International Journal of the Physical Sciences Vol. 5(13), pp. 1974-1980, 18 October, 2010
Available online at http://www.academicjournals.org/IJPS
ISSN 1992 - 1950 ©2010 Academic Journals

Full Length Research Paper

Economic assessment of cured concrete by organic coating materials and double wall corrugated HDPE pipes in sewer networks

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Accepted 11 October, 2010

Resistance to deteriorations (especially corrosion) and initial price are important features in selecting the proper pipe materials for sewers. Among different types of pipe material used in Malaysia sewers, concrete and double wall corrugated high-density polyethylene (DWC-HDPE) pipes are more common. Laboratory tests were conducted using cylindrical concrete samples coated by polyurethane and epoxy materials to investigate their ability to protect concrete pipe against corrosion. Secondly, the cured concrete pipe price was compared to sewer construction costs. Economic analyses were carried out to compare the prices of cured concrete and DWC-HDPE pipe in various diameters. The results revealed that the coatings act as a barrier against the aggressive environment. Besides, their ability was proved to prolong concrete service life. In addition, the results showed that using the coatings to prevent or delay concrete networks' deterioration (against corrosion) was at least 2 times more economical compared to sewer reconstruction. Furthermore, it was concluded that DWC-HDPE pipe larger than 600 mm is not economical to be used for sewers due to well performance of designed coatings on extending the concrete pipe service life. Finally, mathematical models were developed to assist engineers or designers to accurately select the proper pipe based on desired variables.

Key words: Corrosion, cost analyses, service life, sewer pipe, surface treatment.

INTRODUCTION

Varieties of pipe materials (e.g. concrete, asbestos, iron and plastic) are being used for sewer networks. Among all, concrete is the most widely used construction material in sewers, treatment plants, and open channels due to its compatibility with environment, huge material resources, cost effectiveness, far more resistance and strength, and ease of make. Unfortunately, the rapid degradation of concrete structures is reported in wastewater facilities due to the acidic environments mostly generated by bacterial activities (Yamanaka et al., 2002).

The more the pipe resists problems (e.g. corrosion), the longer the service life of network will be. Durability for long life, an abrasion-resistant interior to withstand scouring action of wastewater carrying gritty materials, impervious walls to prevent leakage, and adequate strength to resist failure or deformation under loads (Figure 1) are physical characteristics essential for sewer pipes. In addition, resistance of pipe material to chemical attacks which could lead to corrosion, dissolution, etc. is important enough to be considered in selecting the proper pipe material.

Corrosion deterioration (e.g. in concrete sewer networks) has significant impacts on economy, environment, and society (Zhang et al., 2008; US EPA, 1998). Hence, economical and effective techniques are required to prevent or control corrosion deteriorations in particular areas of sewers (e.g. low-slope pipelines, drops, where H_2S generation is common, etc.). Corrosion process mostly occurs by hydrogen sulfide generation in sewage networks (Vollertsen et al., 2008; Okabe et al., 2007; Roberts et al., 2002). Overtime (usually, about 5 to 30 years), dissolved sulfates in water penetrates hardened

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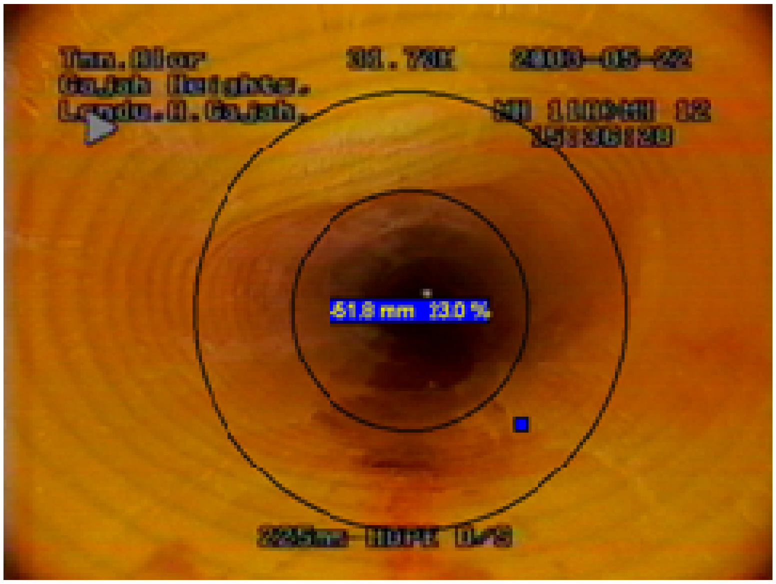

