Stanford CEE 226: Life Cycle Analysis Project

San Francisco Presidio Façade Panels: FRP vs. Limestone

John Basbagill, Carolyn Galayda, Kelly Ju, Daniel Moreno, Ben Welle

December 4, 2009

Abstract

Kreysler and Associates, a manufacturer of fiber reinforced polymer (FRP) materials, is replacing limestone cladding panels with FRP panels on the Public Health Services Hospital in San Francisco's Presidio Park. Buildings consume a significant amount of energy in the United States[1], and Kreysler wants to validate their belief that FRP is a greener material than limestone as well as to pinpoint modifications to FRP panels' life cycle inputs that will result in a greener material. This paper provides a recommendation to Kreysler as well as determines the effectiveness of process-based life cycle analysis (LCA) in meeting Kreysler's objectives.

LCA was used to compare the limestone and FRP panels. Process flow diagrams outlined scope and boundaries, a 1'x1' panel was chosen as a functional unit, and Simapro was used to model the life cycle of the two panels. Results showed that the environmental impact of FRP panels was greater in many categories, and medium density fiber (MDF) particle board used to mold the FRP panels was the biggest contributor. Replacing MDF with plywood resulted in lower environmental impacts than limestone for all categories. The paper recommends FRP panels as the greener material after this modification and concludes that process-based LCA is an effective method of comparing building materials and optimizing inputs to create greener materials.

Table of Contents

Table Summary

Introduction

Buildings are a significant source of energy consumption in the United States, accounting for 40% of all energy used[1]. Materials contribute greatly to this rate due to the cost of excavating, processing, and transporting the materials to the building site. Several types of materials may be chosen depending on the particular building application, and each material has a unique emissions profile. For example, a variety of exterior cladding materials exists including glass, wood, stone, clay, metal, composites, and brick. Which material will contribute least to a building's energy footprint? Can those inputs to the life cycle phases of a material that contribute the most to this footprint be identified, then modified, to create a greener material?

Process-based life cycle analysis (LCA) is a method of answering these questions by comparing building materials. The process determines which material results in a lower energy and emissions footprint for a building. Another potential benefit of this method arises when designing green building materials. Inputs within phases of materials' life cycles can be identified then modified to yield greener materials.

This process-based approach to comparing and "greening" building materials can be applied to a current project of Kreysler and Associates. The company fabricates composite building materials at their headquarters in American Canyon, California, about 45 miles northeast of San Francisco. Currently they are replacing 277 cladding panels on the Public Health Services Hospital (PHSH) in San Francisco's Presidio Park and would like to know whether their replacement material is greener than the old material.

The PHSH is a certified historic structure undergoing a transformation from hospital to luxury apartments. Built in 1931, the hospital was abandoned from 1988 to 2009. Renovation has recently begun to transform the 220,000 square foot building into 154 LEED Silver apartments. Historic windows and facades are being refurbished. The project also qualifies for the Federal Historic Preservation Tax Incentives program: the owner receives a tax credit equal to 20% of the amount spent in the certified rehabilitation of the structure. Materials must either be replaced with identical materials or government-approved substitutions[2].

Kreysler's fiber reinforced polymer (FRP) material, made primarily of unsaturated polyester resin and manufactured at Kreysler's headquarters, has been approved as a replacement for the old limestone cladding material. Kreysler is mid-way through the panel replacement process and has two objectives, to: 1) seek validation that their product is greener than limestone and 2) determine ways in which their FRP panels' life cycle may be modified in order to create a greener material. Kreysler wishes to use the results to create greener building materials. This paper's goals are to provide a recommendation to Kreysler and determine whether process-based LCA is effective in meeting Kreysler's two objectives.

---

[1] US Department of Energy. *Annual Energy Review 2008*, 26 June 2009, accessed 26 November 2009.

[2] National Park Service, US Department of the Interior. *Historic Preservation Tax Incentives*, 2009.

Process Flow Diagrams

The first step in determining process-based LCA's effectiveness in evaluating building materials' environmental impacts is to construct process flow diagrams of the materials' life cycles. Since the life cycle of a given material can have an infinite loop of process inputs, process flow diagrams are a visual way of mapping out scope and boundaries for a life cycle analysis. Appendix I and II show the process flow diagrams constructed for FRP and limestone, respectively. The diagrams identify the key stages of limestone's and FRP's life cycles that were included in the analysis: raw material acquisition and transportation, material processing, panel fabrication, transportation to the Presidio, installation, use, demolition, and end of life. The diagrams also identify the materials that go into manufacturing, finishing, assembling, and installing the two panels as well as equipment and transportation needs at each stage. All phases were considered - from acquisition to end of life - except for the use phase operating costs. Boundaries were also drawn to exclude the following: energy requirements for machinery used in raw material acquisition and components accounting for less than 1% of energy inputs, such as FRP molds that Kreysler uses to manufacture the FRP panels.

Functional Unit

A functional unit of a 1'x1' flat panel was then chosen to compare the two materials. Since the FRP panels are fabricated into complicated shapes with varying weights, depths, and ornamentation details, the panel weights were averaged by referring to shop drawings (see Appendix III). The mean panel weight was 3 lbs, and the average depth was 9 mm. By comparison, the limestone panels all consist of a uniform, flat shape lacking ornamentation details. The limestone panels are 1' deep, and a 1'x1' panel weighs 135 lb.

Methods and Key Assumptions

Simapro was then used to model the life cycle of the two materials in order to obtain data on energy inputs and emissions outputs. Surrogates were used for some of the materials, including low density poly ethylene for the initiator (methyl-ehtyl-ketone peroxide). Outputs from the software program Building for Environmental and Economic Sustainability (BEES) were also used as inputs in Simapro in order to model the production of MDF and plywood molds used to make the FRP panels.

Major assumptions included the functional unit accounted for the complicated shapes of the FRP panels. For example, whereas the old limestone panels are simple flat pieces, the new FRP panels assume more custom shapes: some are flat and some are highly decorative with complicated ornamentation. A second assumption was that reasonably accurate surrogates were modeled in Simapro, and a third assumption was that 50% was an accurate waste percentage for limestone.

Simapro results were then compared for the two materials. The quantities compared were greenhouse gas emissions, ozone emissions, acidification, eutrophication, heavy metals, carcinogens, pesticides, summer smog, winter smog, energy resources, and solid waste. Modifications were then made in Simapro by replacing MDF with plywood. These results were then used to determine whether process-based LCA is an effective method of evaluating building materials and optimizing inputs to create greener materials.

Application and Data Sources

FRPs are composite materials made of a polymer matrix reinforced with fibers. Their biggest advantages are that they are lightweight and durable. The application is 277 cladding panels for San Francisco's Public Health Service Hospital (PHSH) to replace the same number of limestone panels. The FRP panels are fabricated to closely mimic the texture and color of the existing limestone. The comparison material is Indiana limestone. Raw limestone is quarried near Bloomington, Indiana then cut into 1'x1'x1' blocks. As mentioned in the key assumptions, flat panels of each material type were chosen for comparison.

Kreysler and Associates was the major source of data. Kreysler provided data sheets for the FRP component materials including filler, chopped strand mat, Gel Coat, and resin. Kreysler also provided labor and overhead costs, construction method details, and modes of transportation. Kreysler also supplied shop drawings for the FRP panels' installation on the PHSH, as well as the limestone panel fastener system manufactured by R. Cunningham and Co., Inc. BEES (Building for Environmental and Economic Sustainability) 4.0 was used to generate data on the energy and emissions of the production of the plywood and MDF molds for the FRP panels.

FRP Production, Transportation, and Installation Processes

FRP: Material Components

FRP panels' material inputs were considerably more complex than limestone panels' inputs. One functional unit (1ft^2, or 3 lbs) consisted of the following percentages (by mass): 16.67% glass fibers in the form of a chopped strand mat, 16.67% sand (for texture), 16.67% Gelcoat, 25% resin, and 25% filler. In addition, a small amount (1.5% of the resin mass) of initiator (methyl-ethyl-ketone peroxide) was used.

FRP: Production Process

Production of the FRP panels is a complicated process involving four sub-processes. The first phase of the FRP life cycle considered was raw material acquisition, in which the raw materials for the basic components listed above were processed then transported from various locations to Kreysler and Associates for fabrication.

The second sub-process involved in making the FRP panels was the production of molds. Kreysler uses two mold types: plywood is used to make 272 (about 98%) flat FRP panels. The plywood molds are constructed using basic hand tools. The remaining 5 panels (about 2%) are highly ornamental and are molded from MDF molds that are produced on a CNC machine.

The third sub-process is manufacturing of the FRP panels. The basic materials are mixed and applied in layers by hand to the molds at Kreyler's plant. The initiator reacts with the resin to create chemical heat, which cures the panel inside of a nylon vacuum bag. Stainless steel nuts are welded to stainless steel plates 1/8" x 3" x 3"; four of these are typically embedded into the

FRP panel. After curing, the panel is ground to expose the nuts, which are used to fasten the panels to the building.

A fourth sub-process is sandblasting. Approximately 50% of the FRP panels are sandblasted at Kreysler's plant to replicate the texture of limestone. Sandblasting completes the FRP production process.

Table 1 below shows the quantity, location, distance from Kreysler and Associates' plant, cost per functional unit, component makeup, and notes for each of the materials used in the production of the FRP panels. Simapro equivalents and surrogates are also given. A 5% material waste is factored into the table quantities.

Table 1: FRP Component Assemblies

Component	QTY per 3lb; 1ft^2 Panel[*]	Distance[†,‡]	Cost/SF FRP	
Gelcoat: Valspar Composites	0.2387kg	From: St Redem St-Nicolas, QC, Canada = 10,009 km	$0.94	**Actual Component Makeup:** Isophthalic neopenthyl glycol (*saturated*) polyester thermoset resin
				Simapro Model Component Description: *unsaturated* thermoset polyester resin - SimaPro's most similar option
Filler/Binder: J.M. Huber Corps	0.3581kg	From: Marblehead, Il = 3323km	$ 0.28	**Actual Component Makup:** Alumina Trihydrate ATH (SB-336 & 432 - By J.M. Huber Corps.) flame retardant & smoke suppresant made from 64.9% Aluminum Oxide + 34.6% Loss on Ignition; all other ingredients are less than 1% each.
				Simapro Model Component Description: 100% Aluminum Oxide
Resin: Huntsman Advanced Materials Americas inc.	0.3581kg	From: Los Angeles, CA = 713km	$1.00	**Actual Component Makeup:** unsaturated thermoset polyester resin
				Simapro Model Component Description: unsaturated thermoset polyester resin
Initiator: Huntsman Advanced Materials Americas inc.	0.00537kg	From: Los Angeles, CA= 713km	negligable	**Actual Component Makeup:** Organic Peroxide: methylethyl ketone peroxide + 15 seconds stirring by air powered hand drill: 3 or 4 cfm @ 190psi;
				Simapro Model Component Description: Organic Peroxide modeled as "Low Density Poly Ethylene" for use, according to SimaPro, when "no data information is available"; It applies for chemicals used in very low amounts. + .18075 kWh "Electricity ave kWh USA - Low Voltage"
Chopped-strand mat: Owens Corning	0.2387kg	From: Compton CA = 736km	$0.34	**Actual Component Makeup:** 64% glass fiber - source Corbier 1999 plus fillers & binders
				Simapro Model Component Description: 100% glass fiber. **This Represents a highly conservative estimate.*
Sand for Texture: Hi-Grade Materials Co.	0.2387kg	From: Hesperia, CA: 513mi = 826km	$0.02	**Actual Component Makeup:** 99.98% silica sand
				Simapro Model Component Description: Sand ETH U
Sand for Blasting : Hi-Grade Materials Co.	1.474kg	From: Hesperia, CA= 826km	$0.26	**Actual Component Makeup:** 99.98% silica sand
				Simapro Model Component Description: Sand quartz (energy of blasting accounted for in the FRP Process - see below)

