Value Analysis on the Utilization of High-Density Polyethylene (HDPE) Pipes as an Alternative to the Conventional Reinforced Concrete Pipes

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Abstract. Depending on their usage and structural capability, various materials are used for drainage systems. Because of its structural integrity and market availability, the reinforced concrete pipe has been widely used since the 1800s. However, with the introduction of plastic pipes and associated technology, it has become a formidable competitor to reinforced concrete pipes. The main impediment to using HDPE is the lack of knowledge about this technology, its unavailability in the local market, and the high freight and handling costs. This paper compares the cost-effectiveness of high-density polyethylene pipe versus conventional reinforced concrete pipe using value engineering analysis tools such as force field analysis and FAST diagram. Regarding maintenance costs over the product's life, HDPE is more cost-effective than RCP. The lack of awareness about using HDPE pipes and their scarcity in the local market drives up their unit price in the short term. However, due to the ease of installation of HDPE over its RCP counterpart, there is a significant difference in labor costs. Our study found that HDPE pipes can save you about 5.88% in operation and maintenance costs compared to reinforced concrete pipes. This feature makes them an excellent choice for small-scale drainage systems like the ones frequently used in local areas. Our research suggests that using HDPE pipes as an alternative to reinforced concrete pipes in highway drainage design is bright and encourages more designers and engineers to consider them.

Keywords: Drainage · High-Density Polyethylene · Reinforced Concrete Pipe · Utilization · Value Analysis

1 Introduction

Storm sewers transport surface waters, precipitation runoff, and, in some cases, groundwater [1]. A storm sewer system aims to collect stormwater that runs off the surface and gravity-transport it to outfalls. The system's optimal design aims to produce an

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overall cost-effective solution. Storm characteristics (intensity, frequency, duration, and distribution), catchment runoff properties, overland flow process, sewer line layout, pipe material, pipe size and gradient, control facility characteristics, storage size and location, optimization technique, cost model, and design constraints are just a few examples [2]. The intricate design of these systems involves multifaceted considerations, encompassing storm characteristics, catchment runoff properties, sewer line layout, and an array of material choices.

This research delves deeply into an extensive examination focused on comparing how cost-effective different construction materials are compared to conventional reinforced concrete pipes. This evaluation employs a range of tools of value engineering (VE). Highlighting VE's significance in streamlining spending on infrastructure, boosting effectiveness, and reducing resource consumption, this investigation delves into the fundamental functions of storm sewer systems. VE methods, built on logical questioning and functional analysis, aim to enhance performance, reliability, quality, safety, and the overall costs over the system's life [3, 4].

VE's adaptability is not confined to stages in the life cycle of a product or process, as it is versatile across different scenarios. Particularly in construction, VE emerges as a powerful tool to identify better value options by integrating eco-friendly practices and materials. The findings of this study underscore VE's crucial role in understanding how construction materials perform in terms of cost-effectiveness and long-term efficiency. By exploring the junction of materials science, engineering efficacy, and financial feasibility, this research offers compelling insights into optimizing the construction of storm sewer systems through the lens of value engineering [3, 4].

2 Literature Review

2.1 Reinforced Concrete Pipe

In the early to mid-1800s, man's desire and need to provide a healthy environment, transport goods, and improve agricultural development created a demand for a way to move sewerage and accommodate stormwater runoff adequately. Concrete pipe, see Fig. 1, has been used for agricultural drain tile and engineered sewer systems since the early nineteenth century. The first recorded concrete pipe sanitary sewer installation was in Mohawk, New York 1842. There are also several concrete pipeline installations from the late 1800s that are still operational today. The growth of the concrete pipe industry was influenced by related technical and market developments from the late 1800s to the early part of the twentieth century. Engineers began understanding how to predict and quantify stormwater runoff amounts and develop pipeline sizing methods. In addition, Iowa State University researchers addressed many critical components of pipeline design during the first three decades of the twentieth century. They devised methods for calculating the supporting strength of rigid pipe culverts and developed methods for estimating loads on a buried pipe. Polyvinyl Chloride PVC became the preferred choice for small-diameter sanitary sewers in the late 1970s and early 1980s. High-Density Polyethylene (HDPE) pipe began its push into the storm drain market. By the late 1970s or early 1980s, tiny small-diameter concrete pipe was specified or used for sanitary sewer or agricultural drainage needs. By the mid-1990s, HDPE had gained widespread acceptance in the private development market and gained ground in the municipal and DOT market segments [5–7].