Figure 1. Deformation of DWC-HDPE pipe under external loads (case in a sewer network, Malaysia).

concrete and causes deterioration by converting calcium aluminates and sulfoaluminates into calcium sulfoaluminates (Portland Cement Association, 2002). The cracks initiated on the concrete surface by chemical reaction of sulfates, propagate into the concrete core which lead to an increase in porosity, diffusivity, and permeability of concrete structure (Mehta and Monteiro, 2006; Tixier, 2000). The rate of hydrogen sulfide generation depends on sewage parameters such as pH, temperature, turbulence, and so forth (Yongsiri et al., 2005). Various types of control technologies can be used to overcome this issue (e.g. using acid resistant materials, using chemical or biological treatments, and optimizing the sewer hydraulic design) (US EPA, 1998; Othman and Mortezania, 2010; De Beliea et al., 2004).

High performance protective surface coating materials can be used to protect concrete structures from physical, chemical, or biological degradation or increase their durability. The coatings can stay in contact with concrete and provide long-term effective protection especially against corrosion with low maintenance costs (Vipulanandan and Liu, 2005; Almusallam et al., 2003). Researchers (e.g. Almusallam et al., 2003; Shon and Kwon, 2009; Chattopadhyay and Raju, 2007; Liu, 2000) have worked on the quality of various organic coating materials (e.g. acrylic, chlorinated rubbers, epoxy, polymer, and polyurethane) to protect concrete surface against corrosion conducting laboratory and *in-situ* tests. Results pointed out that among all, polyurethane and epoxy materials provide better performance, less absorption rate, and more resistance to corrosion.

In contrast, double wall corrugated high-density polyethylene (DWC-HDPE) pipe has become a popular alternative nowadays because it is flexible, easy to handle, durable, and chemically resistant; it also entails low piping cost, and offers an acceptable service life. Initial price of pipes (as an important part of sewer construction costs) is another desired category in selecting the type of pipe material for sewer network use. Undoubtedly, due to fluctuating prices of DWC-HDPE pipe, selecting the type of pipe material is always a challenging task. Proper pipe material should be used for specific parts of a network to provide better efficiency and more economical advantages against network deteriorations, mostly corrosion.

The main objectives of this study were as follows: (i) to investigate the efficiency of organic coating materials on concrete in order to estimate the time till designed coatings can withstand on concrete surface in aggressive environment; (ii) to determine the cost of coatings based on their ability to extend concrete service life and compare it with concrete network construction costs; (iii) to identify the most economical case by comparing the prices of cured concrete and DWC-HDPE pipes in various diameters; (iv) to develop mathematical models to assist municipals in selecting a proper pipe based on desired variables.

MATERIALS AND METHODS

Cylindrical concretes which represent the concrete pipes were used to conduct tests under laboratory condition. The concrete samples provided with water to cement ratio (w/c) of 0.36, cement content of 350Kg/m^3, Portland cement type V, and dimensions of 10 cm in diameter and 20 cm in length. To conduct this work, two generic types of organic coating materials were selected as follows:

(1) Polyurethane (PU, Natural Polymer Solvent Coating industrial supply, white color, ρ=1.35 g/cm^3, 27 US$/Kg, ratio of wet/dry weight (Vs) =1.07).
(2) Epoxy (Ep, Natural Polymer Solvent Coating industrial supply, grey color, ρ=1.5 g/cm^3, 16 US$/Kg, ratio of wet/dry weight (Vs) = 1.06).