FRP Plates & Fasteners: Glaser & Assoc.				**Actual Component Makeup:** Approx. 4 plates per panel, each: 1/8" x 3" x 3" cut stainless steel w/ welded on nut bonded onto surface & Fiber glassed over, then grinded to expose nuts. Installation: Steel Rod approx at site is epoxied into nut.
Nuts			$2.80	(= 4 nuts at $0.70 per nut - nutsandbolts.com)
Stainless Steel Plate			$12	(= onlinemetals.com - $48 per square ft)
Stainless Steel Rod			$16	(= $28 for a 3 feet stainless steel threaded rod msc-stainless-fasteners.com)
Total:	Total: 1.289 kg Stainless Steel	Martines = 41.7666km *no stop at Sacramento	$30.80	**Simapro Model Component Description:** GX12Cr14 (CA15) I - The corrosion resistance of steels is due to the element Chromium which is added to the steel during steel production. These steels are relatively cheap but have a moderate formability and are not weldable.
MDF Molds: 2% of 278 panels PHSH are made using medium density fiberboard	assume 2 SF at 1.5" deep = 5.215kg	Assume component is supplied from Northern CA (pick Redding) = 350km	$3.88	**Actual Component Makeup:** MDF + 16 - 18 hrs on CNC machine
				Simapro Model Component Description: modeled using similar hard wood: Oak, European I + BEEs energy & emissions qtys.[2]CNC machine electricity is captured in the energy modeled in our FRP Panel Process (see below)
				MDF is most commonly made from Radiata pine; has a typical density of 600-800 kg/m^3 or .022-.029 lbs/in3[3] - assume 700kg/m^3
Plywood Mold: 98% of 278 panels PHSH are made using medium density fiberboard	Silver Fir I =1.7394 kg Birch I = 0.1937		$1.10	**Actual Component Makeup:** 2SF interior grade 3/4" douglas fir core w/ birch outer veneer. *50% of plywood molds are used for approx. 10 - 15 panels ea. 50% are used to make fiberglass, used for approx. 200 panels ea. We have ignored the fiberglass mold because it contributes less than 1% of total components due to the high rate of reuse. We've adjusted our rate of reuse of plywood molds to approx. 55 panels to compensate.
				Simapro Model Component Description: modeled using silver fir & birch + BEEs energy & emissions qtys.[2] Assumed density for Douglas Fir 520 kg/m3 total mass of Plywood = 1.8406 kg (0.003539 cubic meters)[4]; Silver Fir = 90%; Birch = 10%
				** To account for a 55 panel reuse, we've divided the total quantity of plywood molds used per panel by 55 in our FRP Panel Process*
Vacuum Bags: AirTech	0.0047747 kg	From: Huntington Beach, CA = 850km	$0.75	**Actual Component Makup:** A Nylon Product
				Simapro Model Component Description: Modeled using Nylon (Econolon Film - Airtech) + Production of Pouch 2ltr process; From Airtech Bagging film dimensional chart[5]: 16lb per 0.0015"x60"x200' roll = 128lb/cubic foot; 3.539 ltrs good for 10 parts =.3539 ltr bag per part; 1 bag = 30"x30"x.0015" = 1.35 cubic inches = 0.0007813 cubic foot = 0.10 lb/10parts per bag = 0.010 lbs = 0.004536 kg; 6.25 square ft of vacuum bag per functional unit

* Quantities Provided by Kreysler & Associates; includes an additional 5% waste
† Includes distance from nearest manufacturing distributor to "Composite One Distributer" in Sacramento CA, and from there to Kreysler & Associates in American Canyon, CA[6]
‡ Use of 40 Ton ETH U Truck, 50% efficiency, used in modeling all component transportation.

---

2 BEES 4.0 Database
3 Australia National University
4 SI metric.co.uk.
5 Airtech International, Inc.
6 Google maps

FRP: Panel Electricity Requirements

Table 2 summarizes the key assumptions for the various electricity requirements throughout the FRP panel manufacturing phase. The result is 10.611 kWh of power per panel.

Table 2: Electricity Assumptions for FRP Panels
1. Part-load factor of 0.8 for all equipment.
2. Motor efficiency of 0.85.
3. 0.746 kW/hp
4. Air compressor runs 4 times per day, with 1/20 being used for a plywood piece
5. 4 hp equivalent running for 2 hours for jig saw
6. Electric router runs 1 hour per plywood piece.
7. 5 of 78 panels made using CNC machine. CNC machine runs 16-18 hrs per piece.
8. Air Compressor is 35 hp; powers down to 120 psi when at rest
9. Electric Vacuum Pump rated at 7.1 amps @ 115 volts
10. CNC machine has a 2hp motor and a 3 hp motor.
11. Electric router is 3.5 hp.
12. Drill time for 4 holes for limestone is 10 minutes of air compressor
13. Grinding time for FRP is 1 min of air compressor
14. Sand Blasting for FRP is 1 min of air compressor

Using Table 2, Table 3 gives the calculation results for all of the processes in the production of the FRP panels which require electricity. The first column gives the tool used, the second column gives the power usage result, the third column gives the units, and the fourth column gives notes.

Table 3: Electricity Requirements Per Category for FRP Panels

Tool	kWh	Units	Notes
CNC machine - 2hp motor for drill; 3hp motor for conveyor	63.191	Per piece	
Electric Vacuum Pump	1.921	Per piece	2 hrs per part (Note: same time is necessary for any size part)
Air Compressor - 35 HP =26.1 kw	98.296	Per day	
Installation by hand	0.000		
hand tools (all pneumatic):			
pneumatic sand blaster	0.435	Per plywood mold	26.1 kW air; 125 psi (modeled on mid-priced sandblaster[7] - compressor used for 1 min.
pneumatic jig saw	7.021	Per plywood mold	90psi (modeled on mid priced jig saw[8])
electric router	3.072	Per plywood mold	3 1/2 HP, 22,000 RPM, 15 Amp (modeled on mid priced router[9])
Total kWh per ft^2 panel	**10.611**		

[7] Northern Tool and Equipment Catalog Co., *Marco.*
[8] Tool Orbit, *Bosch.*
[9] Northern Tool and Equipment Catalog Co., *Milwaukee.*

FRP: Transportation to Site and Installation Process

The next phases of the FRP panels' life cycles considered were transportation and installation. After the FRP panels are manufactured, they are transported from Kreysler and Associates' plant in American Canyon, California 45 miles to the Presidio building site in San Francisco. Stainless steel rods and epoxy are used to attach the panels to the building façade (see Appendix: IX "plates and fasteners" assembly). The panels are light enough to be lifted into place by hand. The energy used during transportation to site was modeled in Simapro as follows. The mass functional unit was multiplied by the transportation distance in a gasoline truck to yield 225.6 kg*km. The energy for the installation phase was assumed to be done by hand and therefore 0.

FRP: Use, Demolition, and End of Life Phases

In the use phase of the product lifecycle, no maintenance was assumed, per manufacturer specification. The product lifespan was also assumed to be limited by a typical building's lifespan of 100 years. At the end of life, panels are demolished along with the rest of the building. The panel debris is transported 14 miles from the building site to a landfill, the Marin Resource Recovery Center. This requires fuel for transportation. No recycling was assumed.

Limestone: Production, Transportation, and Installation Processes

The limestone panel process flow diagram shown in Appendix II outlines the lifecycle of the limestone panel. The LCA boundary for limestone is all life cycle phases with the exclusion of use phase operating costs. As noted earlier, the functional unit is a 1'x1' panel (which corresponds to a depth of 1' and weight of 150 lbs). The life cycle begins with raw material acquisition from a quarry in Bloomington, Indiana. The material is then transported to a processing plant (less than ten miles away) and cut using a Standish narrow belt saw. A drill creates holes for installing the panels at the building site. The quarrying and cutting result in 50% waste[10]. Panels are then transported by semi-truck 2,320 miles to the building site. They are then lifted by chain hoist or electric lift and attached to the structure using stainless steel rods and epoxy similar to the FRP panels.

The following tables provide assumptions and data for the production, transportation, and installation phases of limestone. Table 4 describes the limestone components, including component name, quantity per functional unit, distance from supplier to the building site via a distributor's site in Sacramento, and component makeup.

[10] USGS.

Table 4: Limestone Component Assemblies				
Component	**QTY 1ft² Panel***	**Distance†,‡**	**Cost/SF Limestone**	
Limestone	61.24 kg (finished)	Bloomington, IN= 3674km (no waste)	$211	**Actual Component Makeup:** Indiana Limestone is classified a Type II (medium density) stone; Density = 135 lb/cubic ft; Indiana Limestone Intitute - Price includes $36 for raw material + $175 overhead
				Simapro Model Component Description: Indiana Limestone
Limestone Fasteners	0.6526 kg	Martinez = 41.7666km *no stop at Sacramento	$16	**Actual Component Makeup:** 4 stainless steel 1/2" diameter, 6" long threaded rods
				Simapro Model Component Description: GX12Cr14 (CA15) I - The corrosion resistance of steels is due to the element Chromium which is added to the steel during steel production. These steels are relatively cheap but have a moderate formability and are not weldable.
Limestone Epoxy + Hardener	0.0658 kg of epoxy + 0.0658 kg of hardener	Martinez = 41.7666km *no stop at Sacramento	$7	**Actual Component Makeup:** Epoxy resin + hardener - price from http://www.chemanchor.com/ - $23 for 14 anchorages 6" long
				Simapro Model Component Description: Epoxy Resin I = .145 lb ; Chemical organic ETHU = .145 lb (hardener surrogate)

* Quantities evaluated for a 1'x1'x1' panel, 50% waste is included, quantity w/ waste = 612.35kg
† Includes distance from nearest manufacturing distributor to "Composite One Distributer" in Sacramento CA, and from there to Kreysler & Associates in American Canyon, CA[11]
‡ Use of 40 Ton ETH U Truck, 50% efficiency, used in modeling all component transportation.

Table 5 gives the transportation and electricity requirements for each panel.

Table 5: Limestone Panel Process Requirements			
Materials:			
	1 of each as listed above with the exeption of quantities listed in red		
Processes:			
Transportation to site	224995.76 kg km	gasoline truck	(75.2 km)
Total Electricity per panel	5.219 kWh	see below	

Table 6 gives data and assumptions for the electricity requirements for a limestone panel. The first column gives the tool and specifications, the second column gives the power requirement, the third column gives the units, and the fourth column gives notes.

[11] Google maps

Table 6: Electricity Requirements Per Category for Limestone Panels			
Tool	**kWh**	**Units**	**Notes**
Cutting/Finishing @ 1 fpm - 50hp = 37.29 kW	0.621	per panel	1 minute to cut/finish 1 ft long panel
Electric lift/hoist - 2 HP = 1.491 kW	0.248	per panel	10 minutes (1/6 hr) use of the lift to hold the piece for epoxy inyection
Installation by hand	0.000		
Air Compressor - 35 HP = 26.1 kW			
hand tools (all pneumatic):			
Hand Drill	4.350	per panel	10 minutes use of the compressor for drilling 4 holes 6 inches long
Total kWh per panel	5.219		
Total kWh per ft² panel	**5.219**		

Limestone: Use, Demolition, and End of Life Phases

No maintenance is assumed during the limestone panels' use phase. Similar to the FRP panels, the lifespan is assumed to be equal to the lifespan of the building, or 100 years. At the end of life, a wrecking ball smashes the panels and transports them to the landfill in Marin. No recycling or reuse of limestone is assumed; 100% of the material goes to the landfill as solid waste.

FRP and Limestone: Use Phase Operating Costs

Use phase operating costs of the FRP and limestone panels were considered as follow. The R-value of an FRP panel was assumed to be 2 BTU/(h °F ft²) less than that of limestone[12,13]. This is a relatively small difference. In addition, these R-values do not take into consideration the additional R-values of the PHSH walls. Furthermore, the thermal mass properties of the limestone would likely reduce operational costs of the limestone option somewhat; this would compensate, to some extent, for the variance in R-value. For these reasons, the impact that this R-value difference would have on heating and cooling costs was considered negligible and is therefore not considered.

Impact Assessment Results and Analysis

Simapro models for both FRP and limestone panels were constructed using the data in Tables 1 through 6. A functional unit of a 1'x1' panel was used. Results showed that the MDF board used in the FRP production process was the material requiring the most significant energy inputs and yielding the highest waste and emissions outputs. Even though the material is used in only 2% of the FRP panel molds, it is the highest contributor of greenhouse gases, energy resources, $N0_x$, and $S0_x$ (see Appendix IV). The single score chart shows that this small amount of MDF results in a single score eight times greater than any other panel component. When compared with the production of limestone panels, this product produces almost four times the amount of $C0_2$ equivalent (greenhouse gases) and consumes twice the amount of energy as the production and use of a limestone panel. FRP panels made with MDF molds score 30 points higher than limestone on a single score scale (see Appendix VI, Appendix VII).

[12] Glacier Bay Inc.
[13] Marble Institute of America

Since the results from the FRP panels made with MDF were worse than limestone in most of the impact categories, a second scenario was considered: FRP panels made with 100% plywood. The assumption is that Kreysler could replace MDF with plywood, and a Simpro model was constructed.

Results showed that the stainless steel fasteners and the FRP process (comprised of the energy required to make the plywood molds and the transportation costs to the building site) were the most impactful components. Appendix VII shows that FRP panels made with 100% plywood molds emit about one-third the greenhouse gases and consume about one-sixth the energy of the limestone option. This modification resulted in an FRP single score reduction of 78%, or 3 ½ times less than that of limestone.

Appendix VII also shows that FRP panels' low weight is a significant advantage. For example, transportation of the limestone panels from Indiana to the Presidio carries the greatest environmental impact in its lifecycle: this step consumes 4½ times the amount of energy consumed in extracting the stone and releases 77% of the total greenhouse gases. The panels' low weight therefore conserves gasoline during transportation as well as yields less solid waste at end of life. Assuming 50% waste, limestone results in the production of seven times more waste than either FRP option.

In terms of emissions ($N0_x$, $S0_x$, Pb, Particulates < 10□□, and C0), the FRP panels made with 2% MDF board are the largest contributor among the three options (see Appendix VII, Emissions: Panel Comparison Chart). They emit 7 1/2 times more $N0_x$, three times more $S0_x$, and five times more CO than the limestone panels. FRP panels made with 100% plywood molds yield $N0_x$ and $S0_x$ emissions that differ by less than .05 kg from the limestone emissions. FRP panels made with 100% plywood molds also yield CO emissions that are ¼ that of the limestone CO emissions.

