Education

Determination of the optimum dry film thickness of polyurethane coating using experimentation and mathematical modeling

Anyanwu Kingsley Onyekachi[1*], Agha Inya Ndukwe[1], Chukwudike Onuoha[1] and Udochukwu Samuel Ikele[1]

[1] Department of Materials and Metallurgical Engineering, School of Engineering and Engineering Technology, Federal University of Technology Owerri, 460114 Owerri, Imo State, Nigeria

*Corresponding author: Anyanwu Kingsley Onyekachi

Received 16 Sep 2026; Accepted 22 Oct 2026; Published 12 Nov 2026

DOI: https://doi.org/10.64171/JAES.6.6.22-32

Abstract

Researchers have shown that dry film thickness (DFT) of corrosion protective coatings is a critical parameter, as it determines the durability and performance of the coating and substrate. In various publications, DFTs have been recommended for polyurethane (PU) coatings but none of the publications showed empirical approach for determining the optimum DFT of corrosion protective coatings, of which this study seeks to achieve. For this study, polyurethane (PU) resin was used as coating, while mild steel coupons were used as the substrate. A total of 63 coupons were produced. The coupons were tagged, weighed, and their initial masses were recorded accordingly. Two experiments were performed; for experiment I, DFTs applied were about 50 µm, 100 µm, and 150 µm. Seven samples were made of each DFT. The samples were submerged in 0.2M dil. HCl solution. Average corrosion rates of the samples were investigated accordingly on weekly and used with corresponding DFTs to calculate the optimum DFTs (t*) in accordance with the proposed model. For experiment II, DFTs applied were 0.25t*, 0.625t*, t*, 1.375t*, and 1.75t*. Seven samples were made of each of the DFTs. The coated samples were used with 7 uncoated (control) to conduct experiment II, following similar procedure adopted in experiment I. Average corrosion rates of the samples were also determined accordingly on weekly basis. The model was also used to estimate corrosion rates of the samples for the various DFTs. Average corrosion rates obtained from experimental results, otherwise referred to as "actual corrosion rate" and those estimated with the model, referred to as "model corrosion rate" were plotted on the same axis against the corresponding DFTs. Parabolic curves were obtained. Chi-square test was conducted to evaluate the association between coating thickness and corrosion rate, taking 0.05 significant level. Also, scatter index (SI), product moment correlation coefficient (R), and Nash-Sutcliffe efficiency coefficient (E) were calculated and used to evaluate the accuracy of the model. Result of Chi-square test shows weak association between DFTs and corrosion rates with ($p = 0.4742$). Optimum DFT of (110 µm) was obtained from the model, against (110.6 µm) actual. Comparing "model" and "actual" corrosion rates, the proposed model also exhibited good performance: ($SI = 3.89$; $R = 0.96$; $E = 0.91$). Thus, the proposed model can supposedly be used to proffer solution to premature failure of coatings related to inappropriate DFT.

Keywords: Modeling, Optimization, DFT, Corrosion, Protective coatings

1. Introduction

Steel has good mechanical, electrical, and thermal properties compared to several other engineering materials. Because of this, they are used for various purposes, covering industrial, medical and domestic applications. However, corrosion is a major challenge often faced with mild steel. Nevertheless, several methods have been developed for mitigating metal corrosion, which includes: cathodic protection, anodic protection, impressed current method, pigging, and application of corrosion protective coating (Anyanwu, 2022) [6]. Komalasari, Utami, Aziz, and Irianti (2018) [17] used banana peel extract as corrosion inhibitor for carbon steel in dilute acid solution. Anand and Anirbid (2016) [5] discussed various types of pigs used for corrosion control.

Aljibori, Al-Amiery, & Kadhum (2023) [3] gave a comprehensive overview on the advances in corrosion protective coatings. Anyanwu (2022) [6] noted that use of corrosion protective coating is cheap and effective method of corrosion control. Polyurethane coating has among other coatings been identified as very effective coating with numerous advantages. Forsgren (2006) [10] explained the various types and applications of polyurethane coatings. Amir (2012) [4] described the use of Polyurethane coating to prevent corrosion in oil and gas Pipelines.

