An Investigation into Alternatives to PVC Drainage Pipelines

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Abstract

Since being introduced in the 1950's, Polyvinyl Chloride (PVC) has quickly become the most common piping material on the market. This lightweight material's healthy combination of flexibility and durability along with it being incredibly affordable make it the go-to option when installing a piping system quickly and efficiently. However, in the last few years, the discovery of the significant health and environmental hazard risks that go along with manufacturing and using PVC have made it necessary to investigate a more sustainable alternative. These negative characteristics of PVC has gotten it put onto the materials "Red List," a group of materials which the University of British Columbia (UBC) has decided to eliminate the use of on school grounds. In order to do this, UBC is investigating alternatives to PVC pipe that can be used in their waste drainage system.

To find a suitable alternative to PVC, this study evaluates a wide variety of potential alternatives using the triple bottom line (TBL) method. The proven piping materials of clay, concrete, High Density Polyethylene (HDPE) and Acrylonite-Butadiene-Styrene (ABS) are evaluated, alongside the experimental piping material bamboo. PVC and recycled PVC are also evaluated and the resulting assessments are compared using decision matrices. Cradle to gate carbon dioxide (CO2) emissions and embodied energy, and recyclability are used as the environmental criteria. The unit price and installation costs are used for the economic assessment and health hazards from manufacturing through to recycling/disposal are used as the social criteria.

The resulting TBL assessments of plastics show HDPE, ABS, and recycled PVC are improvements to original PVC drain pipes in stormwater or wastewater applications. HDPE scores are significantly better in environmental and social criteria while having similar economic costs and similar installation methods. Clay, concrete and bamboo are found to have many environmental and some social benefits. Concrete and clay generally have greater installation and unit costs. The experimental material, bamboo, does not yet meet the BC building code, but future research into processing the material looks promising as a sustainable alternative. Clay and concrete may be viable alternatives in for medium to large pipes, but for 4 inch pipes, the focus of this study, their costs limit them to specialized applications, when cost isn't a large issue. HDPE makes a great alternative to PVC for general applications; HDPE scores the best among the evaluated plastics in social and environmental criteria while its economic costs and mechanical properties are very close to those of PVC making the switch fairly cheap, and easy to implement.

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Glossary

Abrasions: the process of scraping or wearing something away.

Dioxin: a by-product in some manufacturing processes that is highly toxic.

Kiln: a furnace or oven for baking or drying.

Photovoltaic Cells: cells that convert solar energy into electricity.

Phthalates: a plasticizer that is added during the manufacturing process to increase flexibility, durability, transparency and ductility.

Stabilizers: a substance added to a material to maintain a stable or unchanging state.

Vitrify: to convert into a glass-like substance, usually from exposure to heat.

List of Abbreviations

ABS: Acrylonitrile-Butadiene-Styrene
BC: British Columbia
BCE: Before Common Era
CaO: Lime
CaCO3: Carbonate
Ca2: Ionized Calcium
CAW: Canadian Auto Workers
CHBE: Chemical and Biological Engineering
CO: Carbon Monoxide
CO2: Carbon Dioxide
CO3: Carbon Trioxide
HCl: Hydrochloric Acid
HDPE: High Density Polyethylene
HF: Hydrogen Fluoride
kg: kilograms
MJ: Megajoules
NO: Nitrous Oxides
PVC: Polyvinyl Chloride
SO: Sulphur Oxides
TBL: Triple Bottom Line
UBC: University of British Columbia
UN: United Nations
VCP: Vitrified Clay Pipe

1.0 Introduction

PVC is one of the most widely used materials today. Its low cost, versatility and durability have led to PVC becoming a commonly used material in piping systems. However, PVC is known to be a highly hazardous material, being labeled as a "Red List" material due to the serious health and environmental risks it poses over its lifecycle. To preserve the environment and protect the public, many institutions and governments have the objective to reduce PVC pipe usage and replace PVC pipe infrastructure with more sustainable material alternatives (Harvie et al., 2002). In an effort to increase its sustainability, the University of British Columbia (UBC) is researching alternatives to PVC piping using the triple bottom line (TBL) approach. TBL assessments consider the environmental, economic and social ramifications of each material. Sustainable alternatives that achieve positive scores in the TBL assessments will be considered for replacing PVC in the university waste drainage system.

To approach this problem, a variety of alternative piping materials were investigated. Such alternatives involved high-density polyethylene (HDPE), acrylonitrile butadiene styrene (ABS), recycled PVC, clay, concrete, bamboo, and some hybrid materials. The explored alternatives have been previously used or experimented with in piping systems. A TBL assessment was done on each material as well as PVC and a holistic comparison was done using the TBL scores. All the material properties relevant to the TBL assessments was found in existing research. The comparison of TBL scores was done using decision matrices and from the result a sustainable alternative PVC was recommended for UBC's waste drainage system.

2.0 Polyvinyl Chloride

2.1 The Draw of PVC

Second only to polyethylene, PVC is one of the most widely used plastics in the world with over 35 million tonnes of PVC being used per year (Sadat-Shojai et al., 2011). What makes PVC such a common piping material is its low price as well as its high flexibility, light weight, high durability, good tensile strength, and a typical life expectancy of 50 years. Additionally, PVC has a high resistance to corrosion, abrasions and acids making it an ideal candidate in a variety of soil types (Harvie et al., 2002). These characteristics are what makes PVC piping such an attractive piping material to contractors. However the effect PVC has on the environment and public health adds some significant drawbacks to this otherwise excellent piping material.