Land use can also be compared. Appendix VII, Land Use: Panel Comparison Chart shows that the quantity of land use remains approximately the same for the FRP made with MDF molds and 100% plywood molds: 1,200 cm^2a. The limestone panel uses over 42 times this amount at about 5,050 cm^2a. Therefore, choosing an FRP panel over a Limestone panel will significantly reduce land use.

Life Cycle Cost Analysis

A Life Cycle Cost Analysis was performed for the FRP panels made from both MDF and plywood molds and limestone panels. The data source for FRP component material costs was Kreysler and Associates or the closest distributor of a component to Kreysler's headquarters. The data source for limestone costs was the Indiana Limestone Institute. Table 7 provides the results. Limestone is the more expensive material with a total life cycle cost of $331,000; this is nearly three times more expensive than either FRP panel type.

FRP Life Cycle Cost Analysis

The cost of FRP panels made with MDF molds was $108,178.54; the cost with plywood molds was $107,938.76. Therefore, little cost difference existed between the two panel types. Overhead was 27% of material costs, and 5% of materials were assumed to be wasted[14].

Limestone Life Cycle Cost Analysis

The cost of limestone panels was $331,872.64. Overhead was 50%[15] of the materials costs, which included transportation to the Presidio and labor costs. Fifty percent of the raw limestone was assumed to be wasted.

Table 7: FRP & Limestone Life Cycle Cost Analysis

COMPONENT	FRP - 2% MDF		FRP - 100% Plywood		LIMESTONE	
	Per Functional Unit	Total	Per Functional Unit	Total	Per Functional Unit	Total
Raw Materials					$ 36.00[16]	$169,920.00
Resin	$ 1.00	$2,360.00	$1.00	$2,360.00		
Filler	$ 0.28	$660.80	$0.28	$660.80		
Gel coat	$ 0.94	$2,218.40	$0.94	$2,218.40		
Sand	$0.02	$47.20	$0.02	$47.20		
Chopped Strand Mat	$0.34	$802.40	$0.34	$802.40		
Nut plates + Fasteners	$30.80	$72,688.00	$30.80	$72,688.00	$16.00	$37,760.00
Molds	$ 1.18	$2,784.80	$1.10	$2,596.00		
Sand (30 grit mesh)	$0.26	$613.60	$0.26	$ 613.60		
Electricity	$ 1.27	$3,004.75	$1.27	$3,004.75	$0.31	$736.32
subtotal	$36.09	$85,179.95	$36.01	$84,991.15	$52.31	$208,416.32
Overhead	$9.75	$22,998.59	$9.72	$ 22,947.61	$ 26.16	$123,456.32
Grand Total	**$45.84**	**$108,178.54**	**$45.74**	**$107,938.76**	**$78.47**	**$331,872.64**

Regulatory and Performance Drivers

Several regulatory and performance drivers factor into whether FRP or limestone should be used as a cladding material on the PHSH. First is environmental impact: the PHSH is to be LEED

[14] Orris, D. M.
[15] The Indiana Limestone Institute
[16] USGS

Silver certified. Even though LEED does not explicitly reward the choice of a greener material over another, FRP panels made from plywood molds would make the most sense as the more sustainable option. A second driver relates to the National Park Service's 20% tax incentive program for historical buildings. This factor would favor the limestone, since bureaucratic red tape must be fought through in order for a change of material to be permitted from the old material (limestone) to the new material (FRP). A third driver is cost, which favors either FRP option by about a factor of ten. A fourth driver is ease of transportation, installation, and disposal, factors which heavily favor FRP given the lightweight nature and low volume of the material. Finally, a fifth driver is energy savings for the future condo owners: FRP has the higher R-value and will therefore save the owners money over the limestone option.

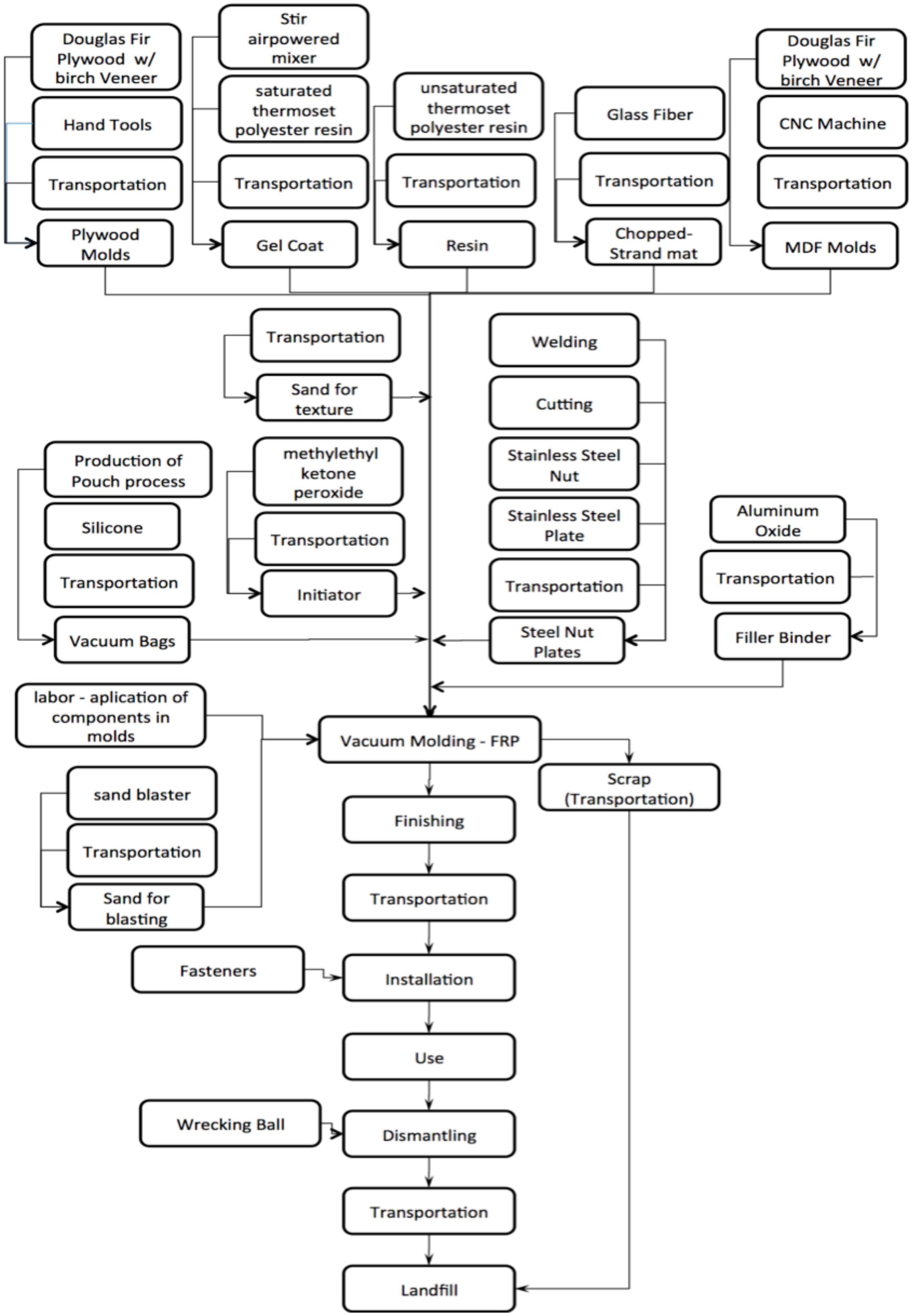
Conclusions and Recommendations

Process-based LCA analysis of FRP and limestone façade panels provides an effective method of comparing the environmental costs and benefits attributable to each option. The individual LCA results pinpointed components and processes that created the greatest impact in terms of energy and land use, emissions, and energy inputs for each panel type. This method also allows easy estimation of reductions in environmental impacts after changes were made to material and process inputs.

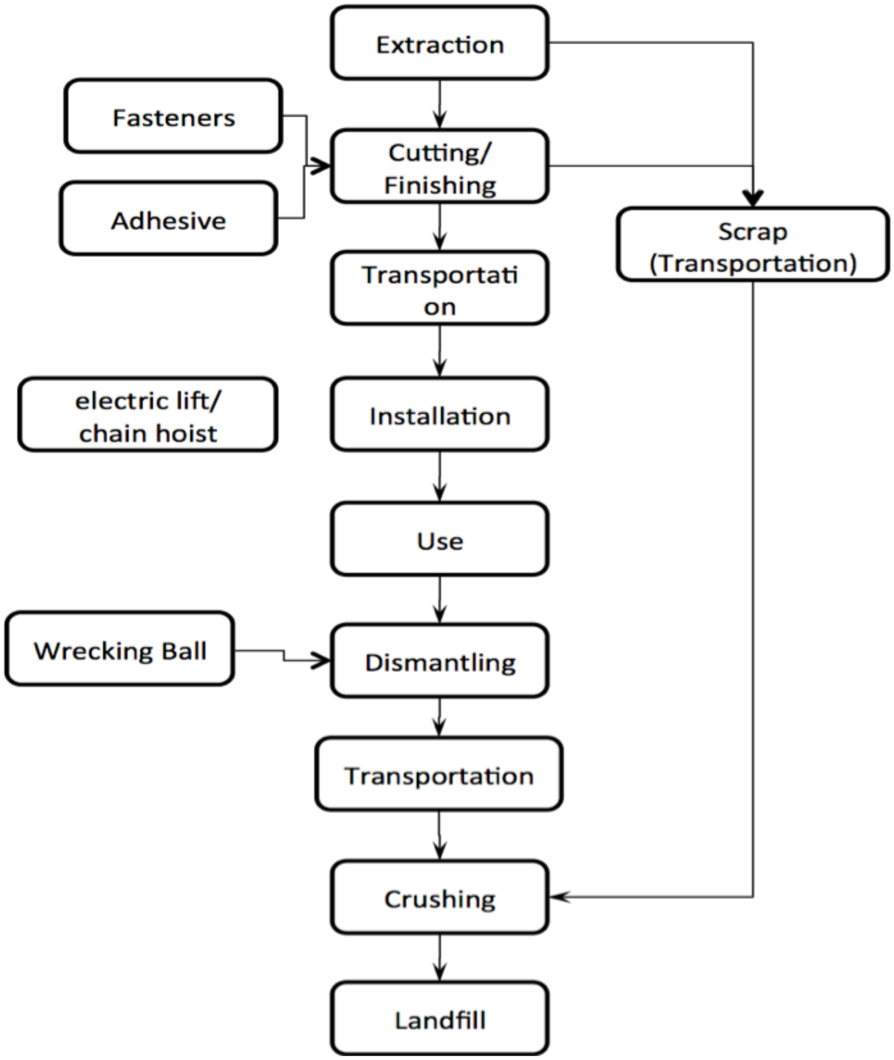
Comparison of LCA results for the two materials showed that the environmental impact of FRP panels made from MDF particle board is greater in many categories, including greenhouse gas emissions, energy resources, NO_x, SO_x, and CO. The most significant environmental impacts are contributed by the MDF particle board. In conclusion, Kreysler's FRP panels cannot be validated as a greener material when compared with limestone panels in terms of these emissions and energy resources. It should be noted, however, that limestone panels produce more solid waste and use more land than FRP Panels by far. In addition, life cycle cost analysis shows that the upfront financial cost of the limestone panels is nearly three times that of either FRP option.

FRP panels made with 100% plywood resulted in lower environmental impacts than limestone across all categories. For this option, the stainless steel fasteners and the FRP process itself were the greatest contributors. Therefore, the recommendation to Kreysler and Associates is to modify the production process of FRP panels so that an alternate mold material than MDF, such as plywood, is used.