Although corrosion protective coatings have been reported to be effective in corrosion mitigation, researchers have shown that excessive or deficient coatings thickness results in premature failure of the coatings and consequently rapid corrosion of the substrate (Baur Julia (2001) [7]. Raghvendra (2024) [20] stated that the performance of corrosion protective coating strongly depends on the DFT of the coating. D&D Coating Industries Ltd, UK. (2024) [8] described some common coating defects that lead to premature failure of coating; such include: delamination, blistering, de-adhesion and debonding. Hitchens (2017) [14], Sean (2017) [21], and Mallory McGuiness (2020) have associated premature failure of corrosion protective coatings with defects resulting from inappropriate coating thickness, such as cracking, porosity, delamination, pin

holes, sagging, brittleness and orange peels). All these defects reduce the quality and performance of coatings. In additions, studies have also shown that excessive thickness of coatings can cause cracking, delamination, sagging, porosity, while insufficient thickness can lead to cracking, pin holes, exposure of the substrate etc (Baur, 2001; Sean, 2017) [7, 21]. Based on previous publications, delamination is the coating defect that is most often associated with dry film thickness of the coating.

According to D & D Coating Industries (2024) [8], coating delamination refers to the separation of one coating layer from another, known as inter-coat adhesion failure, or separation of the coating from its underlaying surface, referred to as substrate adhesion failure. D&D Coating Industries stated that delamination is caused by several factors such as poor surface preparation and prolonged exposure to corrosive environments, such as sea water. It was also stated that further delamination can occur when the substrate is subjected to stress or other surface deformations. Fixing this kind of problem can lead to separation. This separation reduces mechanical strength of the coating, leading to split. When this split is not treated, water ingress can occur, resulting in corrosion. A particular type of delamination, referred to as cathodic delamination often occur in corrosion systems (D & D Coating Industries, 2024) [8].

Cathodic delamination is a process by which coating separates from the substrate at corrosion site (D & D Coating Industries, 2024) [8]. This usually occurs when the electrochemical reaction produces hydroxide ions between the substrate and the coating, resulting in loss of adhesion. This process can create osmotic pressure, leading to further separations. Cathodic delamination often occurs when metals coated with organic materials are immersed in sea water. Another coating defect commonly observed in corrosive environment is debonding. Debonding occurs when the coating fails to adhere to the substrate due to disruption of physical, chemical, or mechanical forces holding the substrate and the coating. Debonding is possibly caused by external forces, contamination during coating or environmental factors, such as temperature and humidity. Figure 1 is a picture showing delamination of metal pipeline caused by inadequate cleaning prior to coating, while Figure 2 illustrates the mechanisms of cathodic delamination. Failure of corrosion protective coatings makes the substrate susceptible to rapid corrosion, which can result in economic consequences and catastrophic failure, which can possibly leads to loss of lives. Therefore, necessary precautions should be taken during coating application to avoid errors that can lead to premature failure of coatings. Optimizing DFTs of corrosion protective coatings is a fundamental practice for enhanced coating performance Raghvendra (2024) [20]. Thus, this study seeks to determine the optimum DFT of polyurethane coating using experimental results.

