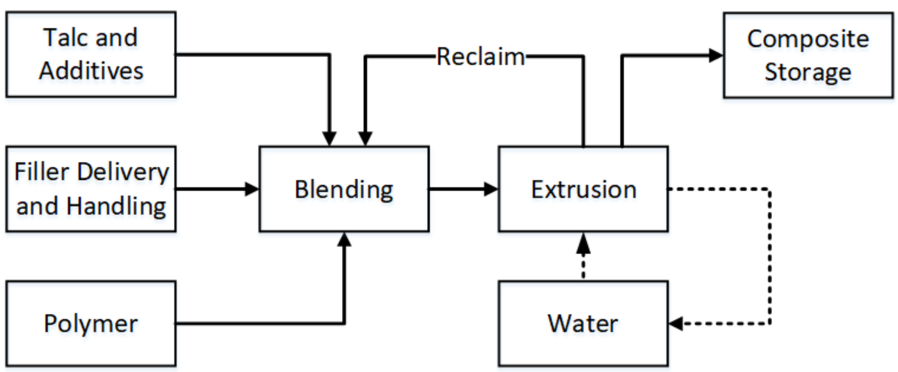

Figure 13. Block flow diagram for a proposed plastic composite manufacturing plant using either wood or coal as the filler material. Cooling water is recycled in the extrusion process.

4.1.2. Base Case Analyses

Using the base assumptions, the overall capital (includes 15% contingency) and operating costs of a new CPC plant compared to a typical new WPC plant is provided in Table 6. The differences between the CPC and WPC equipment costs (also reflected in the taxes and insurance) are mainly due to coal handling equipment. Conversely, the difference between the cost of chemicals is due to the comparative costs of fillers, energy to dry wood flour, and the HDPE polymer consumed in the processes. The wood filler costs are expected to be inelastic because the WPC market is ~10% of the overall wood filler market and these prices (~$200 per ton received) are 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 wood (WPC) and using the base assumptions previously listed.

Cost	Comments	CPC	WPC
Capital Cost	*Equipment*	$41,097,000	$35,507,000
	Building and Land	$11,434,803	
Fixed OPEX	*Labor*	$17,330,000	$17,050,000
	Maintenance and Warranties	$5,650,000	
	Taxes and Insurance	$2,101,272	$1,877,672
Variable OPEX	*Utilities*	$1,777,156	$1,768,971
	Chemicals	$36,458,864	$53,227,181
	Freight and Packaging	$5,650,000	
Manufacturing Cost ($/lb)	*Excludes Capital Cost and intermediary markup*	$0.40	$0.49
Manufacturing Cost ($/linear ft)		$0.74	$0.91

These production costs show a 20% cost advantage for the CPC plant in comparison with the WPC plant based on fixed and variable costs alone. Furthermore, the WPC production costs in this analysis are in close agreement to the values reported in a recent Grand View Research report[15] that estimated a cost per pound of WPC using HDPE, polypropylene, and polyvinyl chloride as $0.48, $0.42, and $0.44 respectively.

4.1.3. Sensitivity Analyses

The sensitivity of manufacturing cost is due to changes in the formulation of CPC or WPC and the unit price of various components as shown in Figure 14.