Fig. 1. Example of a Reinforced Concrete Pipe [1]

Reinforced concrete pipe (RCP) is a composite structure made of concrete and reinforcement. We classify it into five classes, from Class I to Class V, and design it to convey sewage, industrial waste, and stormwater. ASTM C 76 M, or the Standard Specification for Reinforced Concrete Culverts, Storm Drains, and Sewer Pipes, is usually used to test it. The three-edge bearing method measures crushing strength to produce a 0.3 mm crack and determine the ultimate load with its external load. The pipe's water absorption is also measured by Method C 497 and must not exceed 9% [8]. Because they are designed to withstand environmental stresses and can transport huge volumes of liquid, frequent use of these pipes occurs in road and site construction. Because RCP can safely divert large amounts of runoff, flooding, or storm surges away from urban or industrial areas, it is ideal for infrastructure initiatives such as storm sewer conduits [8].

Its laying length, typically one meter, makes it labor-intensive, and the heavy equipment used for excavation and pipe laying makes it costly. Two workers, one foreman, and a backhoe or crane operator must install RCP sections. Workers use a crane or backhoe to manage the pipe securely as they lower it into position. The need for specific installation techniques for concrete pipes due to defective trenches and high-strength concrete pipes to support more oversized loads has been necessary for recent years where proposed roads have a longer radius of curvature, resulting in deeper cuts and higher fills [1, 9].

2.2 High-Density Polyethylene Pipe

Plastic pipe's lighter weight, longer lay length, chemical resistance, and leak-free properties have considerably impacted the concrete pipe business since it became commercially available in the 1950s. Municipal and agricultural engineering primarily uses these for drainage purposes. Engineers now have a wide range of options when choosing pipe materials to meet design requirements thanks to later developments of other flexible pipe materials like corrugated steel pipe (CSP), high-density polyethylene (HDPE), polypropylene (PP), fiberglass pipe, and steel reinforced high-density polyethylene (SRHDPE) [10–12].

Since its discovery in 1933, Polyethylene (PE) has become one of the most widely used thermoplastics globally. Its versatility is evident in applications ranging from electrical insulation during World War II to modern uses like gas and water pipes, landfill liners, and automotive fuel tanks. PE pipes debuted in the 1950s, initially in industry, then for rural water supply and oil field production due to their flexibility and durability. On July 3, 1967, the United States produced the first corrugated PE pipe. It was created to compete with traditional clay or concrete pipes and proved more accessible and more cost-effective to install. The corrugated plastic pipe (CPP) industry has since grown substantially, with annual sales exceeding $1 billion and pipe diameters ranging from 2 inches (50 mm) to 60 inches (1500 mm). CPP is now used in various applications, including housing, commercial development, transportation, mining, forestry, and stormwater treatment, showcasing its adaptability and success [13].

While plastic pipes are generally considered advantageous for drainage and water supply systems, not all plastic pipes available in the market are suitable for installation. Alongside their benefits, there are also drawbacks. Manufacturers should provide test results and material properties, including specific gravity, hardness, impact strength, compression, shear, and tensile strength, to ensure the safety and reliability of their pipes for plumbing purposes. The lack of such technical information poses user risks and uncertainty [14]. Additionally, using support in trenches to lay plastic pipes must be thoroughly observed, as pipe stability heavily relies on the concrete soil surrounding the pipe [15].