2.2 Impact on the Environment and Public Health

What PVC has in superior structural characteristics for piping systems, it lacks in environmental and human safety. PVC has three major stages in its lifecycle:manufacturing, usage and disposal, and during these stages PVC can expose the population to dangerous toxins (Thornton, 2002). The manufacturing stage of PVC exposes workers to the human carcinogen vinyl chloride. Additives such as plasticizers and stabilizers are added during the manufacturing process to give PVC its desired properties. One plasticizer used in the manufacturing of PVC is phthalates, another known human carcinogen, while some stabilizers include heavy metals like cadmium and lead. During the usage stage of PVC, these additives leach out of the material and contaminate the environment. When PVC is exposed to flames the smoldering material releases Hydrochloric acid (HCl), a corrosive compound in contact with human tissue. When PVC reaches the end of its life, the disposal period occurs where more additives are released as well as dioxin, another carcinogen well known to be extremely dangerous to human health even at low concentrations (Ackerman et al., 2003). To avoid disposing of PVC, recycling and reusing the material avoids releasing dioxins and other contaminants into the environment. Recycling can only go on for a limited number of cycles as the quality of plastics reduces after being recycled. Furthermore, PVC has a high average embodied energy of 67.50MJ/kg and a high amount of carbon dioxide (CO2) during the manufacturing process of 2.5kg of CO2/kg of material (Hammond et al., 2008). Due to these factors, it is clear that PVC is not a sustainable material for piping systems or any other application thus it is imperative to seek out a more sustainable alternative.

2.3 Recycled PVC

One option for an alternative would be to recycle PVC and use it to replace old PVC. This would prevent PVC from reaching the disposal phase and releasing dioxins into the environment. This recycled PVC would have similar physical qualities of virgin PVC and could be implemented in the same fashion. However this would just be preventing the inevitable as recycling plastics reduces the quality of the plastic and PVC would eventually end up being disposed of anyway.

3.0 Ceramic Alternatives

3.1 Clay Pipe

Clay is one of the most ancient piping materials, with the earliest known example coming from Babylonia (4000 BCE). Vitrified clay pipes have been used for more than 3500 years and their continued use up to the present day owes much to their durable nature. A chemically inert material leached from rock and soil, clay is transformed into a dense, hard and virtually homogeneous mass through burring in kilns at temperatures of about 2000 degrees Fahrenheit. The hard glassy surface provides resistance to abrasion and promotes fluid flow through the pipe. The low coefficient of thermal expansion makes them relatively insensitive to wide fluctuations in temperature and their inert chemical structure imparts resistance to both chemical and biological attack (Boustead & Hancock, 1981). Other than concrete, clay's weight makes it more costly to transport and more difficult to handle than other drain pipes (Joseph L. Balkan Inc., 2013). Vitrified clay is the only piping material designed to convey the full range of effluents that a community or industry can discharge. It will not rust, shrink, elongate, bend, deflect, erode, oxidize or deteriorate. Clay is structurally sound, leak-proof and impervious to chemical reaction because it is a permanently welded body. It is adaptable to a wide range of sizes and fittings, and highly economical to install and maintain (Globe and Mail, 1972). Clay has a high longevity and has been found in excavated ruins thousands of years old. The National Clay Pipe Institute referenced a photo of VCP pipe which was over 2,500 years old that was reused for onsite drainage, and is still in service today (Locke, n.d.).

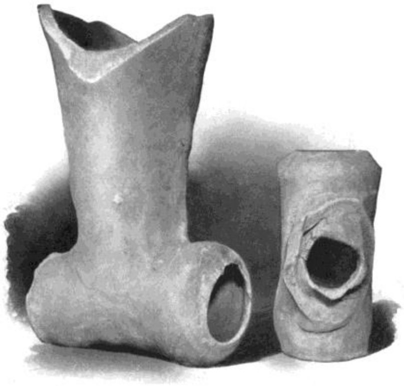


Figure 1: Ancient Clay Joints: Knee and t-joints made about 4000 B.C. Found in the excavation of the Temple of Bel at Nippur, Babylonia. Pipe was made of baked clay. Source: (Cast Iron Pipe, Standard Specifications, Dimensions and Weights, 1914)

Clay is a naturally abundant, raw material with a wide variety of uses and properties which can be mined in most Canadian provinces (Dumont, 2008). Vitrified Clay Pipe is manufactured by grinding shale and clays into powder and adding 12%-15% water. This mixture is then vacuum degassed and extruded into the shape of the pipe. The pipe is dried to a low moisture content using waste heat from other plant processes. The dried pipe is fired to 1093 degrees Celsius and cooled before applying jointing materials. Any off-grade pipes are reground and recycled into future clay pipes. There is essentially no waste generated by this process because the clay can be recycled at any stage (National Clay Pipe Institute, 2009) with almost 100% transformation at little expense. Vitrified clay pipes are 100% natural therefore no harmful substances can diffuse into the soil from the pipe itself (European Federation of the Vitrified Pipe Industry, n.d.) and no ingredients of the pipes are hazardous to human health. Total energy consumption has been shown to be half of that needed to produce the same amount of PVC. The energy study included all processes from mining of raw materials to completion of finished pipe product at the manufacturer's plant (Ohlinger, 2002).

Vitrified clay pipe is considered to have a life span in the range of 100 years(Beieler, 2013). The environmentally-friendly and long-life characteristics of vitrified clay pipes minimise effects on the ecosystem and residents through repairs, new installation.

The most notable hazard with clay is the inhalation of clay dusts during clay production which can cause lung diseases (Noel Arnold & Associates, 2003). Very little information can be obtained about this problem, suggesting this is a rare occurrence. HCL, HF, SO_x, NO_x, CO and CO_2 emissions do occur during clay production and are treated accordingly (Tiles and Bricks of Europe, 2005).

3.2 Concrete

Concrete has been a common building material for thousands of years. The art of concrete composition has had a large impact on the world. The use of concrete drainage systems is nothing new. Most city sewer systems use concrete to transport wastewater from homes to wastewater treatment facilities. The innovation of concrete pipes for small drainage systems (such as stormwater and water runoff) has only recently been considered.

Concrete pipes have the benefit of being a local commodity, with multiple manufacturers and sizes available in British Columbia. However finding pipes with commercial sizes smaller than 5 inches is difficult. Concrete is slightly porous, so water could slowly seep into groundwater. Additives are use in concrete which make water repellent to concrete surfaces, which extend the lifetime of concrete in colder climates (swelling) and eventual wear. Concrete, a mixture of cement with sand and aggregate, requires multiple different chemical reactions from production of cement to the setting and hardening of the material. The chemical reactions of concrete include but are not limited to:

Calcination:	CaCO3 (solid) -> CaO (solid) + CO2 (gas)
Carbonization:	Ca2+ (aq) + CO3 2- (aq) -> CaCO3 (solid)

Table 1: Basic chemical reactions required for cement production, Danish Technological Institute (Kjellson et al, 2005).