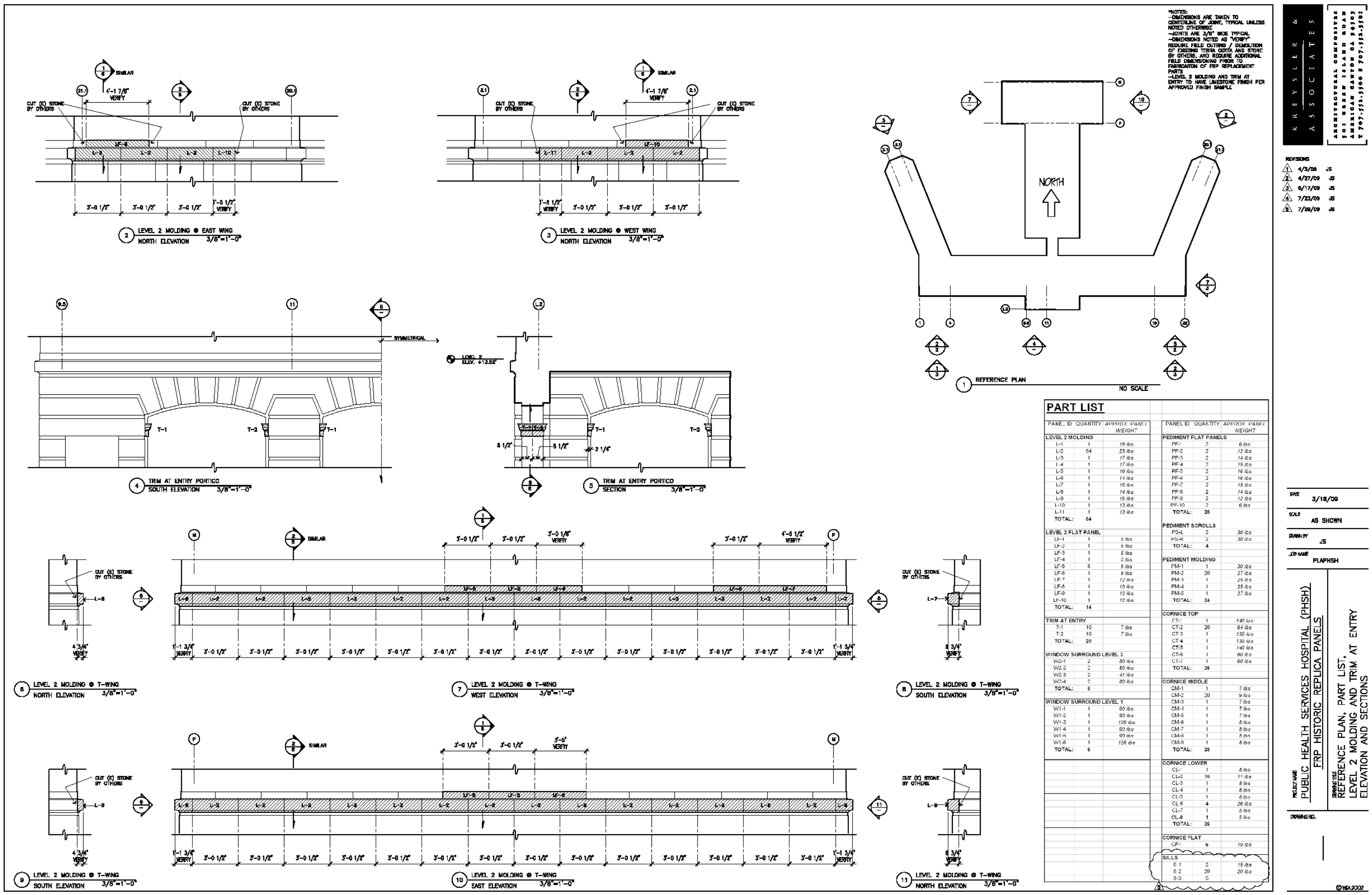
Appendix I – FRP Facade Process Flow Diagram



Appendix II – Limestone Facade Process Flow Diagram



Appendix III – Shop Drawings



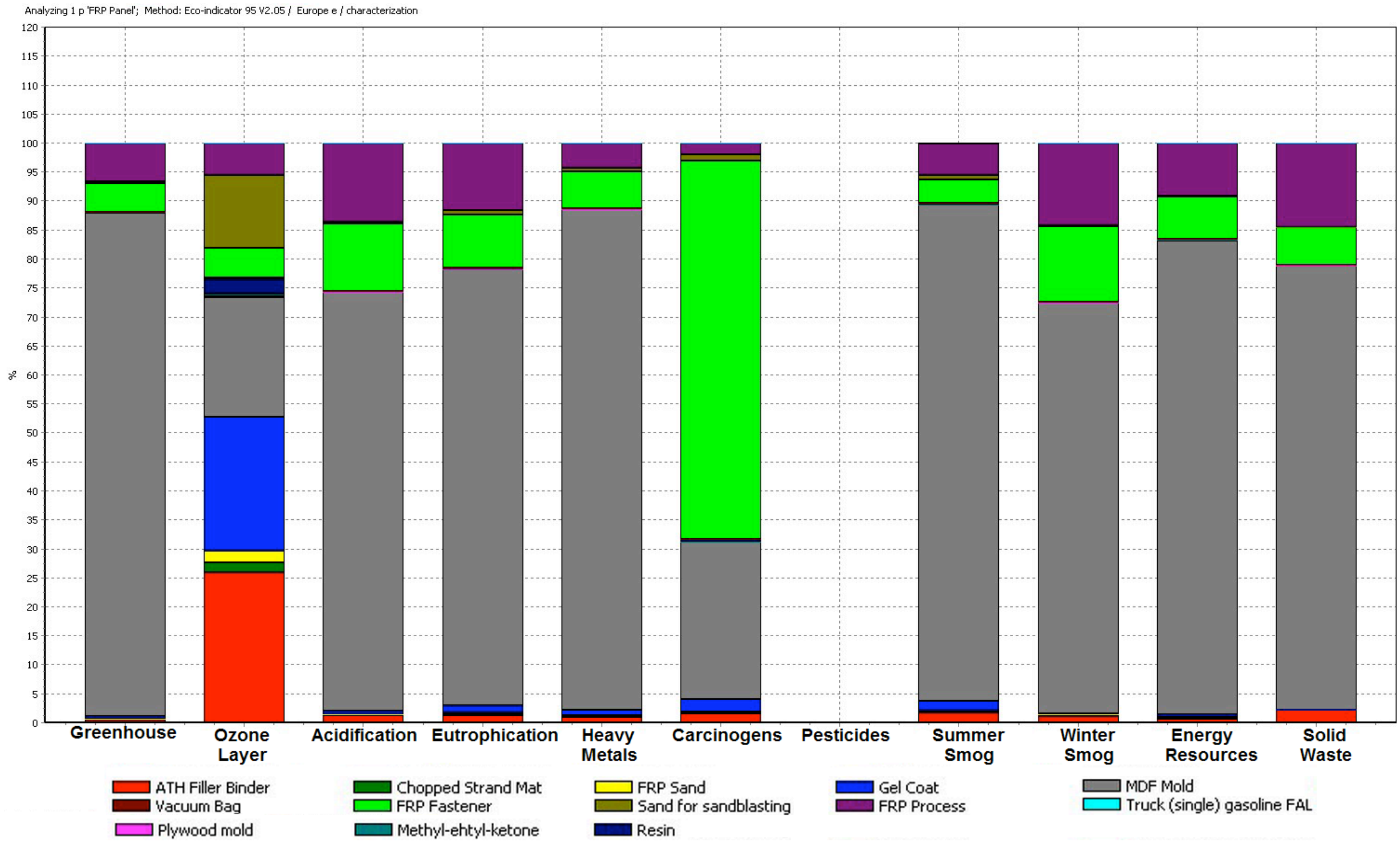
Appendix IV – FRP 2% MDF Molds Results

[eco-indicator 95 used for all charts & graphs]

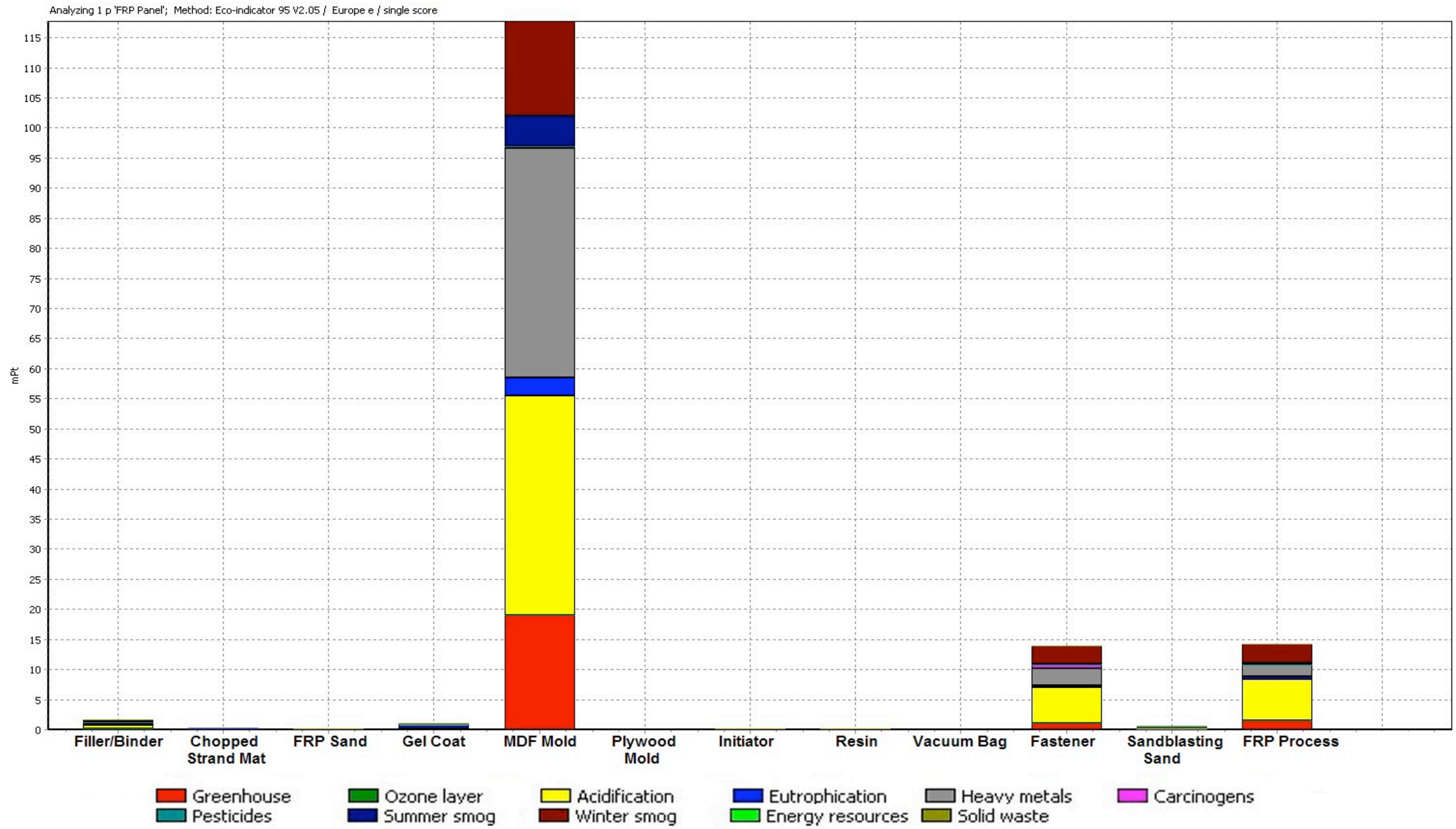
ENERGY & EMMISSIONS TOTALS & CONTRIBUTIONS > 1% : FRP WITH 2% MDF MOLDS									
Impact category	Unit	Total	ATH Filler Binder	Chopped Strand Mat	FRP Sand	Gel Coat	MDF Mold	FRP Fastener	FRP Process
Greenhouse	kg CO_2	114.182					99.300	5.662	7.657
Energy resources	MJ LHV	1442.650	9.567	2.513	0.539	6.656	1179.783	104.365	131.082
$N0_x$	kg	0.229	0.00268				0.175	0.0176	0.027
$S0_x$	kg	0.381	0.00472				0.285	0.0302	0.058
Pb	kg	5.26E-05		7.85E-07			1.59E-31	8.08E-06	
Particulates unspecified	kg	4.75					4.74		
Particulates, < 10 um	kg	.0125					.0102	.00065	.00144
Carbon monoxide	kg	.507					.468	.0316	

LAND USE : FRP WITH 2% MDF MOLDS							
Impact category	Unit	Total	ATH Filler Binder	FRP Sand	Gel Coat	FRP Fastener	Sand blasting Sand
Land use II-III	cm2a	233	33.6	10.6	67.4	32.8	65.9
Land use II-III, sea floor	cm2a	180	36.8		73.8		40.2
Land use II-IV	cm2a	298	55.4	15.2	111		93.8
Land use II-IV, sea floof	cm2a	18.6	3.79		7.62		4.15
Land use III-IV	cm2a	518	113		226		116
Land use IV-IV	mm2a	26.5	4.02	1.75	8.07		10.8