The study procedure started with concrete surface preparation according to ASTM C811-98 standard (ASTM, 2008) using water pressure and wire brusher to remove any sort of dirt before coating application. Polyurethane (PU) and epoxy (Ep) were applied (100 µm thickness) on concrete samples in the lab (no wind) with utmost care to cover all surfaces thoroughly without any defect following the supplier recommendations and left in the lab temperature to be completely dry.

One of the most widely used methods to investigate the chemical resistance of coated concrete is performing accelerated tests in the laboratory. This method is identified as a rapid test (Liu and Vipulanandan, 1996) which can be performed in two ways (Monteny et al., 2000), that is, increasing the aggressive solution (e.g. sulfuric acid) concentration or using specimens with large surface area per volume ratio. For accelerating method using sulfuric acid, keeping the pH of the solution at a certain level (by titration) was recommended. In addition, the pH less than one (that is pH<1.0) represents the worst condition in the sewer systems due to sulfuric acid produced by bacteria. This reported pH is approximately similar to the concentration of 1 - 3% sulfuric acid solution (Islander, 1991).

Before running the laboratory tests, the coated samples were weighed (W_p) by digital balance having a precision of ±0.001. Coated concrete samples are placed (half immersion where exposed to the liquid and vapor phase) in the containers filled by 2 and 10% sulfuric acid solution. The pH of solution was monitored during the test by thermo electron corporation 3-star portable pH meter to provide a constant condition. When coated concrete structure contacts with sulfuric acid continuously, to investigate the long time coatings' behavior, qualifying the failure mechanisms are important. Regularly, the samples were visually inspected for the corrosion sings (coating failure types, e.g. blistering, cracking, or flaking (ISO, 2003)) using high power magnifying glass 30x LED lighted. The failures were picked as indicator to evaluate the experimental results to determine the service life of designated coatings. Accordingly, the time of first failure on coated samples immersed in 10% sulfuric acid solution was determined. After the designed test period (30 days), samples were taken out of the containers, washed by water; the damaged parts were removed and left to dry in the laboratory temperature to determine the weight loss percentage. Experiments were repeated and the average of measured parameters with 5% standard division was calculated and analyzed during the entire experimental stages to achieve the first goal in this work. Afterwards, the cost of concrete pipe coated by designated coatings (P_{co}) was estimated and compared to concrete pipe network construction budgets. Here, the desired service life for data analyses was 25 years. Moreover, economical analyses were developed to compare the price (TP_{Cp}) of cured concrete pipe (that is the summary of initial pipe price (FP_{Cp}) and P_{co}) and DWC-HDPE pipe price (P_{PEp}) in various diameters. In this case, the service life was designed by 50 years for data analyses. In addition, according to the results obtained, mathematical models were developed to assist municipalities in selecting economical pipe based on their desired data.

RESULTS AND DISCUSSION

Coatings' ability to extend concrete pipe service life

Estimation the weight changes of coated concrete structure exposed to aggressive environment is a significant parameter to predict the service life of coating materials (Liu and Vipulanandan, 1996). Ensured the samples were completely dry after the test intervals, the samples were weighed (W_s) to determine the weight loss percentage (W_L) by:

$$W_L = \left(W_p - W_s \right) \Big/ W_p \times 100 \qquad (1)$$

The evaluation of current and future corrosion damage of concrete pipes in sewer networks during their service life has become imperative for engineers which results as aging decrement of the network. Thus, shortens their remaining service life, requires funding for repair or replacement. Sulfuric acid is one of the main substances produced in corrosion process. In order to predict the service life of coated concrete structures, it is important to determine a value of sulfuric acid absorption into coated concrete and its time dependence. However, there is no accurate developed model to describe coated concrete performance under sulfuric acid attack and prediction of coating service life. The service life of coated concrete can be determined by estimating the time for coated concrete to fail. This is the time taken by sulfuric acid to penetrate into the coating film, while letting the corrosion products to cause failures on the concrete cover film. The time to coated concrete failure (e.g. cracking) after corrosion initiation is related to the thickness of coating material (L_t), the liquid absorption by coating, and the time contacting with liquid. In this regard, Equation (2) is proposed by Murray (1995) and Sharifi (1996) for organic coating materials' service life prediction based on their thickness. Here, t represents the time that coating can withstand in aggressive environment or the time of first failure observation:

$$t_2 = \left(L_{t2} / L_{t1} \right)^2 \times t_1 \qquad (2)$$

where L_{t2} and L_{t1} (= 100 µm in this work) are the thicknesses of coating materials, t_2 presents the time of first failure on the coating film using L_{t2} thickness, and t_1 is the time of first failure observed in 2% sulfuric acid solution.

The basis deterioration of coated concrete was designed when the first coating failure (e.g. cracking, blistering) was observed on applied coating film. When coated concrete specimens come in contact with liquids, the liquid will penetrate through the coating film into the concrete. The penetrations of the solutions that do not react with coating materials are similar to water penetration into coating films. In other words, the rate of water absorption to coating film is related to the weight gain by coating film. On the other hand, if the liquid such as sulfuric acid solutions reacts with the concrete and damages the concrete structure, the concrete will be corroded layer by layer starting from the interface of the

Table 1. Experimental results for designed coating materials with 100 µm thickness immersed in 10 and 2% sulfuric acid solution.

Coating material	$W_{L10\%}$	$W_{L2\%}$	Z	$C_{t10\ \%}$
Polyurethane	0.121	0.015	8.06	159 h
Epoxy	0.130	0.018	7.22	131 h

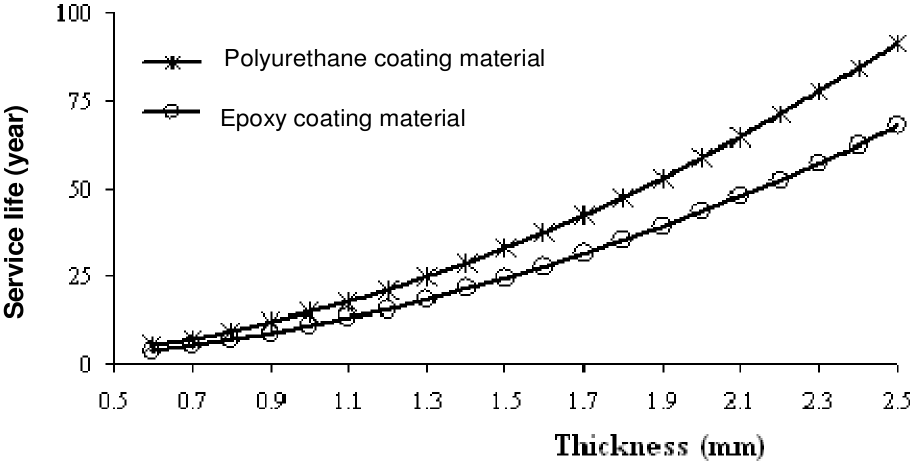

Figure 2. The service life value of designed organic coating materials (polyurethane and epoxy) vs thicknesses.

coating and the concrete substrate. Hence, the rate of acid consumption by coated film is related to the weight loss by coated film and the time the coating material is in contact with aggressive environment (Liu, 2000). The longer the time of first failure on the coating surface, the less is the weight loss (Sharifi, 1996). Accurate prediction of coatings service life under corrosion process should be investigated for a long time in the natural environment. Inverse relationship was designed between weight loss (W_L) by coated sample immersing in sulfuric acid solution and time of first failure (Equation 3):

$$Z = W_{L10\%} / W_{L2\%} = C_{t2\%} / C_{t10\%} \quad (3)$$

where the $W_{L10\%}$ and $W_{L2\%}$ present the weight loss percentage of samples in 10 and 2% sulfuric acid solutions, and $C_{t10\%}$ and $C_{t2\%}$ are the time of first coating failure exposed to designed solutions. Here, $C_{t2\%}$ is equal to t_1 in Equation (2).