Concrete tends to produce large amounts of CO2 in the manufacturing and initial hardening stage of the product. Kilns are required to initiate the calcination process, which generally use natural gas as a fuel. Concrete has also been known to produce multiple air pollution contaminants, which include heavy metals, NOx, SOx, and other various chemicals found in Appendix B (Kjellsen et al, 2005). Green alternatives of concrete look promising for reductions in air pollution and initial testing in contaminant leaching looks promising, but testing for options with fly ash has

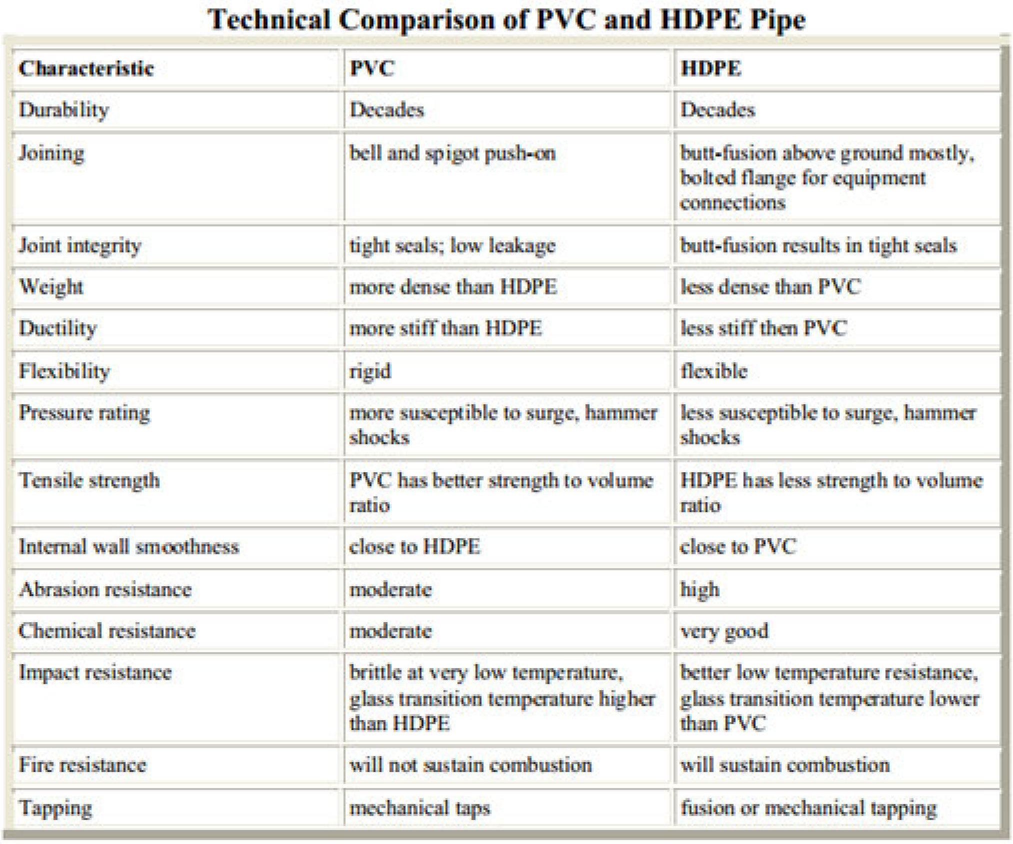
4.0 Plastic Alternatives

4.1 Acrylonitrile-Butadiene-Styrene (ABS)

One of the benefits of plastic piping alternatives is that they have similar mechanical properties which allows for an easy transition between materials. Already a prominent waste drainage piping material, Acrylonitrile-Butadiene-Styrene (ABS) has many similar characteristics to PVC, but has a lower price than PVC and is characterized by its high strength, toughness and stiffness (Chasis, 1988). The main concern with durable ABS, however, is that it contains high amounts of hazardous contaminants. Two of the main ingredients, Acrylonitrile and Butadiene, are both human carcinogens. Acrylonitrile also contains cyanide, a highly toxic substance (CAW, 2011). ABS is slightly less toxic than PVC (Lithner et al., 2011). Equally concerning is how difficult ABS is to recycle (Harvie, 2002) meaning ABS has a high chance of ending up in landfills and releasing contaminants into the environment. ABS has an embodied energy of 95.30MJ/kg and a manufacturing CO2 emissions of 3.10 kg of CO2/kg of material which are much higher values per kilogram than its counterpart, PVC (Hammond et al., 2008). In summary, ABS is not much better than PVC from a TBL perspective as it has its own set of carcinogenic contaminants, it is less recyclable, and its manufacturing creates more CO2 emissions.

4.2 High Density Polyethylene (HDPE)

HDPE is a much more environmentally friendly material, containing less harmful additives than both ABS and PVC with ethylene being a minor toxin (Lithner, 2011). Furthermore, HDPE is more flexible and shock resistant than PVC making it a good option in earthquake prone areas. HDPE uses butt-fusion joints which have a high leak resistance, thus reducing maintenance costs. Finally HDPE has a high resistance to chemicals, abrasions and impacts in low temperatures (Harvie, et al., 2002)



Technical Comparison of PVC and HDPE Pipe

Characteristic	**PVC**	**HDPE**
Durability	Decades	Decades
Joining	bell and spigot push-on	butt-fusion above ground mostly, bolted flange for equipment connections
Joint integrity	tight seals; low leakage	butt-fusion results in tight seals
Weight	more dense than HDPE	less dense than PVC
Ductility	more stiff than HDPE	less stiff then PVC
Flexibility	rigid	flexible
Pressure rating	more susceptible to surge, hammer shocks	less susceptible to surge, hammer shocks
Tensile strength	PVC has better strength to volume ratio	HDPE has less strength to volume ratio
Internal wall smoothness	close to HDPE	close to PVC
Abrasion resistance	moderate	high
Chemical resistance	moderate	very good
Impact resistance	brittle at very low temperature, glass transition temperature higher than HDPE	better low temperature resistance, glass transition temperature lower than PVC
Fire resistance	will not sustain combustion	will sustain combustion
Tapping	mechanical taps	fusion or mechanical tapping

Table 2: Environment Canada Technical Comparison of PVC and HDPE Pipe
Source: (Harvie et al., 2002)

Another important attribute of HDPE is it's ability to be easily recycled, which reduces the amount of waste produced. Like most plastics, the quality of the product is reduced every time the material undergoes recycling. Recycled HDPE, depending on the quality, may not be applicable as pipe and will eventually end up in the landfill. (Goodship, 2007).