SIMAPRO CHARACTERIZATION CHART - FRP WITH 2% MDF MOLDS



SIMAPRO SINGLE SCORE CHART - FRP WITH 2% MDF MOLDS



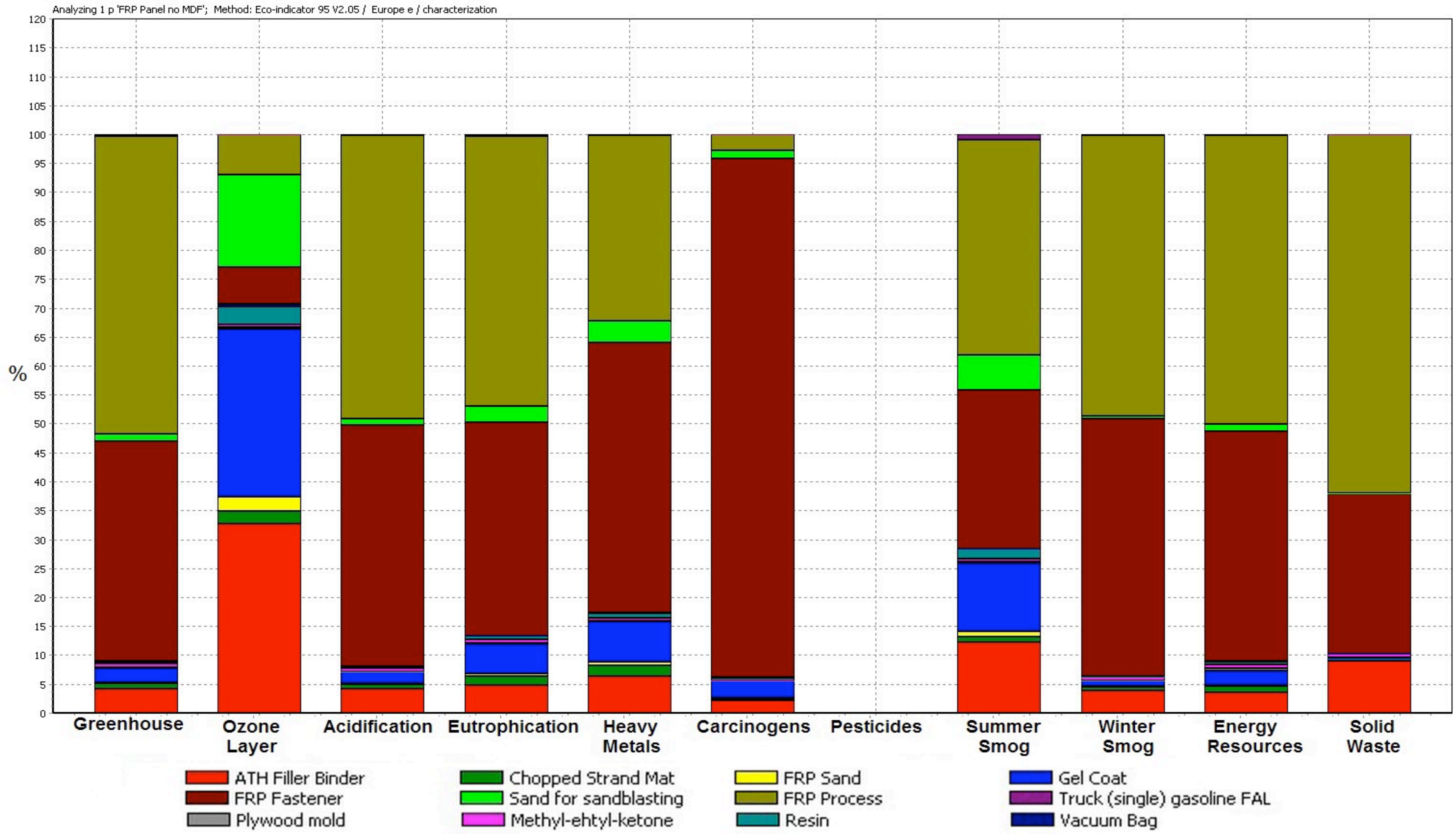
Appendix V – FRP 100% Plywood Molds Results

[eco-indicator 95 used for all charts & graphs]

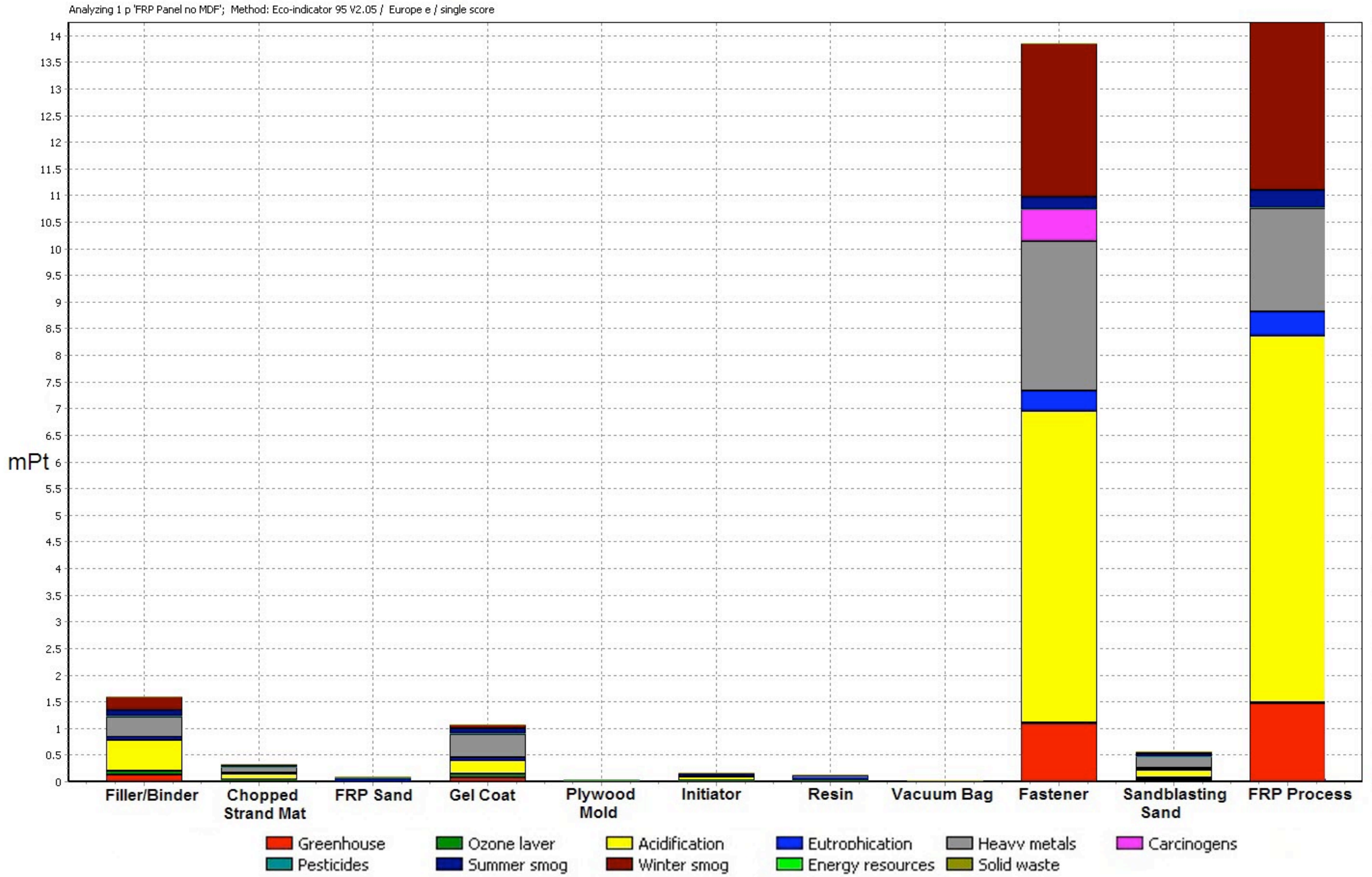
ENERGY & EMMISSIONS TOTALS & CONTRIBUTION > 1% : FRP ALL PLYWOOD MOLDS									
Impact category	Unit	Total	ATH Filler Binder	Chopped Strand Mat	Gel Coat	FRP Fastener	Sand for sandblasting	FRP Process	Transportation to Site
Greenhouse	kg CO2	14.8816	0.6187		0.3589	5.6620		7.6574	
Energy resources	MJ LHV	262.8667			6.6559	104.3653		131.0822	
$N0_x$	kg	0.0538			0.00293	0.0176		0.027	
$S0_x$	kg	0.095				0.0302		0.058	
Pb	kg	1.13E-05		7.85E-07					
Particulates, unspecified	kg	0.00274	0.00273						
Particulates, < 10 um	kg	0.00222				0.00065		0.00144	0.000118
Carbon monoxide	kg	0.0389	0.00058		0.000959	0.0316	0.000511	0.0038	0.000991

LAND USE : FRP ALL PLYWOOD MOLDS							
Impact category	Unit	Total	ATH Filler Binder	FRP Sand	Gel Coat	FRP Fastener	Sand blasting Sand
Land use II-III	cm2a	223	33.6	10.6	67.4	32.8	65.9
Land use II-III, sea floor	cm2a	179	36.8		73.8		40.2
Land use II-IV	cm2a	297	55.4	15.2	111		93.8
Land use II-IV, sea floof	cm2a	18.5	3.79		7.62		4.15
Land use III-IV	cm2a	516	113		226		116
Land use IV-IV	mm2a	26.5	4.02	1.75	8.07		10.8

SIMAPRO CHARACTERIZATION CHART - FRP ALL PLYWOOD MOLDS



SIMAPRO SINGLE SCORE CHART - FRP ALL PLYWOOD MOLDS



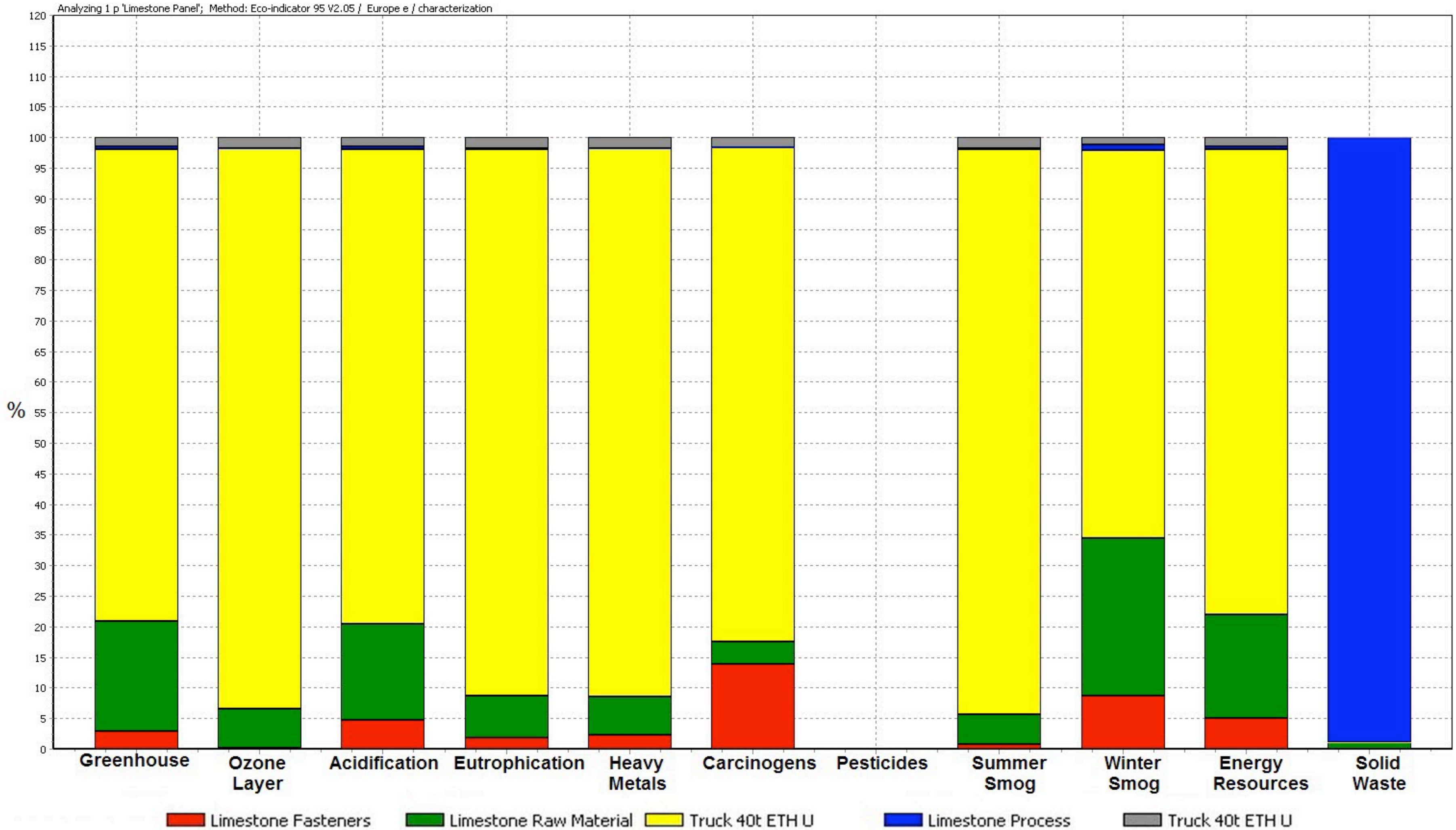
Appendix VI – Limestone Results

[eco-indicator 95 used for all charts & graphs]