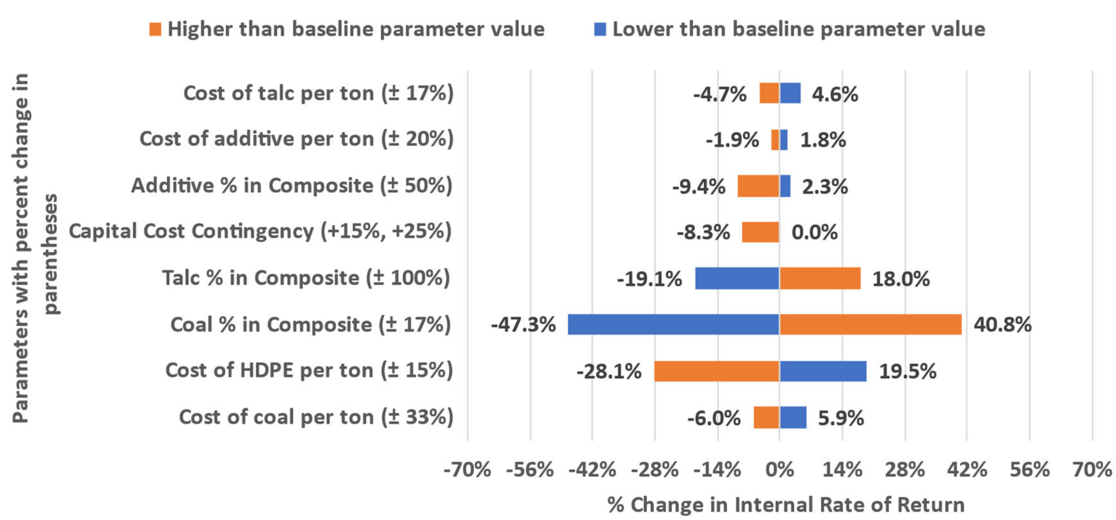

Figure 14. Sensitivity analyses of manufacturing cost based on modification of formulation percentages and component cost.

These values show that the parameter with the highest impact on the manufacturing cost is the amount of coal in the composite, with a 33% increase of this parameter with respect to the baseline resulting in a 12% decrease in cost in comparison to the baseline manufacturing numbers in Table 7. On the other hand, the cost of the additive is relatively inelastic in comparison to the other parameters.

4.1.4. Sales Pricing

For a comparison to current retail pricing, an IRR calculation was used to obtain an expected product sales price FOB manufacturing location with an additional 2-step markup of 40% applied. This 2-step markup accounts for the cost increases at the distributor (step 1) and the retailer (step 2) to account for operating expenses and distributer / retail sales outlet profits on the product. These values are provided in Table 7.

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

Price Basis	Price ($/linear ft)	
	CPC	WPC
30% IRR (FOB manufacturer site)	$0.82	$0.97
30% IRR and 2-step markup of 40%	$1.62	$1.90

The WPC values are in the low range of current market prices for WPC products (see Table 8). Additional price increases are due to some combination of capstock, decking board profile, rating by decking board producer (i.e. good, better, or best categories), variability in negotiated markups, and other factors. For example, the Trex products in Table 8 demonstrate the difference in selling price due to good, better, or best categories: Trex Basics (good) retails for between $1.75 and $2.02 per linear foot while Trex Transcends (best) retails for between $4.57 and $5.78 per linear foot for a price differential of 330%.

Table 8. Current Commercial WPC Decking Retail Sales Price.

Manufacturer/Product	End User Pricing ($/linear ft)
Trex/Enhance Basics	1.75 - 2.02
Trex/Enhance Naturals	2.49 - 3.05
Trex/Transcends	4.57 - 5.78
Choicedek/MoistureShield	3.67
TimberTech/PRO Terrain	4.48
TimberTech/Earthwood	5.15
TimberTech/PRO Legacy	6.68

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.

4.1.5. Lifecycle Analyses

A cradle-to-gate life cycle analysis with specific emissions and energy usage for the TEA scenarios are shown in Figure 15. The CPCs have lower specific attributes in comparison to WPCs, with 29% lower GHG emissions, 31% less energy usage, and varying levels of advantages in every assessed category. Although end-of-life scenarios were not considered in this study, similar disposal scenarios (landfill or incineration) are probable for the CPC and WPC products. Landfilling of CPC materials should not pose an issue as the materials pass EPA method 1311 testing. Interestingly, CPCs potentially offer greater recycling potential and ultimate supply chain sustainability due to coal's greater thermal stability in comparison to wood. Heating to necessary temperatures to separate filler from the thermoplastic matrix would generate pyrolysis products in the case of wood filler preventing reuse of the plastic, whereas

minimal pyrolysis products (if any) would be generated from coal at these temperatures, potentially allowing for recycling of the recovered resin.