Figure 2: Quality Degradation From Recycling HDPE: Colour change of HDPE after ten processes of recycling. Quality of material decreases from upper left corner preceding clockwise.
Source:(Goodship, 2007)

HDPE compares fairly well to other plastics in embodied energy (84.40MJ/kg) and carbon emissions (2.00 kg of CO2/kg of material produced). These relatively high numbers are compensated for by the fact that less HDPE is used per metre of pipe (Hammond et al., 2008). For a 4 inch pipe HDPE outperforms PVC and ABS per metre in both metrics. HDPE is also practically at parity in price with PVC. HDPE seems to be a great alternative to PVC especially in the short term. In terms of mechanical properties and economics they are very similar, meaning little to no change would be necessary to existing design and installation methods. Any added cost would be minimal and HDPE would have less toxins and be easier to recycle. HDPE has the attractive qualities of PVC without the degree of environmental and public health hazards.

5.0 Natural Alternatives

5.1 Bamboo

Probably the biggest concern with PVC piping is that there is a large amount of dangerous contaminants in the material that cause serious health problems and affect the environment. One way to eliminate this issue is to use a naturally occurring material. Bamboo makes an ideal alternative for a piping material because of its tubular shape, low density, low cost and bamboo's innate ability to decompose after use. Currently bamboo is a material that is not defined by the BC building code for the purpose of water transport. The growth of biological contaminants (mold, fungi, bacteria colonies from water contamination, etc.) is a huge concern for bamboo from the natural pipe roughness through woven fibers. Currently, some European nations are experimenting with boric acid treatments to "waterproof" bamboo. Future development of bamboo has potential if a practical process could permit safe and economical water passage and increase the lifetime of the product. Currently, bamboo pipes in Nepal are being used for village drink water from springs or other water sources. The average lifetime for water pipes generally is a year, but replacement of bamboo generally requires one to three days worth of labour cost (UN article, 2011). Bamboo World, a company based in Chilliwack, provides the sale of bamboo as $22.40 per 8 meter pole and states on their purchasing website (Bamboo World, 2013):

> "Many Canadians are unaware of the fact that they can grow certain rare species of bamboo in every Province."

Whether bamboo can be grown in a commercial and sustainable method requires more research and experimentation into local areas and their climates to determine the commercial growth and sustainable harvesting of bamboo.

6.0 Hybrid Alternatives

While economically viable alternatives to PVC, at least in the short term, are limited to plastics, concrete, clay. Experimental composite materials and hybrid piping may be the next stage in sustainable development. Therefore, as a forward looking study, a brief overview of these materials is included in this section.

6.1 Ceramic Tile / Fiberglass Hybrid

An experiment was conducted in Australia to compare the use of PVC pipe with local ceramic tile pipes reinforced with fiberglass on the outside (Obbink, 1970). The uniqueness of the product comes from its failure mechanism. Brittle failure would lead to loss of water through the fiber fabric, but in drain pipe applications, the material would resist ground contamination into the water system. The fiberglass used to reinforce the piping acted as a filter to prevent ground material from entering the pipe. This project is limited to one study performed in Australia for sustainable agriculture and requires further research.

6.2 HDPE / Ceramic Hybrid

An experimental material was developed by introducing nanofiber scale ceramic as a filler with resin. This hybrid matrix could give the material better stiffness and strength performance than plastics, and more elasticity than ceramic materials. The material is unfortunately experimental and currently very expensive to properly apply but it may become viable for special applications with further research and development.

6.3 Surface Coating or Surface Modification

This same technology is used in jet turbines and photovoltaic cells. Through procedures which would force adherence of one type of material (ie ceramics or metals) onto a substrate material (plastic or metal) the contaminant release from current pipe products could be reduced and their lifespans could be extended. The high energy requirements from these experimental processes make piping applications currently impractical.

7.0 Comparison of Alternatives

To determine a proper alternative, the research group investigated multiple materials and developed a decision matrix based on the TBL assessments.

7.1 Environmental Comparison

The environmental comparisons involved data based on the production of CO2, the energy required for manufacturing, and the CO2 emitted while travelling.

The amount of CO2 produced in the manufacturing process was taken from the University of Bath Inventory of carbon and energy version 1.6a (Hammond et al, 2008). As illustrated in Figure 3 (CO2 manufacturing) PVC, Vitrified Clay, and ABS have the highest CO2 production. The large CO2 of vitrified clay is primarily from the firing processes used to solidify the clay. The best options for reduced CO2 emissions are bamboo, concrete and HDPE.

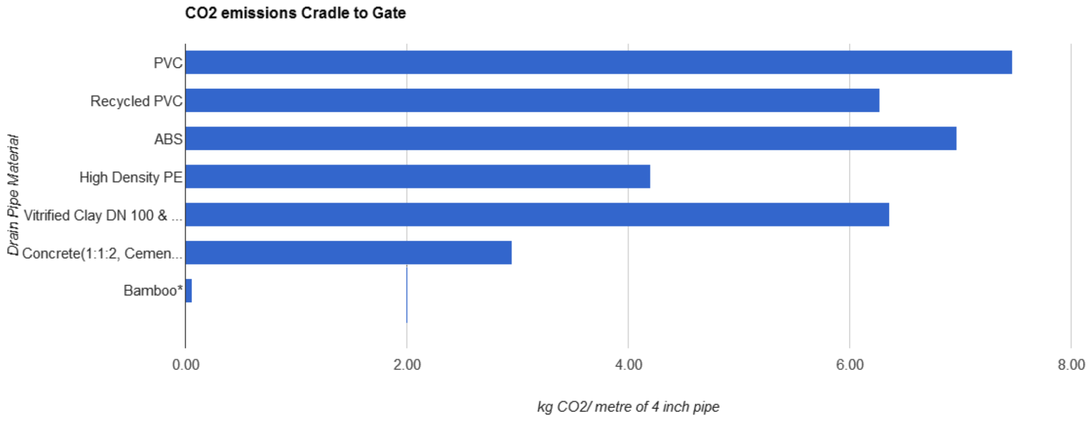


Figure 3: CO2 Production from Manufacturing of Various Piping Material

To analyze the impact of CO2 produced from transportation, the closest large manufacturing plant, not distribution facility, was found. Large manufacturing companies and their various locations were determined for various drain pipe materials:

Pipe Material	**Manufacturing Company**	**Location**
PVC	JM Eagle	California
Recycled PVC	JM Eagle	California
ABS	Bow	Montreal
HDPE	Armtec	Richmond
Clay	National Clay Pipe Institute	Oregon
Concrete	Ocean Concrete	Richmond
Bamboo	Bamboo World	Chilliwack

Table 3: List of Materials and Their Corresponding Manufactures and Source Location

Using google maps, an estimation for various travel distances was compared for different pipe. Recycled PVC included the total distance it took from waste PVC pipe to be returned in pellet form to the manufacturing facility before it could be remanufactured and returned to a Vancouver market. Bamboo World, a bamboo distributor and producers, was found to grow and harvest bamboo locally in Chilliwack. Note this is a general reference from searches that were attainable from the groups: These values may make a general guide, but possible manufacturing companies could be located closer to Vancouver.

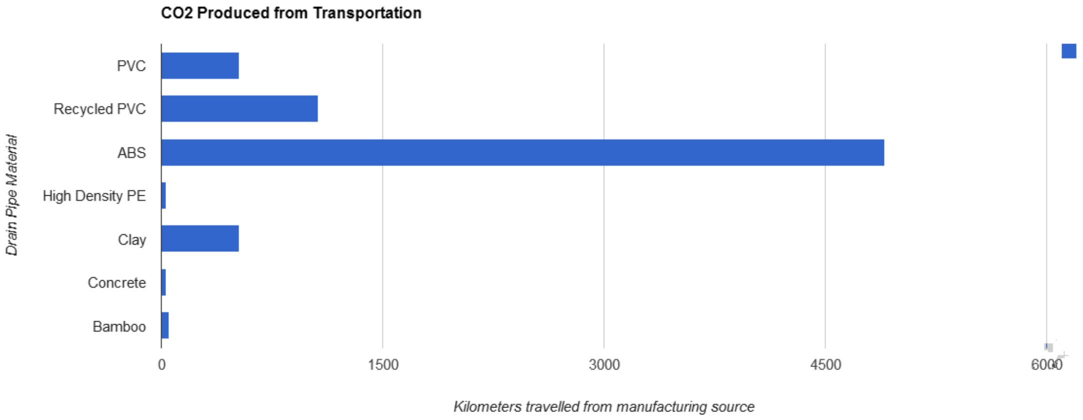


Figure 4: Kilometres Traveled to Reach Vancouver

The required energy for manufacturing all the products were taken from the University of Bath inventory (Hammond et al, 2008). All plastics generally have a large manufacturing energy. The reduced energy requirement from manufacturing recycled PVC was based on the elimination of the feedstock energy, a substantial but necessary simplification. If all the alternative plastic sources used recyclable materials, the energy footprint would be noticeably reduced at the cost of some strength and stiffness.

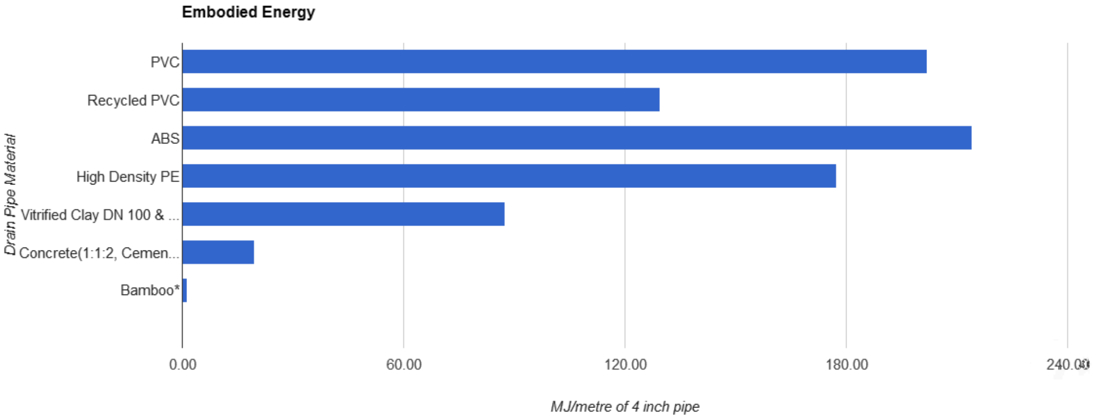


Figure 5: Embodied Energy From Cradle to Gate of Various Piping Materials

7.2 Economic Comparison

When comparing the economics of each material, the labour cost of installation and the material cost were summed up to form the total overall cost of each material. Machinery costs were ignored because the largest equipment brought to install the pipe would be the equipment to dig the trench. Analysis of larger diameter pipe, generally larger than 15 inches, would require extra machinery, but the research groups selection of 4 inch diameters eliminates the need for large mechanical tools.