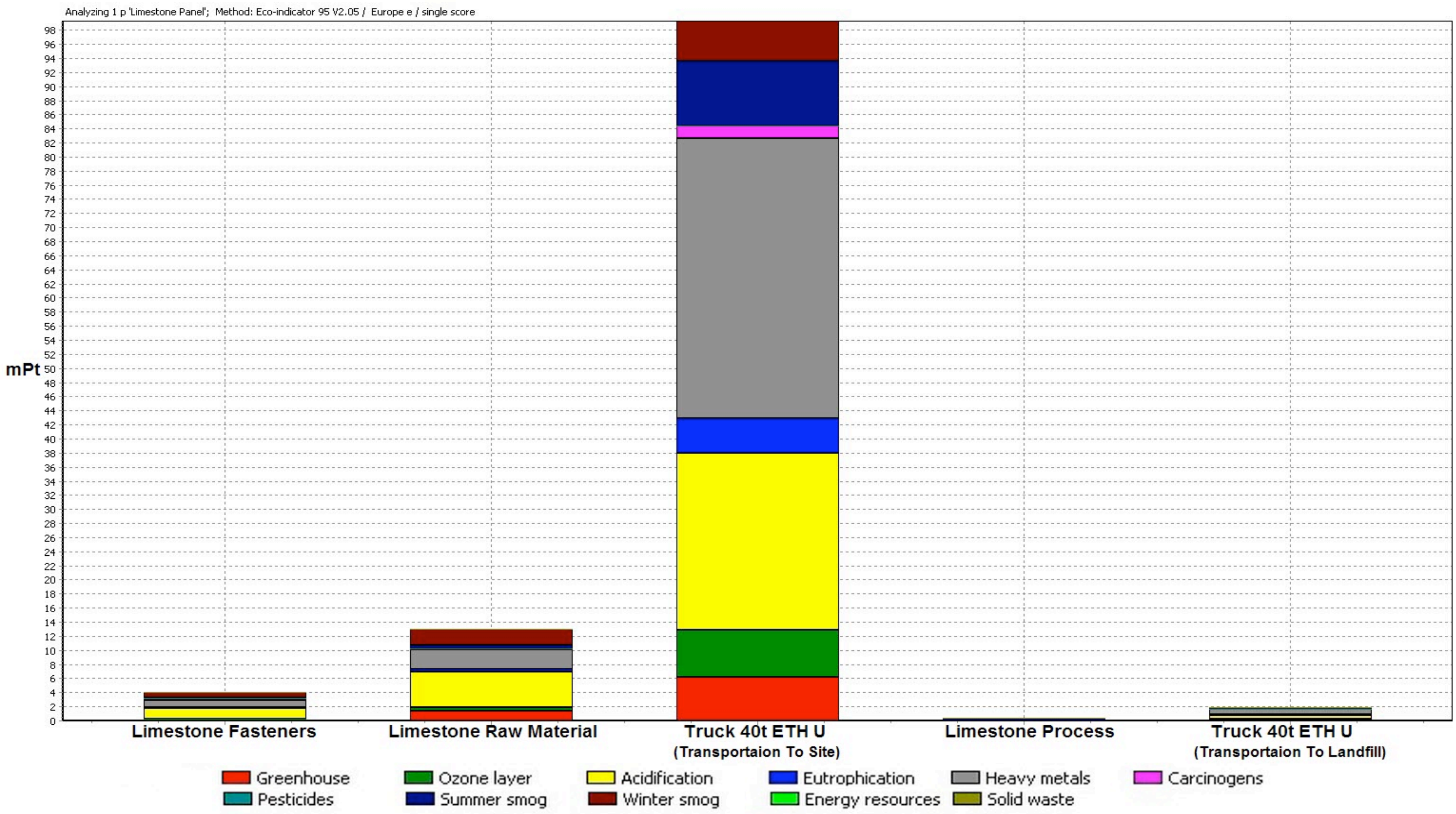
ENERGY & EMMISSIONS TOTALS & CONTRIBUTION > 1% : LIMESTONE PANEL							
Impact category	**Unit**	**Total**	**Limestone Fasteners**	**Limestone Raw Material**	**Transportation to Site**	**Limestone Process**	**Transportation to Landfill**
Greenhouse	kg CO2	41.6453903			32.152754		
Energy resources	MJ LHV	754.397738		127.8180793	574.59019		
$N0_x$	kg	0.037			0.282		
$S0_x$	kg	0.136		0.0421	0.0899		
Pb	kg	0.0000938			0.0000888		
Particulates	kg	0.00351		0.00334		.000167	
Particulates, < 10 um	kg	.000709		.000675		3.37E-5	
Carbon monoxide	kg	.112	.015	.00503	.0919		

LAND USE : Limestone						
Impact category	**Unit**	**Total**	**Limestone Fasteners**	**Limestone Raw Material**	**Transportation to Site**	**Transportation to Landfill**
Land use II-III	**cm2a**	9120	73.5	2560	6360	1250
Land use II-III, sea floor	**cm2a**	7600	15.2	478	6970	137
Land use II-IV	**cm2a**	11200	3.07	298	10500	206
Land use II-IV, sea floof	**cm2a**	784	1.57	49.3	719	14.1
Land use III-IV	**cm2a**	21800	4.72	47.9	21300	418
Land use IV-IV	**cm2a**	23.6	0.00639	15.8	7.62	0.149

SIMAPRO CHARACTERIZATION CHART – LIMESTONE PANELS



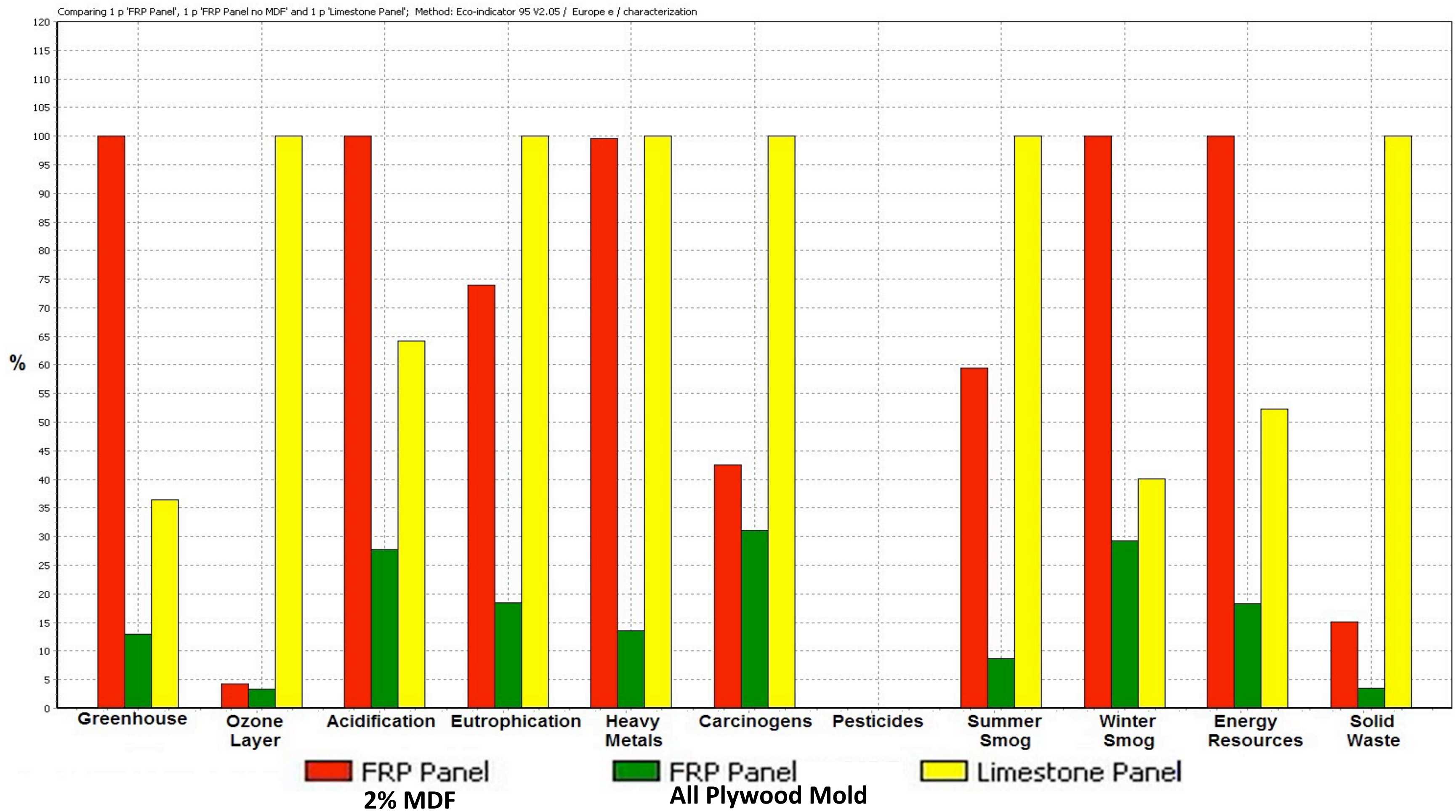
SIMAPRO SINGLE SCORE CHART – LIMESTONE PANELS



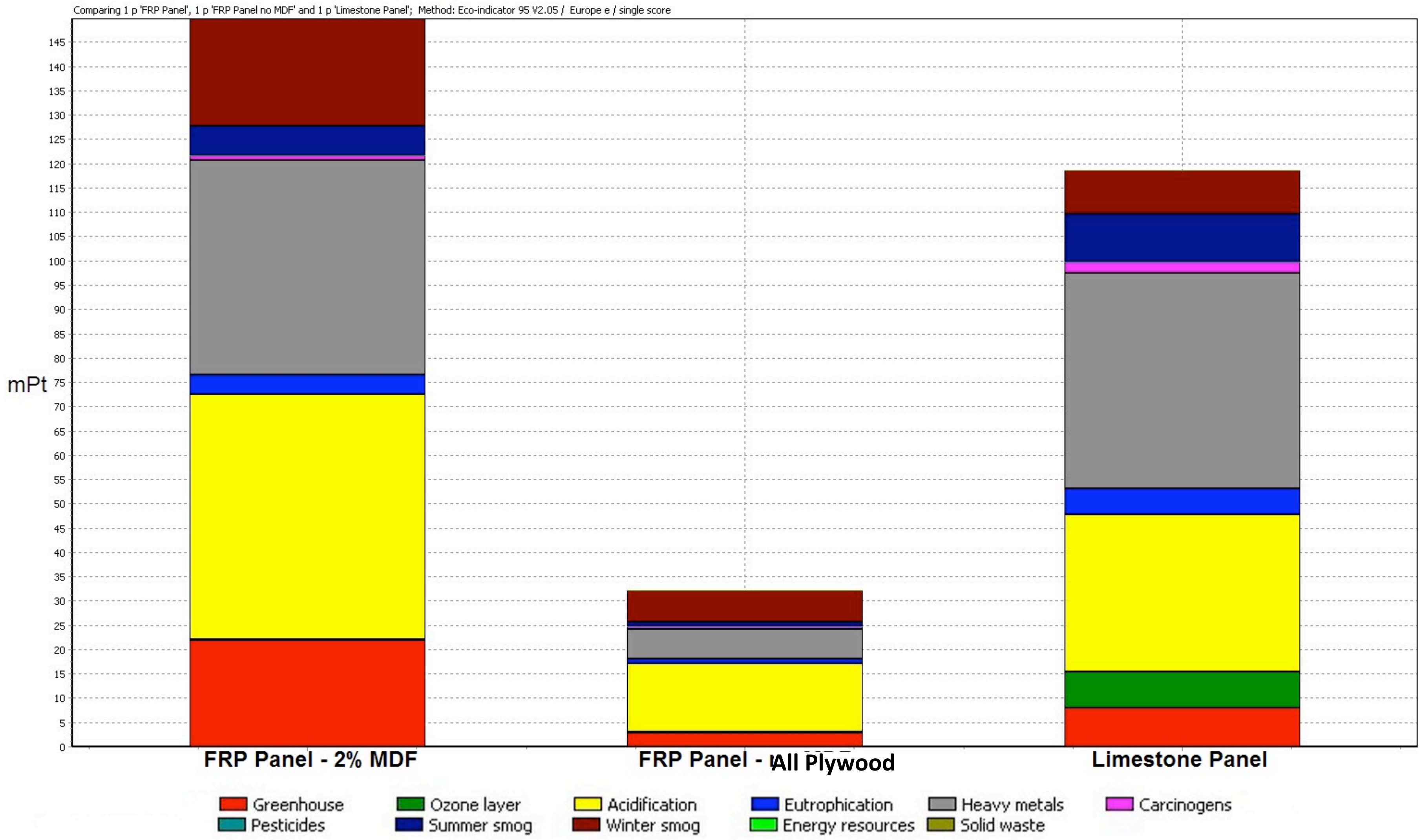
Appendix VII – FRP vs. Limestone Results