Flexible pipes differ from concrete pipes as they rely partially on the surrounding soil for structural support. These materials deform under the weight of soil, making them sensitive to strain and prone to gradual deformation (creep). Corrugated HDPE, see Fig. 2 and PP pipes are commonly installed in open-cut trenches and backfilled with compacted material, while smaller-diameter pipes are suitable for agricultural use. The cost of the pipe system includes installation expenses. The level of soil compaction, which stiffens the soil and prevents pipe deformation, is crucial. This effect is known as 'positive arching'. Flexible pipe installation is more demanding than concrete pipe installation regarding trench shape and backfill compaction. This happens because flexible pipes can adapt to uneven settling, ensuring the efficiency of municipal water supply and drainage projects. Unfortunately, there is a widespread misconception about the installation requirements of flexible and rigid pipes, often putting concrete pipes at a disadvantage [10–12, 16, 17].

The reviewed literature focuses on utilizing large-diameter High-Density Polyethylene (HDPE) pipes in highway drainage systems and culverts, particularly emphasizing their benefits and challenges. Several states, including Texas, have adopted specifications for large-diameter HDPE pipes ranging from 36 to 60 inches in diameter, presenting them as competitive alternatives in construction projects [18]. People praise these pipes for their potential cost-saving attributes. The research conducted by Taylor and Marr in Minnesota highlights the longevity of culvert pipes, emphasizing the corrosion resistance of plastic pipes like HDPE. However, concerns related to material creep and oxygen degradation persist. While the Florida Department of Transportation suggests a potential 100-year service life for HDPE pipes, the literature underscores the need to account for freeze-thaw effects. Despite being lightweight, easy to install, and corrosion-resistant, the successful implementation of HDPE and similar plastic pipes hinges on carefully considering factors such as temperature variations, installation methodologies,

Fig. 2. Example of a High-Density Polyethylene Pipe [1]

backfilling practices, and thorough inspections [19]. Similarly, Wenzlick's study in Missouri demonstrates cost savings when replacing concrete pipes with HDPE pipes on US Route 63. While some deformations and cracks were observed during construction, standardized installation procedures and material investigations can make HDPE pipes a cost-effective and durable alternative [20]. Finally, Stuart's research on HDPE and PVC pipes in highway cross-drains emphasizes the importance of adequate pipe coverage and trench width to accommodate construction loads, which tend to exceed those of regular highway traffic [21]. These studies contribute valuable insights into the growing acceptance and practical considerations surrounding using large-diameter HDPE pipes in highway drainage and culvert applications.

3 Methodology

Value Engineering (VE) is a highly effective technique for enhancing value and reducing waste across various domains, including product design, manufacturing, construction, operations, etc. It originated during World War II at General Electric Corporation and finds wide use in defense, transportation, construction, and healthcare sectors. VE aims to optimize infrastructure spending, boost efficiency, and reduce resource consumption. VE involves analyzing the functions of a system or product to improve performance, reliability, quality, safety, and life cycle costs. It can be applied at any stage of a product's or process's life cycle. VE uses rational questioning techniques and function analysis to find the best value, achieved when an item or process consistently fulfills its function with the lowest life-cycle cost. In the context of construction, applying VE can yield better value by incorporating environmentally friendly and energy-efficient practices and materials [3, 4, 22].

The Society of American VE International defines VE as a systematic approach that involves a multidisciplinary team. It identifies the function of a product or service, establishes its value, generates creative alternatives, and ensures reliable function at the lowest cost. VE recognizes that spending is focused on functions rather than mere ownership. Given environmental concerns, energy considerations, and rising prices, VE emphasizes examining the functional requirements for safe and efficient project implementation while minimizing ecological disruption. While VE is often seen as a cost-cutting tool, it is a step-by-step problem-solving process. In VE, value is the ratio of function to cost, and increasing value involves improving function or reducing cost, as depicted in Eq. 1 [3, 4].

$$Value = \frac{Function}{Overall\ Cost} \quad (1)$$

We will use value engineering to identify the material that will be more cost-effective overall and provide superior performance. The high-density polyethylene (HDPE) pipe offers a variety of laying lengths but is more prone to deformation due to its flexibility and being scarce on the local market. The conventional reinforced concrete pipe (RCP) has a limited laying length but has excellent resistance to soil surcharge on top of it.