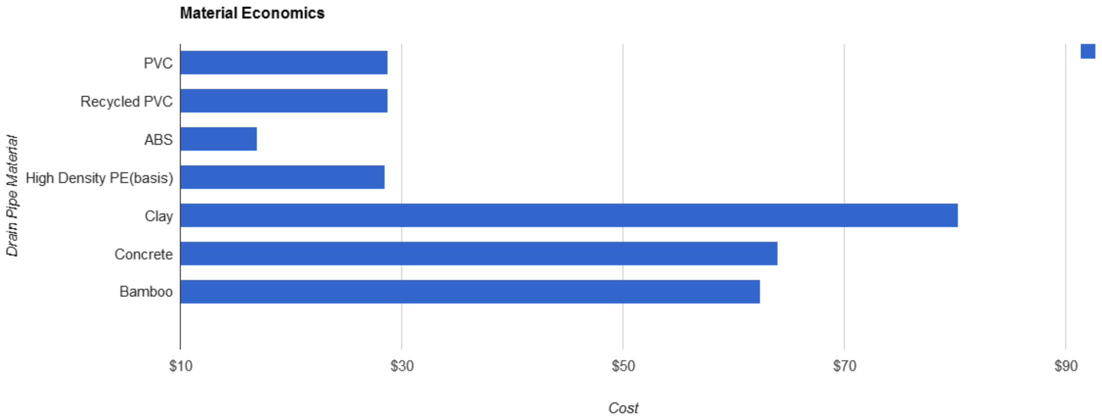


Figure 6: Unit and Installation Cost of Various Piping Materials

The price of clay pipes is more than three times as much as PVC pipes and the prices of concrete and bamboo are two and a half times as much as PVC pipes. Considering the limited institutional budget and residential budget at a public university, clay, concrete and bamboo pipes cannot be the best choice. The price of recycled PVC pipes is similar to newly-produced PVC pipes, but new PVC pipes have better quality. The HDPE pipes have a similar price range to the PVC piping, however ABS has the lowest price and would be the clear choice in an economically focused decision.

7.3 Social Comparison

To compare each piping material effectively the potential health risk, the inconvenience of construction and the recyclability of each material was investigated. By using a decision matrix each material was compared against the others and the best material in each category was determined.

To compare the health hazards, the potential risk that each material posed to the human population was taken into account. This matrix was given a higher weight in the final comparison as social health is a key criterion for UBC. Each material was given a score based on the qualitative knowledge of its toxins. The scores are subjective but they reflect a consensus of the perceived health risk. The plastics were deemed as the most harmful to social health because of the amount of dangerous additives in each material with PVC and ABS having the highest risk because they contain human carcinogens. Typically the ceramics, concrete and clay, are low risk materials with the majority of their hazard risk being respiratory illnesses stemming from inhaling the dust caused by the demolition of the material, thus they received a lower score. Finally, Bamboo was given the lowest risk rating as it is a natural material and does not contain any harmful additives. Note that bamboo has a greater tendency to produce biological cultures(such as molds, fungi, algae, etc.) on an untreated surface.

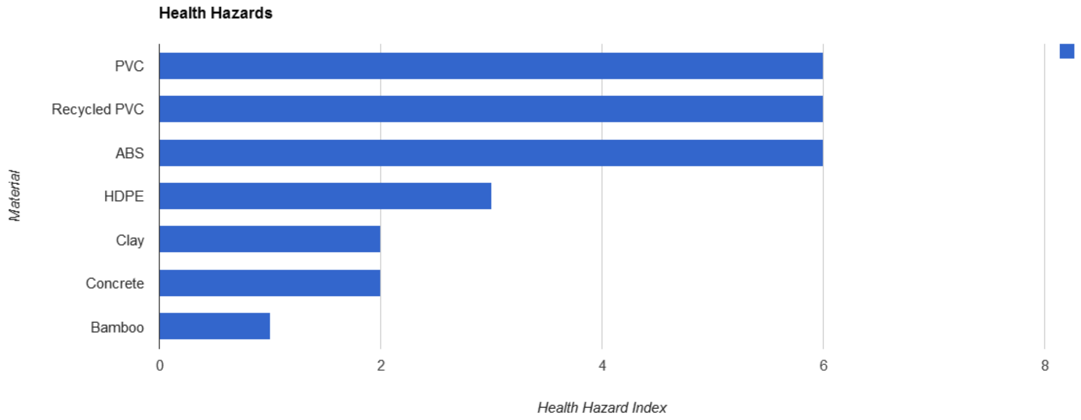


Figure 7: Health Hazard Rating for Contaminants of Various Piping Materials

The inconvenience of construction received the least amount of weight in the social comparison as it does not have a significant effect on society. The plastic alternatives were given the best score as they are the easiest to install, thus reducing installation time. Concrete received the highest score due to its heavy weight and long installation time. Bamboo and clay received intermediate scores, as they also have long installation times.

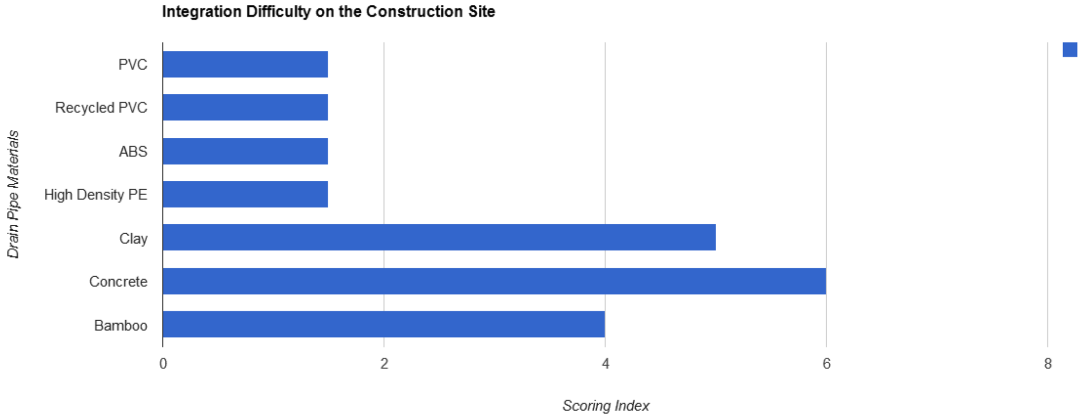


Figure 8: Evaluated Difficulty of Installation for Various Piping Materials

The third social comparison was recyclability, because recycling is held in high regard in society and reduces the amount of dangerous contaminants into the environment. For this process we took into account the energy and carbon dioxide emissions produced during the recycling process. Plastic alternatives received poorer scores than the other materials because significant amounts of energy are required to recycle plastics. Most plastics are recycled mechanically which requires each plastic to be sorted and recycled separately in a long and arduous process (Goodship, 2007). The ceramic alternatives scored better than plastics due to their simpler recycling processes with minimal energy requirements, via crushing and rehydrating the material. Bamboo has intermediate score because it decomposes at the end of its lifecycle, but sustainable cultivating and harvesting of bamboo is questionable. From these matrices, it was determined that plastics had the most negative effect in the social comparison with HDPE being the most sustainable plastic. Ceramics (Concrete and Clay) and bamboo came out with the best social scores.