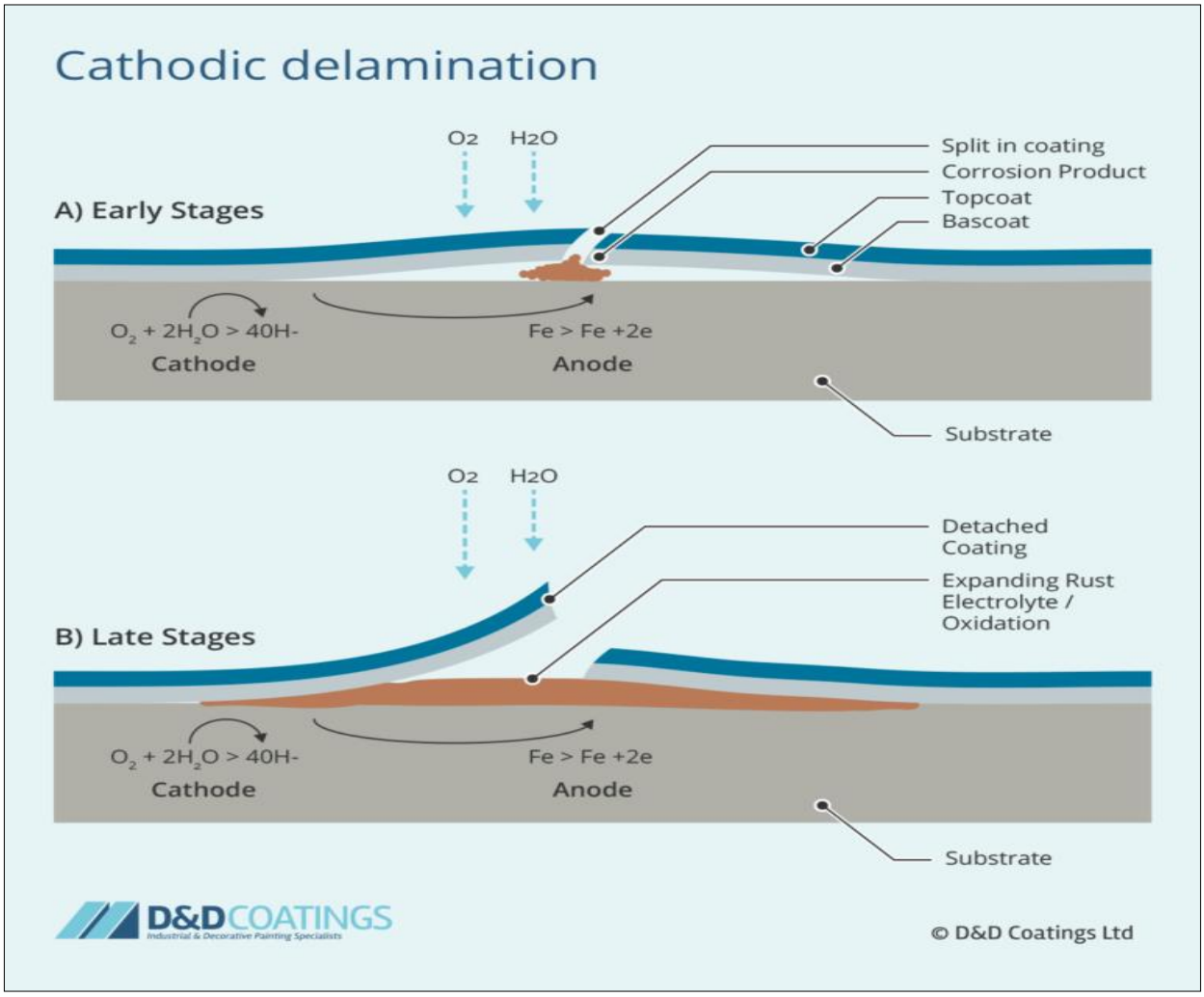


Fig 1: Cathodic delamination mechanisms (D&D Coating Industries, 2024) [8]



Fig 2: Picture showing delamintion on pipeline caused by inadequate cleaning prior to coating (D&D Coating Industries, 2024) [8]

Polyurethane are polymers whose molecular structure depended majorly on carbamate groups (-$NCHO_2$). They are produced when isocyanate (R–N=C=O) reacts with hydroxyl groups, amines, or water (Forsgren, 2006) [10]. Polyurethanes are classified into two, depending on their curing mechanisms: moisture-cure urethanes and chemical-cure urethanes. Both moisture-cure and chemical-cure polyurethanes can be produced from either aliphatic or aromatic isocyanates Forsgren (2006) [10]. Somarathna, Raman, Mohottid, Mutalib, and Badri (2018) [23] and GZ Industrial supplies (2026) [12] described the use of polyurethane for corrosion protective coatings. Optimization of DFT of corrosion protective coating, such as polyurethane is any technique adopted to obtain the most appropriate DFT of the coating during application. Researchers have made attempts to achieve this, and further investigations are ongoing. Winniki, Malachowska, and Ambroziak (2014) [26] used Taguchi method to estimate optimum thickness of corrosion protective coating. In a study, Aisyah (2020) [2] gave a model in which the optimum thickness of insulation was deduced from the plot of temperature change between surface of insulated pipe and ambient temperature against coating thickness. Optimum thickness can also be estimated as the minimum point of the graph of coating thickness versus edge-bead ratio (Ying, Ping, Shang-Xiong, Xiao Guang, and Dong-Ming, 2018) [27]. In another study, Herman, Felita, & Wimala (2021) [13] analyzed the effects of abrasive materials and polyurethane coating thickness variation on ASTM A36 steel towards corrosion rates in sea water environments. A total of 18 samples were used for the study. Nine (9) samples were blasted with silica sand while (9) samples also were blasted with steel grit. For silica sand blasted samples, three samples each were coated with polyurethane to thicknesses of 60 µm, 80 µm, and 100 µm. Also, for the samples blasted with steel grit, three samples each were coated with polyurethane to thicknesses of 60 µm, 80 µm, and 100 µm. The specimens were exposed in sea water and monitored accordingly for corrosion behaviour.

