So You Want to Replace Your PVC

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ABSTRACT

PVC is often a material chosen for replacement when it comes to green products. This is due to PVC's chlorine content. Carcinogenic materials are used in making PVC and are released when it's combusted. Other toxic materials can leach out of the PVC while in use. Replacement materials are often chosen simply for not containing PVC. In this paper, a three metric system is developed for product replacement assessment and applied to PVC piping. The assessment metrics include functionality, economics and sustainability. Functionality is assessed using mechanical properties, economics by linear cost, and sustainability by life cycle assessment. Both off the shelf and reinforced plastics are compared to PVC piping using the three metric system. None of off the shelf plastics can compare to PVC's good mechanical properties and low cost. However, glass or natural fiber reinforced polypropylene has the potential to replace PVC based on all three metrics.

Keywords: pvc, metrics, lca, piping, replacement

1 INTRODUCTION

As environmental knowledge and awareness increase, materials that are known to be, or suspected as being, harmful to humans or the environment become less desirable to consumers and alternative materials are sought after. It is preferable that these new materials can be considered 'green' alternatives. One material that is under scrutiny is polyvinyl chloride, or PVC. The drive behind this scrutiny can mostly be traced to the fact that PVC is about half chlorine by weight. Chlorine production is very energy intensive and may involve the use of mercury or asbestos. Also, many environmental toxicants are chlorine based. Though there are many uses for chlorine worldwide, about one third of all chlorine produced is used for the production of PVC. Of the PVC produced, more than one third goes to piping [1]. For this reason PVC piping was chosen as the focus of our study.

Often when materials such as PVC are replaced not much decision making goes into deciding on a replacement. An alternative material is used simply so that the offensive material is not used. It is not known whether or not the replacement material is actually better or not. To solve this problem some kind of decision making metric needs to be used to assess and compare the existing material and the proposed replacement. A metric is simply a system to measure some aspect of a product. There is one single metric that will say if the potential alternatives are good replacements or not. An alternative product needs to be able to perform the same function, to cost the same or less, and have lowered environmental impact than the original material. This is the basis for a three metric system for assessing alternative products.

2 METHODS

When new products are developed there is often desired to have a product that is cheaper (economic metric) or a product that performs better (functional metric). Sometimes the optimization of these two metrics is both pursued, but they are often inversely proportional. More recently the environmental friendliness, or greenness (environmental metric), of a product has also become a metric of concern. However, it has often been accepted that for a product to be greener you will sacrifice quality and probably pay more. If a new material is going to replace PVC for plastic piping, the material needs to be able to match or beat out PVC on the functional and economic metrics and beat PVC on the environmental metric. If a material cannot do this it will not likely be able to gain any market share in plastic piping.

2.1 Functionality

To replace PVC piping, a material must be able to perform the same function as PVC. PVC is used for transporting water in distribution systems as well in buildings. Two areas that the replacement material needs to comparable to PVC are strength and resilience. The pipe must be able to withstand the operating pressures that are occurring in water distribution systems as well as overpressures experienced while in use. The ability of the pipe to withstand these pressures, P, can be related to the tensile strength, σ, of the material and the thickness, t, and outer diameter, OD, of the pipe as shown in equation (1).

$$P \approx \frac{t \cdot \sigma}{OD} \tag{1}$$

PVC has set the standards for piping material performance quite high. PVC has a tensile strength and modulus of approximately 50 MPa and 3 GPa respectively

[2]. If a potential replacement piping material cannot compare to these properties, it will not likely be able to become a viable option.

2.2 Economics

If a new material is going to replace PVC in piping, being able to perform the same function is not enough. The material must also be able to meet or beat PVC economically. To compare the economics of different materials for piping, several aspects need to be taken into account. The first and most obvious is the cost of the pipe itself. Pricing for bulk plastics can be readily found, however comparing bulk prices is not an accurate comparison for pipe. The cost per unit length of pipe needs to be compared. The cost per unit length is a function of the bulk cost, the density, and the material strength. This relationship is shown in equation (2) where C_l is the linear cost and C_w is the bulk cost.

$$\begin{aligned} C_l &= C_w \cdot \pi\left(OD \cdot t - t^2\right) \\ &\cong C_w \cdot \pi \cdot OD \cdot t \cdot \rho \\ &\approx \frac{C_w \cdot \pi \cdot OD^2 \cdot P \cdot \rho}{\sigma} \end{aligned} \tag{2}$$

PVC has a relatively low bulk cost of \$1.10/lb [4] when compared to other common plastics. It does however, have a relatively high bulk density of 1.4 g/cm3 [2]. This high density causes the linear cost of pipe to be higher than would be expected than if only the bulk costs were compared. The strength of PVC helps bring down the linear cost relative to other common plastics.