The original plan was to construct and maintain a storm sewer system on a busy road using a 1000 mm diameter RC pipe. For ease of installation, the proposed alternative is to use HDPE. Table 1 shows the cost breakdown for each type of material. Tables 2 and 3 present the detailed cost analyses for each material.

Table 1. Original Plan vs. Alternative Plan.

100 L.m.	RCPC	HDPE
Labor	$ 463.00	$ 81.45
Equipment	$ 1,580.00	$ 400.44
Materials	$ 11,996.00	$ 33,459.00
TOTAL	$ 14,039.00	$ 33,940.89

We can see that while the initial total cost of using an HDPE pipe is higher than that of an RCPC, the installation cost of operating an HDPE pipe is lower than that of an RC pipe; this observation is also stated in the Plastic Pipe Institute Manual, being HDPE pipes are manufactured in a longer length usually 6 m, while they manufacture RCPC up to a maximum of 2.50 m only. Additionally, smaller diameter pipes are lightweight and can be handled and maneuvered without using large equipment, saving time and costs during installation [16, 23]. Value engineering between those two materials will determine which is more cost-effective and produces better results.

3.1 Force Field Analysis

Kurt Lewin introduced force field analysis as a technique for introducing change in the early 1950s. The concept is widely used in organizational development to implement structural, technological, and people changes. Many organizational behavior texts include force field analysis to evaluate forces influencing change. The concept of force field analysis originates from the physical sciences. In physics, for instance, you can precisely measure vectors and their relative strengths. A scientist's measurement of forces

Table 2. Cost Analysis of RCP

RCPC	100	l.m.	no. of hours	100	
1000 mm Class IV	1	l.m./hour			
Labor	No. of person	No. of hours	Hourly rate	Amount	
Foreman	1	0.57	1.73	0.99	
Skilled	2	0.57	1.25	1.43	
Laborer	4	0.57	0.97	2.21	SUBTOTAL
				4.63	$ 463.00
Equipment					
Backhoe 0.8 cu.m	1	0.29	50.08	14.52	
Plate Compactor	1	0.29	2.84	0.82	
Minor Tools				0.46	SUBTOTAL
				15.80	$ 1,580.00
Materials					
Portland Cement	bags	1.08	4.56	4.93	
Sand	cu.m.	0.061	14.49	0.89	
RC Pipes	pc	1	112.28	112.28	
Sand Bedding	cu.m.	0.128	14.49	1.86	SUBTOTAL
				119.96	$ 11,996.00
				TOTAL	**$ 14,039.00**

allows for predicting movement direction and speed. Forces operating in an organization implementing strategic changes are not subject to such precise measurement. However, identifying the salient forces operating in an organization should allow management to better assess the organization's likely direction and speed of movement in implementing a new strategy [24].

Figure 3 depicts the application of Force Field Analysis to use RC pipe and HDPE pipe. This type of analysis considers the advantages and disadvantages of using HDPE pipe instead of RC pipe. We can see that the resistance to switching from traditional RC pipe to HDPE pipe has a minor disadvantage. With this, we will use another value engineering tool to clearly define which material will produce a lower cost while providing better long-term performance.

3.2 FAST Diagram

In 1964, Charles Bytheway created the Function Analysis System Technique, a system for function analysis (FAST). Since 1965, value engineers worldwide have used this diagramming technique to correctly identify the interrelationship of the functions under study. Like most VE tasks, creating a FAST diagram is best accomplished collaboratively. The interaction of different points of view leads to more profound thought about the