Based on regular observations, the time of first failure for polyurethane coated sample immersed in 10% sulfuric acid solution was approximately 159 h of exposure, followed by epoxy at 131 h (Table 1). Data analyses were performed to determine the time of first failure ($C_{t2\%}$) or the maximum service life (t_1) for coated samples immersed in 2% sulfuric acid (using Equation 3 and Table 1). In such way, maximum service life or time (t_1) for PU coating material to resist 2% sulfuric acid solution was determined at approximately 1282 h while for epoxy it was lower (that is 946 h). According to the tests conducted by Sharifi (1996), for Ep coated on concrete surface with 100 µm thickness immersed in 1% sulfuric acid solution, the maximum service life of 1680 h was reported.

Using Equation 2 and previous data, the designed coating materials service life by various coating thicknesses are shown in Figure 2. To resist concrete surface in aggressive environment or to delay concrete deterioration by 25 years, for instance, the effective thicknesses of PU and Ep coatings were approximately estimated by 1.3 and 1.5 mm, respectively (Figure 2).

Comparison of designed coatings and concrete network construction costs

Decisions based on early estimates in the planning phase of a construction project become the basis for proper resource allocation and selection of the best strategy for asset development during the life of the project. Costs are important parameters for any categories in investigations and engineering measurement. At the early stages of the project, cost estimates are needed by cities

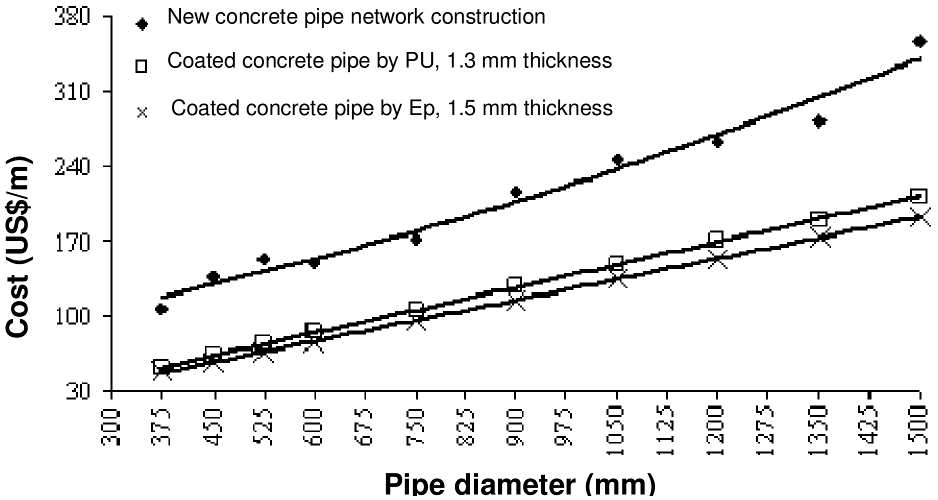

Figure 3. Comparison of coating materials with effective thickness and concrete network construction costs based on designed service life of 25 years (network construction costs based on IWK (Malaysia) data, March 2008).

for several purposes, e.g. determination of project feasibility, financial evaluation of a number of alternative projects, establishment of an initial budget, and costs investigation against project service life.

As mentioned previously, concrete service life can be lengthened by using designed coating materials. However, this will increase the initial price of concrete sewer pipe. Economic analyses were performed using Equation (4) to determine the cost of coating materials (P_{co} (US$)) for 1 m length of concrete pipe based on their obtained effective thickness. Here, the wasting percentage (w) of PU coating during a coating application was determined as 5% followed by Ep coating as 6%:

$$P_{co}=((A_p \times L_t/10) \times \rho_M \times Vs) \times (1+w/100) \times P_M \quad (4)$$

where A_p (cm^2) represents the area of coating on concrete surface ($=\pi \times d_p \times L_p$), d_p (cm) is the internal pipe diameter, L_p (cm) represents the length of pipe (100 cm in this work), L_t (mm) is the coating thickness, ρ_M (g/cm^3) is the density of coating material, and P_M (US$/gr) represents the coating material price in the Malaysian market.