2.3 Sustainability

Finally, to replace PVC as the material of choice for piping, the new material must be more environmentally friendly and more sustainable. There is much debate about quantifying how 'green' or sustainable a product is. First of all the entire life cycle of the product must be taken into account. The use of life cycle assessment (LCA) is probably the most common method to assess this environmental metric. The traditional inclusion of environmental aspects during product development would be at best what is called a gate-to-gate LCA; only looking at the environmental impacts within the production facility. A cradle-to-gate LCA looks at every environmental impact associated with the product from material extraction, transportation, raw material processing, and final product processing. The goal of applying LCA to product development is to minimize the total impact of the product. Reducing the embodied energy and use of renewable raw materials are two aspects that make a significant difference on the total environmental impact of a product.

When looking at PVC under the framework of life cycle assessment, some areas stand out as negatives. The production of chlorine from salt is produced using electrolytic cells. These cells consume approximately 3000 kWh of electricity per ton of Cl2 produced. Two intermediates, ethylene dichloride (EDC) and vinyl chloride monomer (VCM), in the production of PVC are known carcinogens. Some of the fillers and stabilizers used to improve the performance of virgin PVC are also of concern to human health.

3 SUGGESTED REPLACEMENTS

Due to the various issues associated with PVC there have been attempts to replace it in its various roles including piping. Few of these suggested replacements have been fully assessed as to whether or not they would stand up to all three metrics discussed above. Most of the suggestions were off the shelf alternatives. This is probably why none of them have taken much, if any, of the market for piping. In the rest of this section several suggested and potential alternatives will be assessed using the three metric system.

3.1 Off the Shelf Alternatives

The first and probably easiest way to replace PVC would be using an off the shelf alternative. Off the shelf alternatives would mean using a material that doesn't need to be modified to make pipe with it. Such alternatives would be other plastic resins such as ABS (acrylnitrile butadiene styrene), PE (polyethylene), or PP (polypropylene). The first metric we need to look at is the strength of these materials as compared to PVC.

	PVC	ABS	PE	PP
Tensile Strength (MPa)	51.3	37.9	25.2	33.8
Tensile Modulus (GPa)	3.1	1.8	0.2-1.5	1.0
Density (g/cm^3)	1.4	1.04	.91	.94

Table 1: Physical properties of off the shelf alternatives and PVC.

As can be seen in Table 1, none of the off the shelf alternatives are going to be able to match up to PVC's strength. To compensate for the lower bulk strength of the materials, the thickness of the pipe wall must be proportionally thicker. Equation (1) can be solved for thickness to shown this relationship. The linear cost can then be found using equation (2) assuming a 1.5" outer diameter pipe with 100psi maximum pressure.

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Material	Bulk Cost, C_w (\$/kg)	Linear cost, C_l (\$/ft)
PVC	1.10	0.049
ABS	2.20	0.098
PE	1.72	0.101
PP	1.54	0.070

Table 2: Bulk costs and linear costs of the off the shelf alternatives.

With the higher bulk costs as well as lower strength, therefore thicker walls, none of the alternatives can compare to the linear cost of PVC pipe.

Finally we have to look at the environmental metric to see if the off the shelf alternatives have lower environmental impacts than PVC does. Cradle-to-gate LCAs of the materials were performed. These LCAs look at the production of the plastic resin necessary to make an equivalent length of pipe from each of the alternatives. The United States Environmental Protection Agency's TRACI impact method was used for impact assessment of the LCA. Normalized impacts for the off the shelf alternatives are shown in Figure 1.

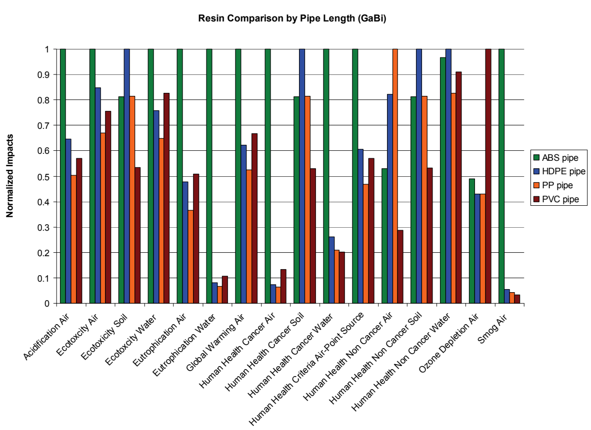

Figure 1: Comparison of off the shelf LCA impact categories.

This is the one metric where PVC is not a clear winner; however it is not a clear looser either. ABS is the worst material in the majority of the categories and PE, PP, and PVC are close in many of the categories. However, of the three alternatives, PP tends to have the lowest impact.