Table 3. Cost Analysis of HDPE

HDPE	100	l.m.	no. of hours	20.62	
1000 mm dia	4.85	l.m./hour			
Labor	No. of person	No. of hours	Hourly rate	Amount	
Foreman	1	1	1.73	1.73	
Skilled	1	1	1.25	1.25	
Laborer	1	1	0.97	0.97	SUBTOTAL
				3.95	$ 81.45
Equipment					
Backhoe 0.8 cu.m	1	0.16	50.07	8.01	
Boom Truck	1	0.09	17.86	1.61	
Generator Set	1	0.46	15.31	7.04	
Portable Air compressor	1	0.22	4.32	0.95	
Electrofusion machine	1	0.24	4.04	0.97	
Plate compactor	1	0.16	2.84	0.45	
Minor Tools	1			0.39	SUBTOTAL
				19.42	$ 400.44
Materials					
HDPE pipe 100 mm dia	m	1	282.85	282.85	
Freight/Handling cost	m	1	45.08	45.08	
Electrofusion wire	m	3.14	1.43	4.49	
Sand Bedding	cu.m.	0.15	14.49	2.17	SUBTOTAL
				334.59	$ 33,459.00
				TOTAL	**$ 33,940.89**

subject and, as a result, more thorough execution of the information phase in the Job Plan [3].

We will reduce or eliminate items of work that are not necessarily required in installing pipes once we have identified the critical functions using the FAST diagram in Fig. 4. In addition, we will add necessary system functions that will affect the cost in the original plan.

Operation and Maintenance Cost. Considering service life and maintenance costs per year, there is a significant increase in RCP maintenance cost than HDPE. According to the Plastic Pipe Institute, the pipe system's desired service life must be considered when conducting an engineering economic analysis. Many state DOTs now require culverts and storm drain systems to have a 75- or 100-year service life. Corrugated HDPE pipe, whether made of virgin, recycled, or both materials, has a service life of 100 years, depending on its installation and environmental conditions [15, 25]. As