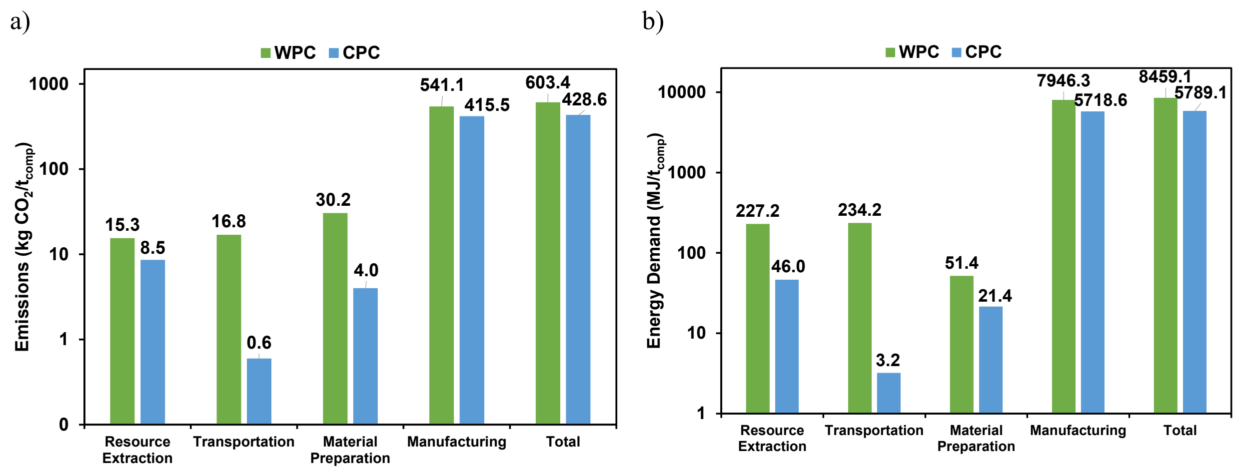

Figure 15. Cradle-to-gate (a) specific CO_2 emissions and (b) specific energy demand associated with WPC and CPC decking materials.

Energy use in manufacturing advanced carbon-based composite fillers including carbon fiber, graphene, and carbon nanotubes (CNTs) has been estimated. Carbon fiber manufacturing from petroleum-based pitch is estimated to be 183−186 MJ/kg [16], [17]. Arvidsson *et al.* estimated graphene manufacturing energy use from coal utilizing chemical reduction and ultrasonication routes to be 450 and 1100 MJ/kg, respectively [18]. CNT manufacturing energy usage from a host of sources such as carbon monoxide, methane, ethane, and benzene using methods such as chemical vapor deposition, arc discharge, and high-pressure carbon monoxide is between 1 and 900 GJ/kg [18]–[21]. These results indicate that the direct utilization of coal as filler in construction composite applications may yield lower-cost products with lower associated emissions and energy demand compared to that of the existed WPC materials, potentially yielding a new more sustainable end use for the natural resource than current uses such as power production.

4.2. New CPC Markets

The continued focus of this program will be on economically manufacturing decking boards, as it is the largest market; however, the project team will also evaluate the use of CPCs to replace WPCs in other applications (Table 9). Further, while polyethylene is the largest thermoplastic used in these composites, the team will also evaluate the use of polyvinylchloride and polypropylene in coal plastic composites.

Table 9. New Markets

Building and Construction	Automotive	Industrial and Consumer
Decking Fencing Molding Railing Doors Siding	Seat cushions Cabin linings Backrests Dashboards	Furniture Injection Molding

Grand View Research [15] forecasts that each of these markets will about double in volume by 2025. They estimate that these markets will grow at about a 9%/year rate. In 2025, North America will comprise 48% of the wood plastic market. In order to pursue the new markets, the research team has contacted the automobile industry to determine their interest in replacing WPC with CPC components, market size, component price targets, product performance specifications, and likely product entry points. The team will evaluate the safety and environmental aspects of converting from WPC to CPC. Although the team has focused on extrusion for WPC and CPC decking, furniture and other industrial components may require injection molding to manufacture complicated structural shapes. To economically evaluate CPC components, a comparison will be made between the composition of the CPC and WPC shapes fabricated using injection molding and potential improvements in the CPC performance specifications. The project team has reviewed the Grand View market survey and has identified several product areas of interest.

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