3.2 Polypropylene with Fiber Reinforcement

Since off the shelf alternatives cannot beat out PVC in all three metrics, the areas where the alternatives do beat out PVC should be exploited and the areas where the alternatives lose to PVC should be designed to perform better. Given the results from the off the shelf alternatives, PP was chosen to be the starting point for our next alternative. PP performs fairly well compared to PVC in the environmental metric, however loses out when it comes to strength. Also, the price of PP is the lowest of the off the shelf alternatives. Two different types of fibers are considered for reinforcement of the PP. These reinforcements are glass fibers and natural fibers. Many natural fibers exist that can potentially be use for reinforcing the PP. The fiber looked at in this case is China Reed. Fiber reinforced plastics are often used in areas such as the automotive industry, but have not been used for piping.

Fiber reinforced plastics can have significantly different properties than the virgin material. Due to the very high tensile strength and modulus of glass fiber only small amounts are necessary to make significant changes in the properties where higher fractions of natural fibers are needed to make equivalent changes. 10% glass fiber by weight of reinforced PP has a tensile strength of approximately 60 MPa. The density of the material is increased due to the high density of the glass fibers, however by keeping their fraction low the density is only slightly increased. The tensile strength of natural fibers is usually between .5 and 1.5 GPa [5,6]. Assuming a value of 800 MPa and applying the Series/Reuss Model given as equation (3), a tensile strength for a natural fiber composite is about 52 MPa.

$$\sigma_c = \frac{\sigma_m \cdot \sigma_f}{\sigma_f \cdot V_m + \sigma_m \cdot V_f} \qquad (3)$$

These properties are all shown in Table 4. For comparison the properties of virgin PP are also shown.

	PVC	PP	PP-Glass	PP-CR
Tensile Strength (MPa)	51.3	33.8	60	52
Density (g/cm^3)	1.4	.94	1.1	1.2

Table 3. Tensile strength and density of composite materials.

Looking at these properties we can see that both glass fiber and natural fiber reinforced PP can compare to PVC on the functional metric. The properties of the plastic-fiber composite can actually be adjusted for optimal performance by adjusting the fiber fraction in the composite.

Next, the economic metric must be assessed. A value of \$1.80/kg of glass fiber and \$0.90/kg of natural fiber is used for the bulk cost [7]. For a 10% glass fiber by weight composite, a linear cost for the pipe would be \$0.047/ft. For a 40% natural fiber by volume a linear cost of \$0.044/ft is calculated. Compared to the values for PVC of \$0.049/ft and virgin PP of \$0.070/ft, the fiber reinforced composites show an economic advantage over PVC and off the shelf alternatives.

Finally the environmental metric must be assessed. Again, LCAs were performed for both the pipe per length as well as the pipe installed per length. The TRACI LCA impact results for both of these cases are then compared to PVC and virgin PP. The results of these LCAs are shown in the following figures.

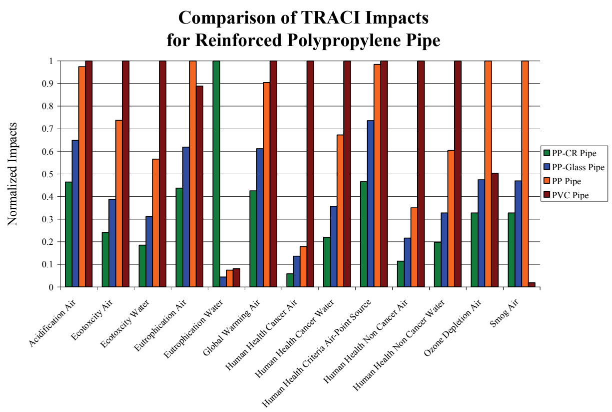

Figure 2. Comparison of TRACI impacts per length of pipe.

PVC has the worst impacts in most of the categories. Propylene release from the manufacture of PP accounts for PP having higher impacts in the ozone depletion and smog. Agricultural releases from fertilizers account for the natural fiber composite having a significantly higher water eutrophication impact number than the other options.

These proposed alternatives for PVC piping have a good potential for becoming viable alternatives according to the three metric system. Both glass and natural fiber PP composites can obtain similar properties to PVC and satisfy the functional metric. Adjusting the percentage fiber content allows for adjusting the functional parameters of the composite. Because reinforcing PP can result in a stronger material, the walls of the pipe do not need to be as thick and therefore less PP has to be used to make the pipe. This results in a pipe that is cheaper than if virgin PP is used. The composite materials have slightly cheaper linear costs than that of PVC, therefore satisfying the economic metric. Finally, the environmental impacts for the composites look pretty good compared to those for PVC. Even though the composites do not perform better on every impact category, PVC tends to fair worse on the majority. This satisfies the environmental metric. By comparing these three metrics, it can be seen that both composite materials have the potential to be good alternatives to PVC piping.

4 CONCLUSIONS

This paper discussed the development of a three metric system for the assessment of products. The three metrics discussed were a functional metric, an economic metric, and a sustainable metric. With the goal of finding a feasible replacement for PVC piping, this metric system was applied to several potential replacements for PVC. Three off the shelf alternatives were assessed and none were found to be feasible alternatives. However, reinforced polypropylene appears to be a viable option. Both glass and natural fiber provide similar results.

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