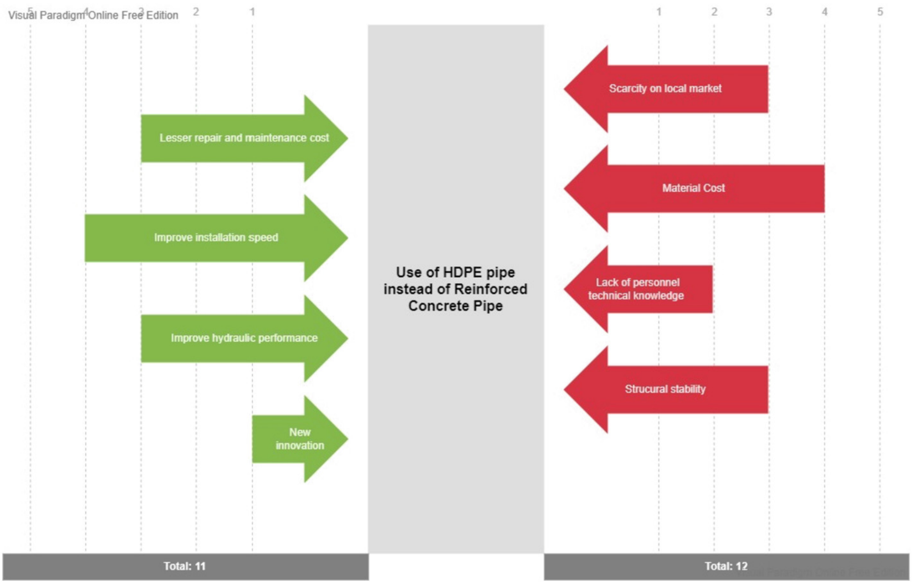

Fig. 3. Force Field Analysis between RCP and HDPE

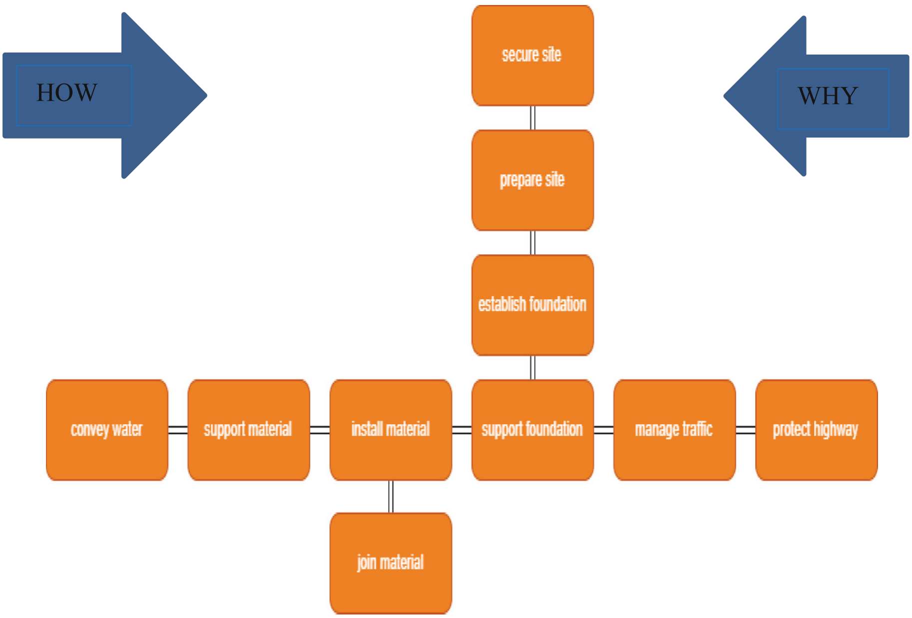

Fig. 4. FAST Diagram

the state of Florida's Department of Transportation stated in their protocol, HDPE can achieve the said life service using the Arrhenius equation. The pipe's service life in the given conditions falls short of what the owner requires; the life cycle cost analysis must factor in the cost of replacing the pipe [13, 15, 16, 26, 27].

On the other hand, the US Army Corps of Engineers assigned the life expectancy of reinforced concrete pipes to be 70–100 years, the same as that of plastic pipes [28]. Using the life cycle analysis from Plastic Pipe Institute for various pipes based on average installed operating and maintenance costs, the monthly fee per meter for RC and HDPE pipes is $5.87 and $3.87, respectively. This mainly occurs because Smooth-lined CPP is easy to clean, thanks to the low friction coefficient between debris and the pipe wall. Additionally, longer pipe lengths minimize the number of joints. CPP typically has less sediment build-up than RC pipes; the cement collar is usually placed inside the pipe between joints, which can also cause build-up through the years [16]. It is evident in the study of Vahidi et al. that RC pipes have more significant head loss than HDPE, with values of 2.72 and 3.13, respectively [27].

Additionally, HDPE pipe production consumes less energy, reducing possible health and safety risks compared to traditional concrete pipes [15]. To substantiate this claim, Mortezania's computer program, based on mathematical models, compares the costs of CC (cured concrete) pipe and DWC-HDPE (double wall corrugated high-density polyethylene) pipe, with HDPE pipe yielding a lower maintenance cost than concrete pipe [29]. However, in long-term planning, choose concrete for larger pipes over 100 years, as it withstands external loads, while plastic pipes are better for smaller ones [26]. We present detailed unit cost analyses using Value Engineering (VE) between RC and HDPE pipes in Tables 4 and 5.

4 Results and Discussion

Table 4. Cost Analysis of RCP using VE

RCPC	100	l.m.	no. of hours	100	
1000 mm Class IV	1	l.m./hour			
Labor	No. of person	No. of hours	Hourly rate	Amount	
Foreman	1	0.57	1.73	0.99	
Skilled	2	0.57	1.25	1.43	
Laborer	4	0.57	0.97	2.21	SUBTOTAL
				4.63	$ 463.00
Equipment					
One bagger Mixer	1	0.29	3.02	0.88	
Water Truck	1	0.1	42.98	4.30	
Backhoe 0.8 cu.m	1	0.29	50.08	14.52	

(*continued*)

Table 4. (*continued*)