Figure 3 shows the comparison of coating materials prices (P_{co}) using Equation (4) and concrete pipe network construction costs in various pipe diameters. The economical calculations (Figure 3) indicate that using the designed coatings with effective thickness is more economical compared to construction of a network for the designed service life of 25 years. The figure depicts that the construction of concrete sewer network costs 2 to 3 times more than curing the concrete pipes by designed coatings to prevent or delay network deterioration by nearly 25 years. It is also obvious that the renovation or rehabilitation costs of existing sewers are greater compared to new network construction costs.

Comparison of cured concrete and DWC-HDPE pipe prices

To select a proper sewer pipe, providing a desired level of life at minimum cost is essential. One of the major and most costly problems in sewer networks and treatment plants is the replacement of such structures, which is observable in warm climates. Figure 4 demonstrates the comparison between initial price of concrete pipe (FP_{Cp} (US$/m)), price of cured concrete pipe (TP_{Cp}) based on their extended service life by designed coatings to approximately 50 years (25 years for concrete pipe individually and 25 years for coatings), and DWC-HDPE pipe (recommended service life of 50 years). TP_{Cp} (US$) was determined as follows:

$$TP_{Cp} = FP_{Cp} \times L_P/100 + P_{co} \quad (5)$$

Although, designed coatings extended the service life of concrete pipe by 25 years; Figure 4 illustrates that the coating materials by effective thickness (PU of 1.3 mm and Ep of 1.5 mm) increased the initial price of concrete pipe by approximately 3 and 2.7 times for PU and Ep, respectively.

Apgar and Witherspoon (2007) and Stewart (2005) recommended the use of corrosion resistance pipe materials such as HDPE pipe for sewer networks. Nielsen et al. (2008) indicated that the plastic surfaces are inert and acid will not be neutralized in contrast to

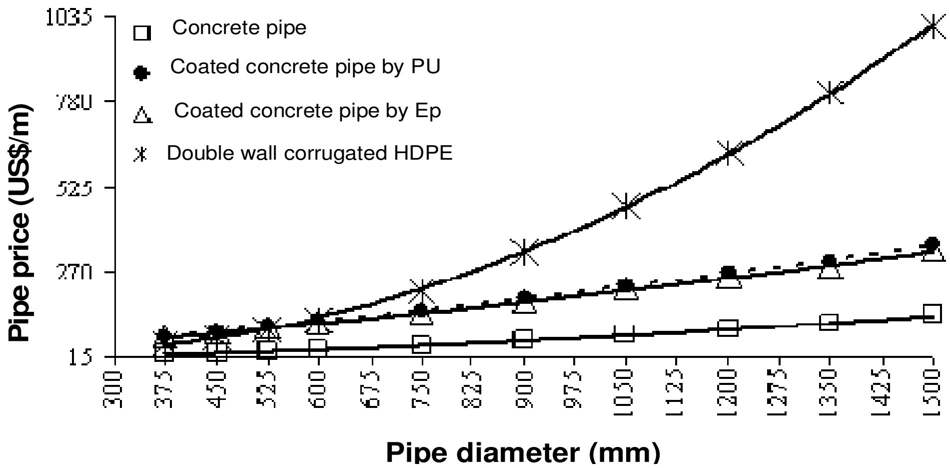

Figure 4. Comparison of concrete pipe using designed coating materials with effective thickness and DWC-HDPE pipe in available diameters for the desired service life of 50 years (initial pipes' price based on data of IWK and ResinTech Plastics (Malaysia), March 2008).

concrete pipes. Moreover, Lahav et al. (2004) recommended that small diameter sewer pipes are almost made of plastic materials whereas the larger diameter lines (>800 mm) are normally made of concrete. According to the Figure 4, using DWC-HDPE pipe is recommended for sewer networks below 600 mm in diameter. In this case, the maximum price of DWC-HDPE pipe is roughly 99US$/m for 525 mm followed by cured concrete pipe using Ep coating of approximately 101US$/m and PU coating of 107US$/m.