The results obtained show that for silica blasted samples 100 µm coating thickness displayed the lowest corrosion rate (about 0.00023 mm/a) while 60microns coating thickness exhibited the highest corrosion rate (about 0.02203 mm/a). A similar result was observed with the samples blasted with steel grit: lowest corrosion rate (about 0.000081 mm/a) occurred with 100 µm coating thickness, followed by 80microns coating (about 0.000859 mm/a), while 60 µm coating displayed the highest corrosion rate (about 0.00965). Finding from the study is indicative that coating performance depends on the DFT of the coating. Furthermore, the results of the study suggest that the DFT of polyurethane coating required for optimum coating performance is about 100 microns. Marlin Steel Wire (2013) [18] recommended 0.032 inches to 0.058 inches for polyurethane coating. Raha Bitumen Company (2018) recommended 24µm for bituseal. Ferrum (2022) recommended minimum thickness of 80nm, 250nm and 1.8mm to 3.7mm. Various algorithms have been adopted for optimizing dry film thickness of corrosion protective coatings. Machine Learning (ML), Taguchi Model, Artificial Neural Network (ANN), Finite Element-Based Model (FEM) (Shahbaz *et al*., 2025) [22], Recurrent Neural Network (RNN) (Ji & Ye, 2025) [15], and Convolutional Neural Network (CNN) (Shahbaz *et al*., 2025) [22]. However, none of the cited authors considered the effect of coating thickness on the corrosion rates of the substrate in their modeling. Also, the authors had not published any mathematical model or empirical test that can be used to evaluate the optimum DFT of corrosion protective coatings.

Anyanwu (2022) [6] proposed a mathematical model for determining the optimum dry film thickness of corrosion protective coating, assuming that the graph of corrosion rate (CR) of the substrate against coating thickness (t) is also a parabola, whose coordinates at turning point consist of optimum thickness (t*) and minimum corrosion rate (CR*). The model also suggests the graph of coating durability (D) against coating thickness is a parabola whose coordinate at turning point consist of optimum thickness (t*) and maximum durability (D*). However, this study is focused only on using various DFTs of polyurethane coatings on mild steel substrates, and the corresponding corrosion rates of substrates to determine the optimum DFT (t*) of the coating as proposed by Anyanwu (2022) [6]. Figure 3 is a graphical illustration of the proposed parabolic model.