RCPC	100	l.m.	no. of hours	100	
Boom Truck	1	0.29	17.86	5.18	
Plate Compactor	1	0.29	2.84	0.82	
Minor Tools				0.46	SUBTOTAL
				26.16	$ 2,616.00
Materials					
Portland Cement	bags	1.08	4.56	4.93	
Sand	cu.m.	0.061	14.49	0.89	
RC Pipes	pc	1	112.28	112.28	
Sand Bedding	cu.m.	0.128	14.49	1.86	SUBTOTAL
				119.96	$ 11,996.00
O & M	cost	mtr	years		SUBTOTAL
	5.87	100	100		58,700.00
				TOTAL	**$ 73,775.00**

Table 5. Cost Analysis of HDPE using VE

HDPE	100	l.m.	no. of hours	20.62	
1000 mm dia	4.85	l.m./hour			
Labor	No. of person	No. of hours	Hourly rate	Amount	
Foreman	1	1	1.73	1.73	
Skilled	1	1	1.25	1.25	
Laborer	1	1	0.97	0.97	SUBTOTAL
				3.95	$ 81.45
Equipment					
Backhoe 0.8 cu.m	1	0.16	50.07	8.01	
Boom Truck	1	0.09	17.86	1.61	
Generator Set	1	0.46	15.31	7.04	
Portable Air compressor	1	0.22	4.32	0.95	
Electrofusion machine	1	0.24	4.04	0.97	
Plate compactor	1	0.16	2.84	0.45	
Minor Tools	1			0.39	SUBTOTAL
				19.42	$ 400.44

(*continued*)

Table 5. (*continued*)

HDPE	100	l.m.	no. of hours	20.62	
Materials					
HDPE pipe 100 mm dia	m	1	282.85	282.85	
Electrofusion wire	m	3.14	1.43	4.49	
Sand Bedding	cu.m	0.15	14.49	2.17	SUBTOTAL
				289.51	$ 28,951.00
O & M	cost	mtr	years		SUBTOTAL
	3.87	100	100		$ 38,700.00
				TOTAL	**$ 68,614.78**

Table 6. Revised Cost Plan after using VE

100 L.m.	RCPC	HDPE
Labor	$ 463.00	$ 81.45
Equipment	$ 2,616.00	$ 400.44
Materials	$ 11,996.00	$ 28,951.00
O & M	$ 58,700.00	$ 38,700.00
TOTAL	$ 73,775.00	$ 68,614.78

Table 6 presents the updated cost plan following the implementation of value engineering. In the long term, HDPE pipes are more cost-effective than RC pipes due to lower Operation and Maintenance Costs. Moreover, the significant differences in installation costs and time make HDPE pipes a favorable substitute for traditional RC pipes, particularly in road drainage construction, especially in locations where smaller-diameter pipes are a common choice.

5 Conclusion

Reinforced concrete pipes have been widely used for drainage network designs since they can withstand environmental stresses and transport large volumes of liquids. The emergence of plastic pipes, especially HDPE, significantly impacts the concrete pipe business as its lighter weight, longer laying length, chemical resistance, and leak-free properties create competition between concrete pipes. However, due to HDPE's higher materials cost than RC pipes, most still prefer using the latter. However, the installation costs for HDPE and RC pipes are significantly different, making HDPE installation more cost-effective in terms of labor costs. Value engineering is pivotal in determining these materials' cost-effectiveness and long-term performance. Our analysis reveals that HDPE offers superior cost efficiency in maintenance over the product's lifespan, despite initial concerns about its higher unit price due to limited local availability and awareness.

The lack of awareness about using HDPE pipes and their scarcity in the local market drives up their unit price in the short term. However, due to the ease of installation of HDPE over its RCP counterpart, we can see a significant difference in labor costs. The −5.88% difference in maintenance costs makes the latter more cost-effective for use in a drainage system in a local setting. Furthermore, HDPE takes less time to install than RC pipes [11, 16, 23], and it does not cause traffic congestion during construction, which can further lead to economic loss [30]. The study's use of value engineering conclusively supports the adoption of HDPE pipe as a preferred alternative to RC pipe in highway drainage design, particularly for small-diameter pipes ranging from 1.0 to 2.0 m in diameter. However, further research in structural integrity is warranted for a comprehensive understanding of this material shift, as the current study does not provide a detailed examination of this aspect.

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