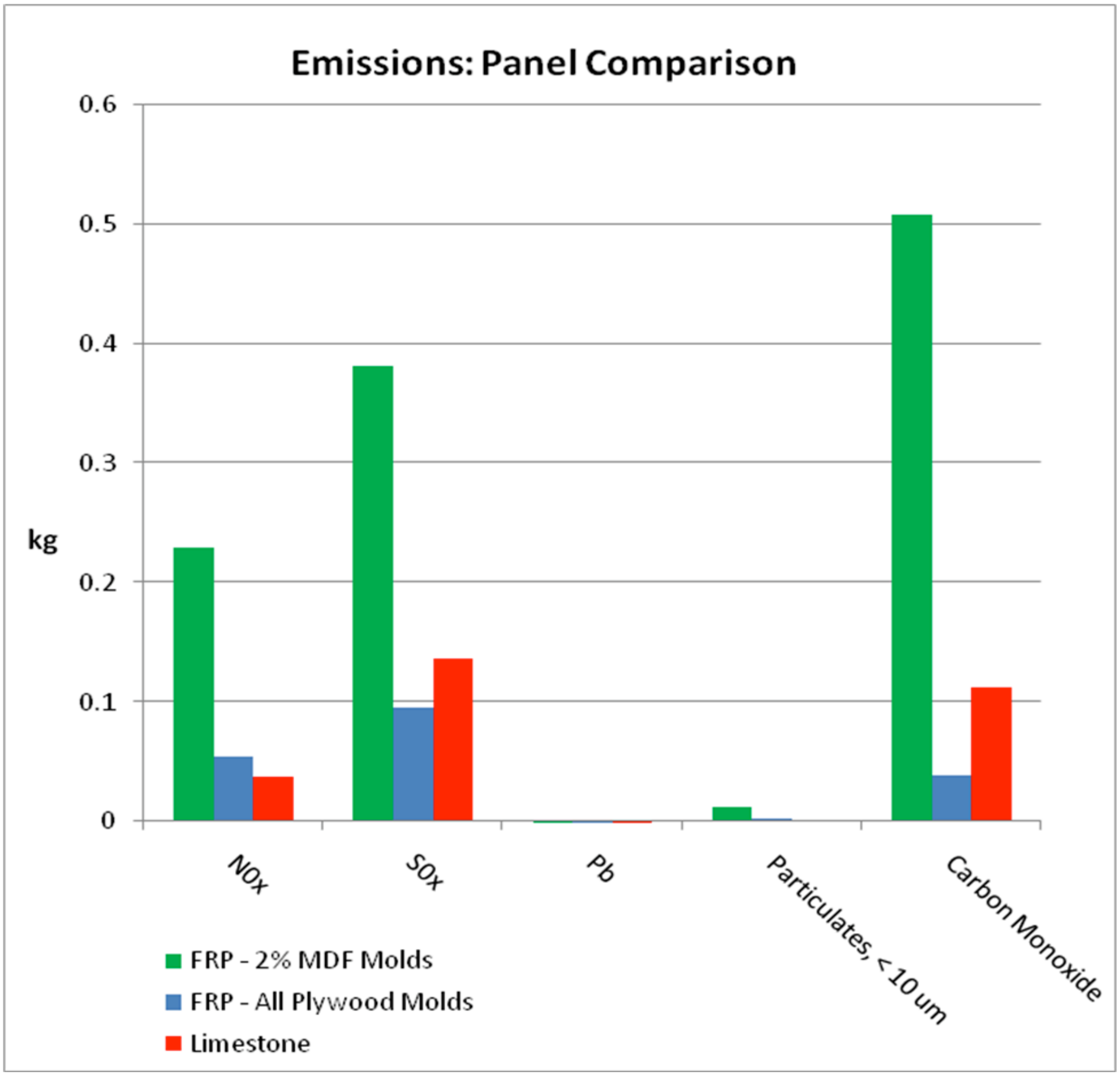
[eco-indicator 95 used for all charts & graphs]

SIMAPRO CHARACTERIZATION CHART – PANEL COMPARISON

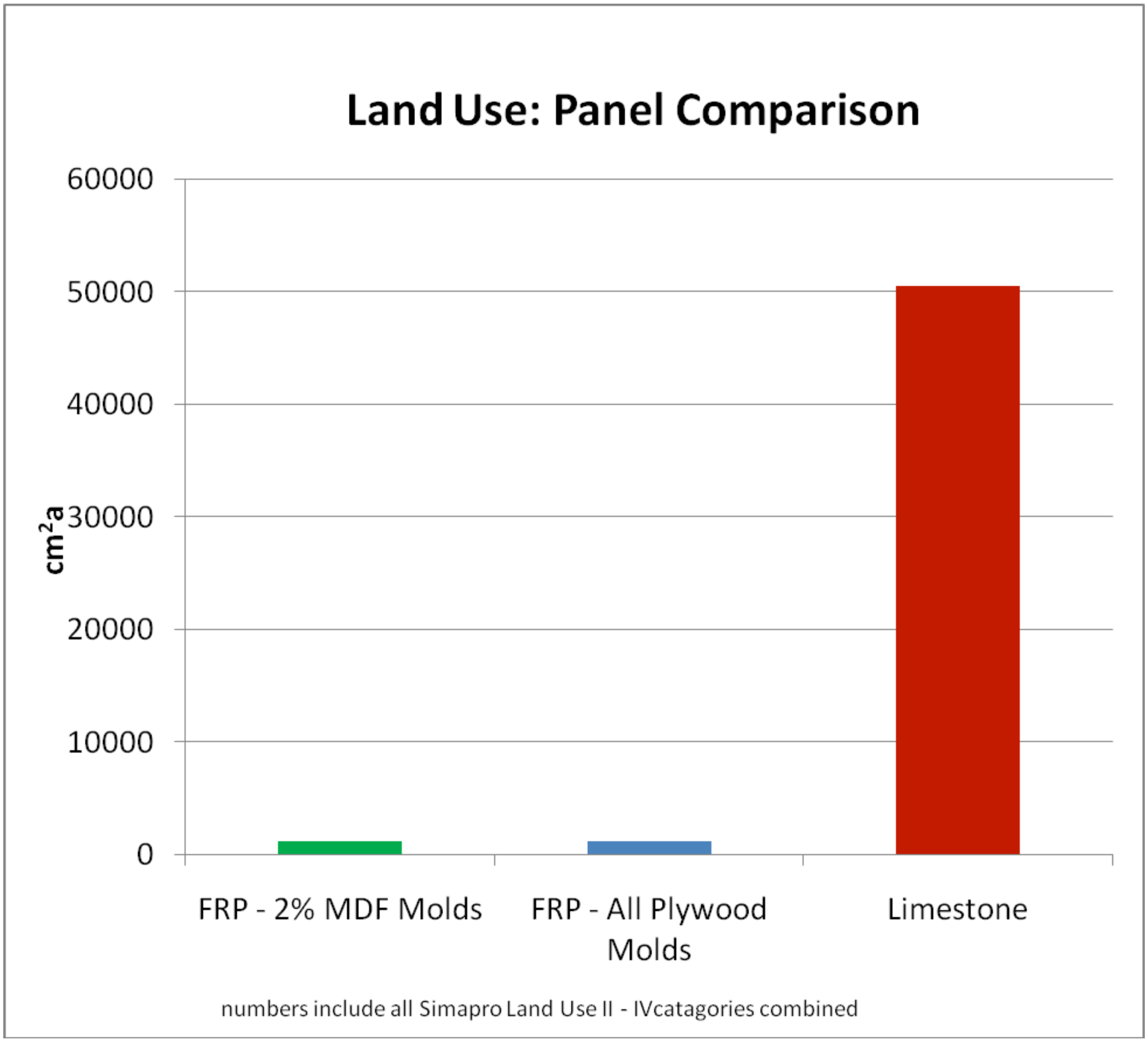


SIMAPRO SINGLE SCORE CHART – PANEL COMPARISON





Emissions: Panel Comparison
0.6
0.5
0.4
0.3
0.2
0.1
0
kg
N0x
S0x
Pb
Particulates, < 10 um
Carbon Monoxide
FRP - 2% MDF Molds
FRP - All Plywood Molds
Limestone


Land Use: Panel Comparison
60000
50000
40000
30000
20000
10000
0
cm²a
FRP - 2% MDF Molds
FRP - All Plywood Molds
Limestone
numbers include all Simapro Land Use II - IVcatagories combined

Appendix VIII – FRP Component Data Sheets

Valspar Composites

TECHNICAL DATA

Print Date: 10/2/2009

5776T90001 Gel Coat Translucent Base

PRODUCT DESCRIPTION

5776T90001 is a premium performance ISO/ NPG gel coat which incorporates rheological characteristics resulting in excellent leveling, sag resistance and repair qualities with minimum porosity. It cures to an extremely tough, high-gloss finish that provides superior resistance to weathering, water, corrosion and chalking.

5776 Series gel coats are ideal where highest quality performance is a must. They are currently being used in the marine and transportation industries and can also be used in other applications requiring resistance to severe outdoor exposure. The 5776 Series is the base for Valspar's Quick Tint system and is available in a wide range of colors.

TYPICAL PHYSICAL CHARACTERISTICS (all tests at 77° F.)

Weight Per Gallon:	9.5 – 10.5 Pounds
Viscosity:	3000 - 3400 cps.; Brookfield RVT #4 @ 50 rpm
Thixotropic Index:	6.0 - 8.0
Gel Time:	8 – 10 Minutes; 2% MEKP @ 77° F
Cure Time:	1 Hour
Flash Point, Seta-Flash closed cup	88° F.
Shelf Life:	3 Months From Date of Shipment
VOC per SCAQMD Method 304-91:	95 Grams/Liter
% Monomer:	40% Maximum Depending on Color

Values listed are typical indicators only. In-mold coating physical properties may vary with usage and storage conditions.

APPLICATION SUGGESTIONS

WORKS EXTREMELY WELL IN CONVENTIONAL EQUIPMENT

5776 Series gel coats are formulated for spray application as supplied. Thinning is not recommended. For catalyzation, use MEKP @ 2% for gel times of 8 - 10 minutes at 77° F. Do not catalyze at levels below 1-1/2% or above 3%. Apply in several thin overlapping coats rather than a single thick coat. This will help avoid sagging, porosity, solvent entrapment and other defects. Make sure the air pressure is adjusted properly, and that the spray gun lines are free of solvent, water and oil. Apply to a thickness of 18 - 25 mils wet. Brush application is not recommended.

- Store containers indoors or under cover.
- Normal storage area temperature should be 65° F. - 80° F.
- Use only original containers full and sealed.
- Keep containers away from heating pipes or radiators.
- Use a "first-in-first-out" system of stock rotation to ensure use within 90-day period.

The data on this sheet represent typical values. Since application variables are a major factor in product performance, this information should serve only as a general guide. Valspar assumes no obligation or l for use of this information. UNLESS VALSPAR AGREES OTHERWISE IN WRITING, VALSPAR MAKES NO WARRANTIES, EXPRESS OR IMPLIED, AND DISCLAIMS ALL IMPLIED WARRA INCLUDING WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR USE OR FREEDOM FROM PATENT INFRINGEMENT. VALSPAR WILL NOT BE LIABLE FOR ANY SPE INCIDENTAL OR CONSEQUENTIAL DAMAGES. Your only remedy for any defect in this product is the replacement of the defective product, or a refund of its purchase price, at our option.

www.valsparcomposites.com • (800) 397-1062

A FAMILY OF SOLUTIONS

ENGINEERED MATERIALS

J. M. Huber Corporation
1000 Parkwood Circle
Suite 1000
Atlanta, GA 30339
800-313-6888
www.hubermaterials.com

SB-336
ALUMINA TRIHYDRATE

DESCRIPTION

SB-336 is a medium particle size ATH product that provides low cost flame retardancy and smoke suppression in a variety of applications. The unique particle size is specifically designed for low viscosites, high filler loading levels, and excellent processing characteristics. SB-336 is recommended for spray-up or hand lay-up FRP applications, filament winding, panel production, resin injection, SMC/BMC, foam materials, and cast polyester and epoxy parts.

A complete range of surfacing modifications is available to aid processing and enhance physical properties. These include silanes, stearates and wetting agents. Technical service is available.

TYPICAL CHEMICAL ANALYSIS

Al_2O_3, %	64.9
SiO_2, %	0.005
Fe_2O_3, %	0.007
Na_2O (total), %	0.2
Na_2O (soluble), %	0.025
Loss on ignition (550°C), %	34.6
Free Moisture (105°C), %	0.2

TYPICAL PHYSICAL PROPERTIES

Screen Analysis	
% on 100 mesh	0
% on 200 mesh	0
% on 325 mesh	10
% through 325 mesh	90
% less than 10 microns	33
Median Particle Diameter, microns	15.5
Surface Area (m^2/gm)*	1.5
Specific Gravity (gm/cm^3)	2.42
Bulk Density – loose (gm/cm^3)	0.75
Bulk Density – packed (gm/cm^3)	1.2
Oil Absorption**	23
TAPPI Brightness***	87

* As measured with a Quantachrome monosorb surface area analyzer (BET)
** Oil absorption, ml, boiled linseed oil per 100 gm filler
*** TAPPI Brightness measured with a Hunterlab Colorimeter

The information contained herein is believed to be accurate and reliable, but **A HUBER MAKES NO WARRANTIES OR MERCHANTABILITY OR FITNESS FOR PARTICULAR PURPOSE, OR ANY OTHER EXPRESS OR IMPLIED WARRANTY.** The information herein relates only to the specific product described and not to such product in combination with any other product. Providing information as herein contained is not to be regarded by implication or otherwise as conveying any rights or permission for use which would violate any patent rights, property rights or violate any law, safety code or insurance regulation. Natural mineral products are subject to the normal variations related to the deposits from which they are mined.