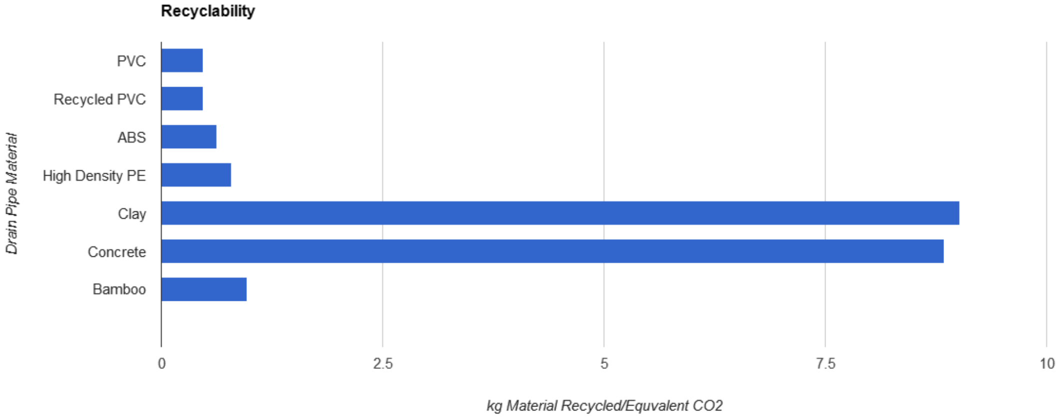


Figure 9: Recyclability of Various Piping Materials

8.0 Conclusion and Recommendations

After compiling all of the data, scores from each material comparison matrix were entered into a final table. The overall impact of each material was interpreted from data taken from existing research to find the lowest final score. Bamboo has the best TBL score, but it is currently an experimental material and not included in North American Building Codes. Concrete and clay score well in social and environmental criteria, for 4 inch pipes, but are significantly more expensive than plastics. HDPE scores the best among the plastics; it is economically competitive while having fewer health risks, greater recyclability, and lower emissions per metre than both ABS and PVC. Additionally the transition from PVC to HDPE can be done quickly and cheaply because both plastics use similar installation procedures. In conclusion, it is recommended that UBC switch to HDPE for the short term. However HDPE is not fully recyclable or toxin free, and the eventual necessary transition to clay, concrete, or a currently experimental material should be kept in mind.

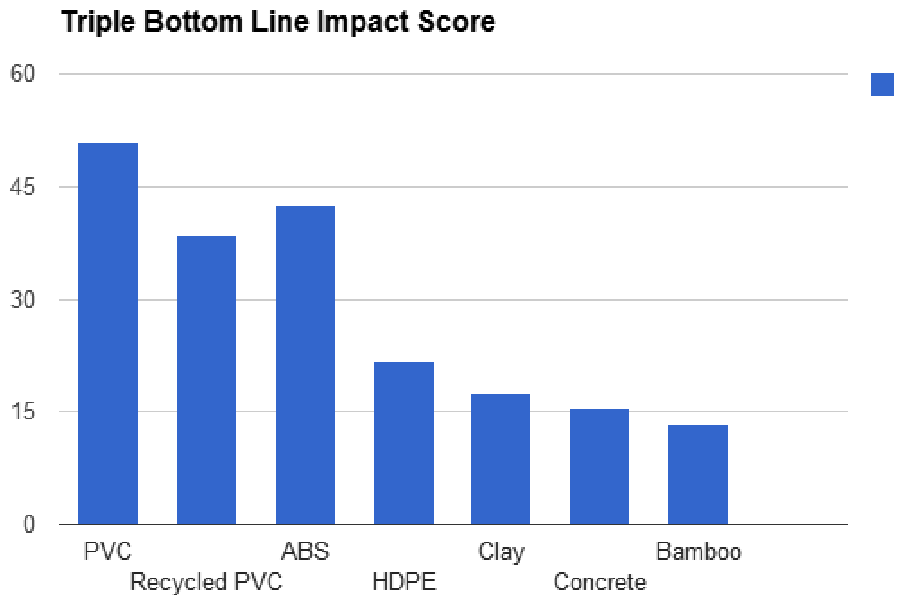


Figure 10: TBL Impact Decision Graph - based on a weighted decision matrix in Appendix ##

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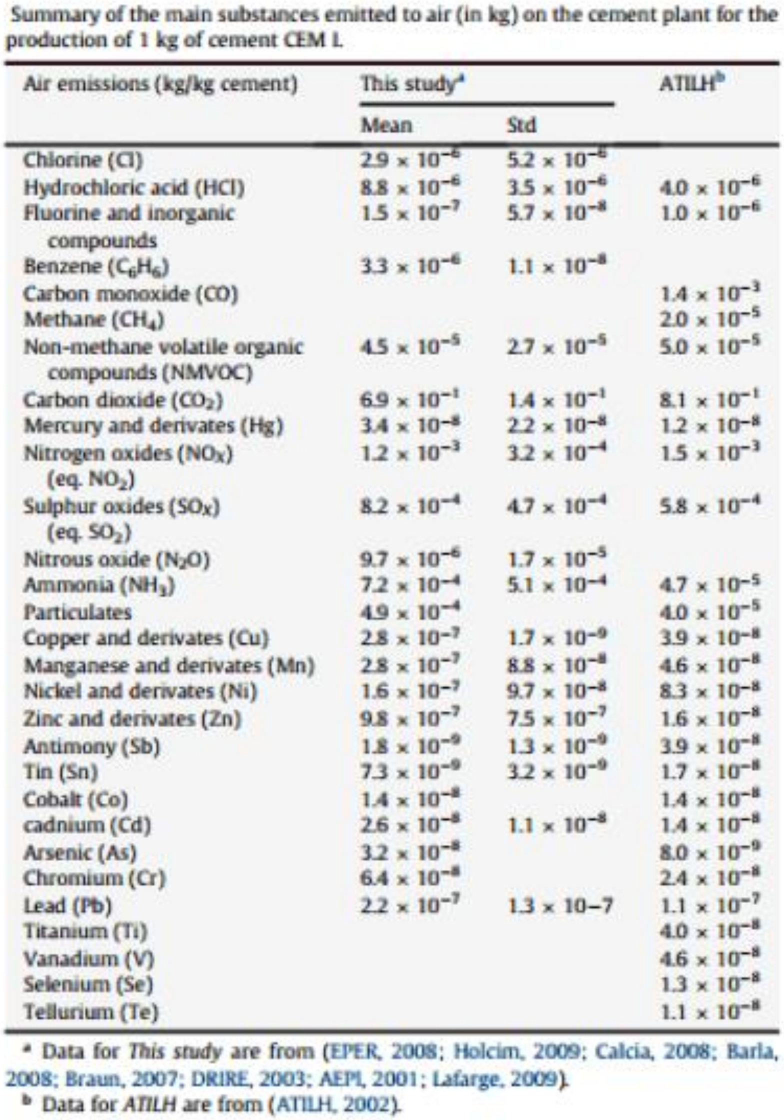
Appendices:

Appendix A: Weighted Decision Matrix based on Various

Materials	ENV - CO2 Manufact	ENV - Transport	ENV - Contaminant	ENV - Energy	SOC - Health	SOC - Recyclability	ECONOMICS	**Total Overall Score**
Weighted Decision	**3**	**1**	**4**	**2**	**4**	**3**	**1**	
PVC	2.2569	0.8915	4.4500	2.5729	**3.0000**	2.3782	1.6607	51.4033
Recycled PVC	0.9018	2.6820	3.5200	0.6563	**3.0000**	2.3782	0.8166	40.7312
ABS	1.0018	1.6466	4.4500	1.0878	**3.0000**	1.7933	0.4175	42.4250
High Density PE	0.6008	0.0063	1.6600	0.8994	**1.4167**	1.4103	0.8082	**20.9532**
Clay	0.9144	0.1751	0.7300	0.4413	**0.8889**	0.0755	2.5579	**13.0609**
Concrete	0.4202	0.0063	0.7300	0.0947	**0.8889**	0.0782	2.0073	**10.1736**
Bamboo	0.0007	0.0131	0.7300	0.0006	**0.3611**	1.1399	1.9532	**9.7538**

Table 4: Weighted Decision Matrix Scoring for Triple Bottom Line Analysis

Appendix B: Air Pollution Contaminant Tables for Concrete

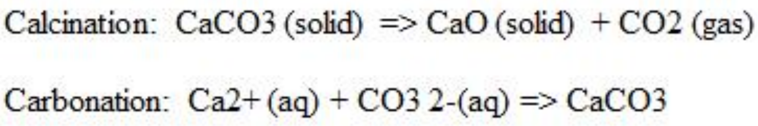


Summary of the main substances emitted to air (in kg) on the cement plant for the production of 1 kg of cement CEM I.

Air emissions (kg/kg cement)	This study[a]		ATILH[b]
	Mean	Std	
Chlorine (Cl)	2.9×10^{-6}	5.2×10^{-8}	
Hydrochloric acid (HCl)	8.8×10^{-6}	3.5×10^{-6}	4.0×10^{-6}
Fluorine and inorganic compounds	1.5×10^{-7}	5.7×10^{-8}	1.0×10^{-6}
Benzene (C_6H_6)	3.3×10^{-6}	1.1×10^{-8}	
Carbon monoxide (CO)			1.4×10^{-3}
Methane (CH_4)			2.0×10^{-5}
Non-methane volatile organic compounds (NMVOC)	4.5×10^{-5}	2.7×10^{-5}	5.0×10^{-5}
Carbon dioxide (CO_2)	6.9×10^{-1}	1.4×10^{-1}	8.1×10^{-1}
Mercury and derivates (Hg)	3.4×10^{-8}	2.2×10^{-8}	1.2×10^{-8}
Nitrogen oxides (NO_X) (eq. NO_2)	1.2×10^{-3}	3.2×10^{-4}	1.5×10^{-3}
Sulphur oxides (SO_X) (eq. SO_2)	8.2×10^{-4}	4.7×10^{-4}	5.8×10^{-4}
Nitrous oxide (N_2O)	9.7×10^{-6}	1.7×10^{-5}	
Ammonia (NH_3)	7.2×10^{-4}	5.1×10^{-4}	4.7×10^{-5}
Particulates	4.9×10^{-4}		4.0×10^{-5}
Copper and derivates (Cu)	2.8×10^{-7}	1.7×10^{-9}	3.9×10^{-8}
Manganese and derivates (Mn)	2.8×10^{-7}	8.8×10^{-8}	4.6×10^{-8}
Nickel and derivates (Ni)	1.6×10^{-7}	9.7×10^{-8}	8.3×10^{-8}
Zinc and derivates (Zn)	9.8×10^{-7}	7.5×10^{-7}	1.6×10^{-8}
Antimony (Sb)	1.8×10^{-9}	1.3×10^{-9}	3.9×10^{-8}
Tin (Sn)	7.3×10^{-9}	3.2×10^{-9}	1.7×10^{-8}
Cobalt (Co)	1.4×10^{-8}		1.4×10^{-8}
cadnium (Cd)	2.6×10^{-8}	1.1×10^{-8}	1.4×10^{-8}
Arsenic (As)	3.2×10^{-8}		8.0×10^{-9}
Chromium (Cr)	6.4×10^{-8}		2.4×10^{-8}
Lead (Pb)	2.2×10^{-7}	1.3 × 10−7	1.1×10^{-7}
Titanium (Ti)			4.0×10^{-8}
Vanadium (V)			4.6×10^{-8}
Selenium (Se)			1.3×10^{-8}
Tellurium (Te)			1.1×10^{-8}

[a] Data for *This study* are from (EPER, 2008; Holcim, 2009; Calcia, 2008; Barla, 2008; Braun, 2007; DRIRE, 2003; AEPI, 2001; Lafarge, 2009).

[b] Data for *ATILH* are from (ATILH, 2002).



Calcination: CaCO3 (solid) => CaO (solid) + CO2 (gas)

Carbonation: Ca2+ (aq) + CO3 2-(aq) => CaCO3

Table 5: List of contaminants in concrete production through calcination and estimated concentrations