In addition, for 600 mm pipe diameter, the maximum price of DWC-HDPE and cured concrete pipe using designed coatings (PU and Ep) were determined by 125, 123, and 118 US$/m, respectively. The price of DWC-HDPE is maximum 6% more than concrete pipe price coated by designed coating materials. Due to well performance of DWC-HDPE pipe (e.g. resistance to corrosion, low piping cost, and easy handling) selecting proper pipe of 600 mm diameter should be considered by decision makers. Afterwards, the price of the DWC-HDPE pipe increased sharply compared to cured concrete pipe. Based on the investigations and economic analyses, it was concluded that using DWC-HDPE pipe (as a corrosion resistance material) larger than 600 mm in diameter is not economical for sewer networks. The price of DWC-HDPE pipe for 750 mm is 216 US$/m whereas the amount for concrete pipe cured by PU is 155 US$/m, followed by Ep of 145 US$/m. Therefore, coated concrete pipes using PU and Ep are 40 and 49% respectively, more cost effective than DWC-HDPE pipe.

Developed models

Pertinent Equations (6) and (7) represent more specifically the service life values of PU and Ep materials which obtained from the results illustrated in Figure 2. The second order curves fitted the data well:

$$SL_{PU} = 14.63\,L_t^{\,2} - (2\,exp - 13)\,L_t \tag{6}$$

$$SL_{Ep} = 10.797\,L_t^{\,2} - (6\,exp - 14)\,L_t \tag{7}$$

where SL_{PU} (year) and SL_{Ep} (year) are the service life values of PU and Ep coating materials respectively, based on coating thickness (L_t (mm)).

Using Equations (4)-(7), mathematical models (i) and (ii) were developed to make the economic comparison of different diameters of cured concrete (using PU and Ep coating materials) and DWC-HDPE pipes. To achieve this matter, estimated ratio of DWC-HDPE pipe price to its expected service life (P_{PEp}/SL_{PEp}) should be compared with the results achieved by variables X (model (i) for PU coating material use) and Y (model (ii) for Ep coating material use). The variables X and Y show the ratio of cured concrete pipe price to its total service life (summary of concrete pipe and coating service life). These models reported herein can assist municipalities in nominating economical pipe for sewer networks use.

$$X = \left(FP_{Cp} \times L_P/100 + \left(\pi\, d_p\, L_p\, L_t / 10 \right) \times \left(\rho_{PU}\, Vs\left(1 + w/100\right) \right) \times P_{PU} \right) \times \left(1 \middle/ \left(SL_{Cp} + 14.63 L_t^{\,2} - (2\,exp - 13)\,L_t \right) \right) \tag{i}$$

$$Y = \left(FP_{Cp} \times L_P/100 + \left(\pi\, d_p\, L_p\, L_t / 10 \right) \times \left(\rho_{Ep}\, Vs\left(1 + w/100\right) \right) \times P_{Ep} \right) \times \left(1 \middle/ \left(SL_{Cp} + 10.797\, L_t^{2} - (6\,exp - 14)\,L_t \right) \right) \tag{ii}$$

where SL_{Cp} (year) is the service life of concrete pipe and P_{PU} (US$) and P_{Ep} (US$) are the price of PU and Ep coating materials, respectively. Other variables are represented previously.

Conclusion

Chemical tests and economic analyses were carried out to select a proper pipe for sewer networks. The designed organic coating materials (Polyurethane and Epoxy) have fulfilled their function to withstand in aggressive environment and increase the concrete service life. The results pointed out that although, the designed coating materials (PU and Ep) exceed the initial price of concrete pipe but it is more economical compared to network construction costs based on supposed service life (that is, 25 years). Furthermore, it was concluded that DWC-HDPE pipe larger than 600 mm was not economical compared to cured concrete pipe with designed service life of 50 years. Based on the findings of this work, models were developed which aid engineers to nominate the proper pipe for optimum cost saving and performance, as selecting such pipes is a challenging task in sewer networks.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Indah Water Konsortium (IWK) cooperation and financial support from the University of Malaya in performing this work.

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