©1999 J.M. Huber Corporation. Huber and the Huber logo are registered trademarks of J.M. Huber Corporation

A FAMILY OF SOLUTIONS

ENGINEERED MATERIALS

J. M. Huber Corporation
1000 Parkwood Circle
Suite 1000
Atlanta, GA 30339
800-313-6888
www.hubermaterials.com

SB-432
ALUMINA TRIHYDRATE

DESCRIPTION

Huber Engineered Materials' SB-432 developed especially for SMC, BMC, resin injection and high solids coatings, has a unique particle size distribution that provides the best possible combination of viscosity, flame, electrical and molding properties that can be derived from an ATH filler. A closely controlled top size with a large super fine faction yields rapid dispersion in resin. Excellent mold flow and wet-out characteristics result in superior surface profile, minimal porosity, even pigmentation, and excellent filler and reinforcement distribution throughout the molded part.

A complete range of surface modifications is available to aid processing and enhance physical properties. These include silanes, stearates and wetting agents. Technical service is available.

TYPICAL CHEMICAL ANALYSIS

Al_2O_3, %	64.9
SiO_2, %	0.005
Fe_2O_3, %	0.007
Na_2O (total), %	0.2
Na_2O (soluble), %	0.03
Loss on ignition (550° C), %	34.6
Free Moisture (105° C), %	0.3

TYPICAL PHYSICAL PROPERTIES

Screen Analysis	
% on 100 mesh	0
% on 200 mesh	0
% on 325 mesh	0.1
% through 325 mesh	99.9
% less than 10 microns	53
****Median Particle Diameter, microns	9
Surface Area (m^2/g)	2
Specific Gravity (g/cm^3)	2.42
Bulk Density - loose (g/cm^3)	0.65
Bulk Density - packed (g/cm^3)	1
Oil Absorption	28
TAPPI Brightness	89

* As measured with a Quantachrome monosorb surface area analyzer (BET)
** Oil absorption, ml. boiled linseed oil per 100 gm filler
***TAPPI Brightness measured with a Hunterlab Colorimeter
****By Sedigraph

The information contained herein is believed to be accurate and reliable, but **A HUBER MAKES NO WARRANTIES OR MERCHANTABILITY OR FITNESS FOR PARTICULAR PURPOSE, OR ANY OTHER EXPRESS OR IMPLIED WARRANTY.** The information herein relates only to the specific product described and not to such product in combination with any other product. Providing information as herein contained is not to be regarded by implication or otherwise as conveying any rights or permission for use which would violate any patent rights, property rights or violate any law, safety code or insurance regulation. Natural mineral products are subject to the normal variations related to the deposits from which they are mined.

©2001, 2000, 1999 J.M. Huber Corporation. Huber and the Huber logo are registered trademarks of J.M. Huber Corporation

Revised 3/01

PPG Fiber Glass

TECHNICAL DATA SHEET
PPG CHOPPED STRAND MAT

Application: *Chopped Strand Mat is a powder-bound multi-compatible mat designed for use in orthophthalic and isophthalic polyester, vinylester, and epoxy resin systems.*

PRODUCT DESCRIPTION			
Type of Fiber	E-Glass (ASTM D 578-00, paragraph 4.2.2)		
Chopped Strand Lengths	2 inch (5.1 cm)		
Glass Sizing	Silane		
Mat Binder	High Solubility Polyester		
Densities (oz/ft^2)	1.5	2.0	3.0
(g/m^2)	450	600	900
Ignition Loss, nominal	3.2%	3.2%	3.2%
Roll Lengths (at 11" (28cm) diameter)	190 ft (58 m)	150 ft (46 m)	100 ft (31 m)
Standard Widths	38, 50, and 60 inches (97, 127, and 152 cm)		

- **Excellent weight uniformity**
- **Minimal loose fibers**
- **High wet and dry tensile strength**
- **Increased mat loft for optimal laminate thickness**
- **Ease of air release during rollout**
- **Multi-compatible sizing allows for use in both general purpose and corrosion resins**
- **Laminate clarity is excellent in a multitude of resins**
- **Supported by PPG's technical resources**

PACKAGING & PALLETIZING DATA

Standard Widths

- All rolls and densities are 11 inches in diameter
- 16 stretch wrapped rolls per 45"x 45" pallet

For further information, please contact your local distributor or PPG sales office.

When ordering, specify:

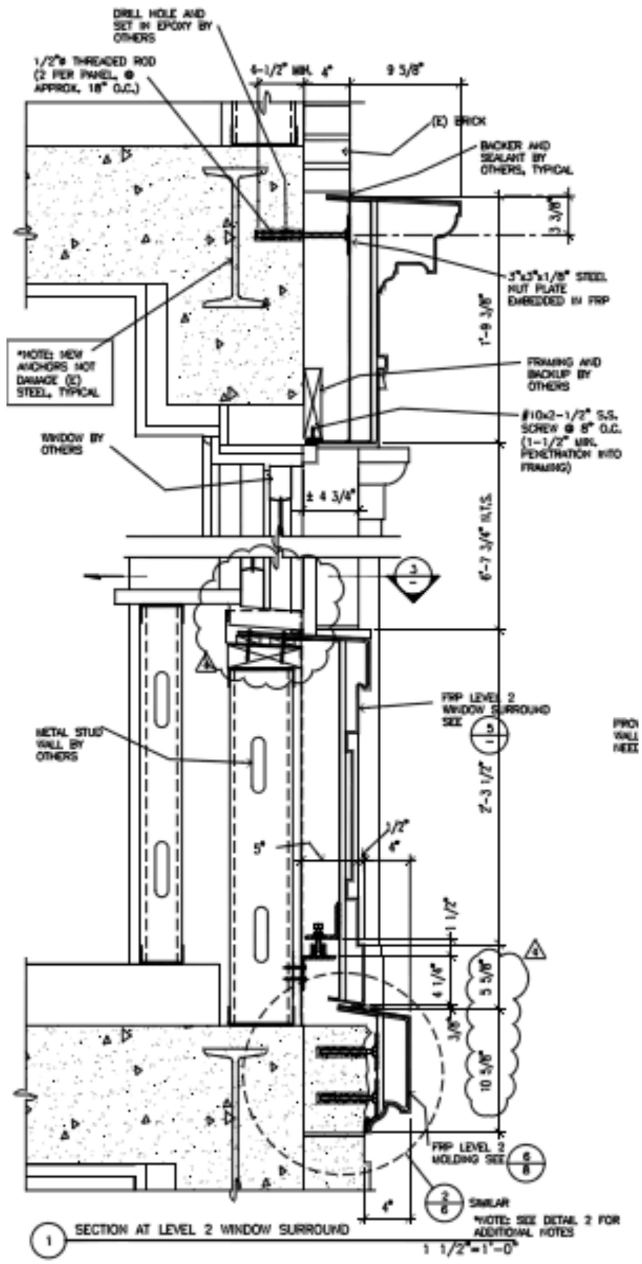
- Chopped Strand Mat
- Density (oz/ft^2)
- Width (inches)
- Weight desired for each density/width combination (number of pallets)

Storage: These products should be stored at room temperature and at a relative humidity of 65% +/- 10%. To avoid problems with humidity or static electricity, the glass product should be conditioned in the working area prior to use.

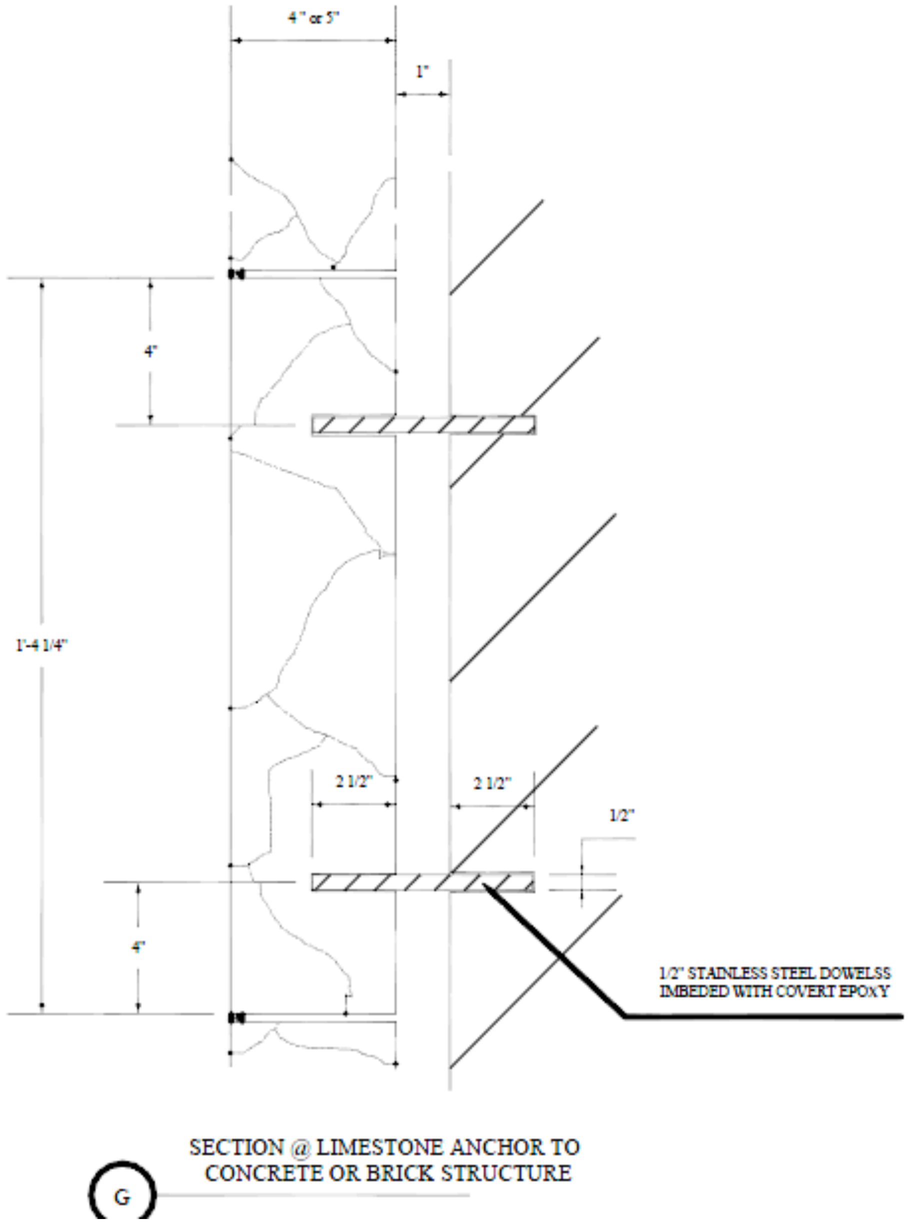
Caution: To avoid the possibility of potential injury, maintain column stability by limiting pallet stacking to two high as noted on individual shipping container.

1-800-613-0155 ■ fgcustservice@ppg.com ■ www.ppgfiberglass.com

Appendix IX – Panel Fasteners



TYPICAL FRP FASTENER DETAIL



TYPICAL LIMESTONE PANEL FASTENERS

Bibliography

Airtech International, 2003. Accessed 20 November 2009, https://www.airtechonline.com/htm/defaultnetscape.htm.

Australia National University, *The Manufacturing Process: Medium Density Fibreboard*. 1 November 1996. Accessed 30 November 2009. http://sres-associated.anu.edu.au/fpt/mdf/manufacture.html.

BEES 4.0 Database. National Institute of Standards and Technology, Building and Fire Research, 2007.

Bosch. (2009). Retrieved November 2009, from Tool Orbit: http://www.toolorbit.com/Bosch/Bosch-7561-118.html.

Energy, U. D. (2009, June 19). Accessed 25 November 2009, http://www.eia.doe.gov/aer/pdf/aer.pdf.

Glacier Bay Inc. *Transmission of Heat Conduction, Convection and Radiation*, 2009. Accessed 25 November 2009, http://www.glacierbay.com/Heatprop.asp.

Google. (2009). *Google maps*. Accessed 20 November 2009, http://maps.google.com/maps?f=s&utm_campaign=en&utm_source=en-ha-na-us-bk-gm&utm_medium=ha&utm_term=google%20maps.

The Indiana Limestone Institute of America, Inc. *The Indiana Limestone Handbook*, 2009.

Kreysler, B. (2009, Sept - Dec.). CEO, Kreysler & Associates. (CEE 226 Group 9, Interviewer).

Marble Institute of America. (2009). *R-Value for Natural Stone*. Accessed 14 November 2009, http://www.marble-institute.com/industryresources/rvalue.cfm.

Metric, S. (2009, April). *SI metric.co.uk*. Accessed 12 November 2009, http://www.simetric.co.uk/si_wood.htm.

Northern Tool + Equipment Catalog Co., "Milwaukee", 2009. Accessed 15 November 2009, http://www.northerntool.com/webapp/wcs/stores/servlet/product_6970_200190674_200190674.

Northern Tool and Equipment Catalog Co., "Marco", 2009. Accessed 15 November 2009, http://www.northerntool.com/webapp/wcs/stores/servlet/product_6970_200229924_200229924.

Orris, D. M. (2007). *Dimension Stone.* Retrieved November 2009, from USGS Publication Warehouse: http://pubs.usgs.gov/of/2007/1214/PDF/11.0-dimension-stone-FINAL.pdf

Pre Consultants, Simapro Software, 2009.

USGS. (2008, November 17). Stone (dimension) statistics U.S. Geological Survey. Retrieved November 2009, from USGS: http://minerals.usgs.gov/ds/2005/140/stonedimension.pdf