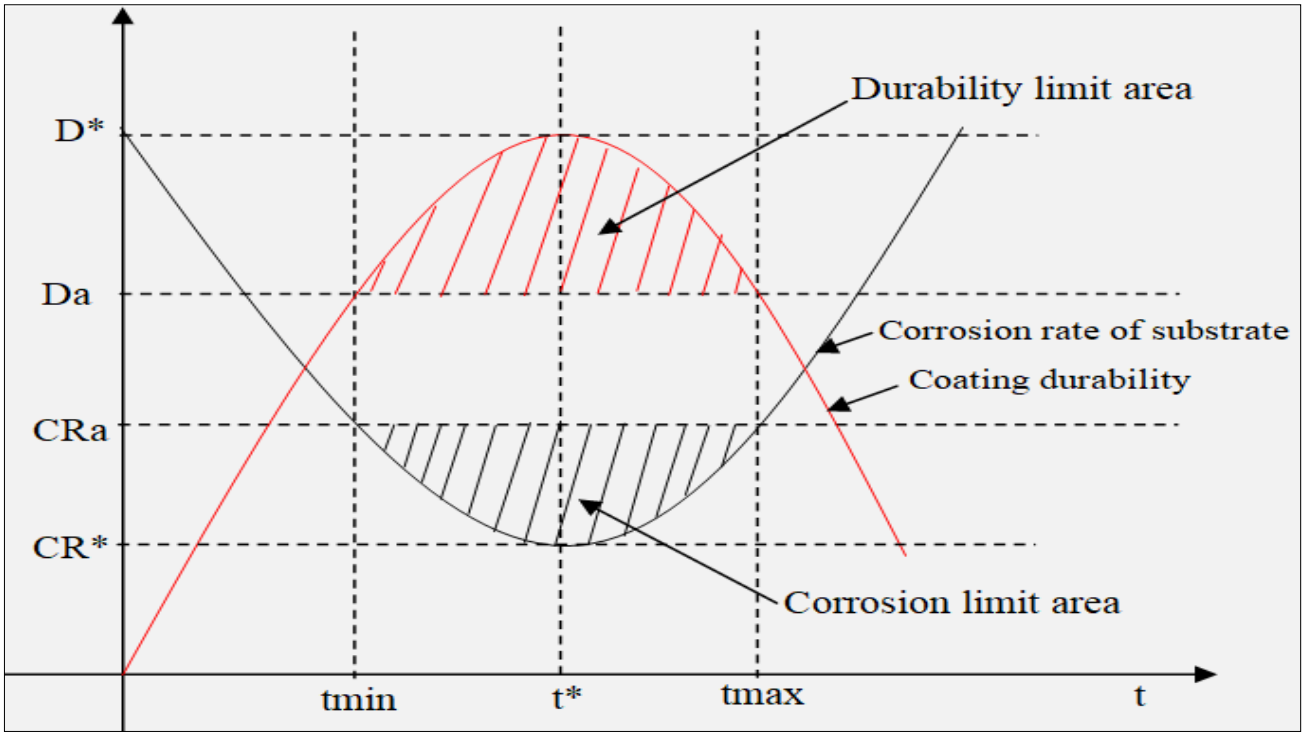


Fig 3: Proposed parabolic model for optimum DFT of corrosion protective coatings (Anyanwu, 2022) [6]

Anyanwu (2022) [6] proposed Eq. (1) for the corrosion rate of substrate given in Figure 3, which is simplified to get Eq. (2).

$$CR = a(t - t^*)^2 + CR^* \quad (1)$$

$$CR = at^2 - 2at^*t + at^{*2} + CR^* \quad (2)$$

Substituting three assumed values of t, i.e. t_1, t_2 and t_3 into Eq. (2) gives Eq. (3), Eq. (4) and Eq. (5) respectively.

$$at_1^2 - 2at^*t_1 + at^{*2} + CR^* = CR_1 \quad (3)$$

$$at_2^2 - 2at^*t_2 + at^{*2} + CR^* = CR_2 \quad (4)$$

$$at_3^2 - 2at^*t_3 + at^{*2} + CR^* = CR_3 \quad (5)$$

Solving Eq. (3), Eq. (4), and Eq. (5) simultaneously gives Eq. (6), which was used in this study for determining the optimum dry film thickness of polyurethane coating on mild steel coupons.

$$t^* = \frac{1}{2}\left[\frac{(t_2^2 - t_3^2)(CR_1 - CR_2) - (t_1^2 - t_2^2)(CR_2 - CR_3)}{(t_2 - t_3)(CR_1 - CR_2) - (t_1 - t_2)(CR_2 - CR_3)}\right] \quad (6)$$

Where:

t^* = optimum thickness of coating.

t_1, t_2, and t_2 are assumed thicknesses.

CR_1 = average corrosion rate of the substrate when the coating thickness is t_1.

CR_2 = average corrosion rate of the substrate when the coating thickness is t_2.

CR_3 = average corrosion rate of the substrate when the coating thickness is t_3

CR^* = critical corrosion rate of the substrate

CR_a = maximum allowable corrosion rate of the substrate

CR_a = maximum allowable corrosion rate of the substrate

a = Coating material constant.

2. Materials and Methods

2.1 Materials and Equipments

- Single Component Polyurethane – used as coating.
- Acetone – used for washing coupons.
- 63 pieces of mild steel coupons – used as substrates.
- Grades 60, 120, 220, 400, 600, 800 and 1000 emery cloths – used for polishing coupons.
- 0.2M dilute HCl at ambient temperature – used as the tests medium.
- Two (2) plastic containers of dimensions 30cmx40cmx40cm – used to set up experiment.
- H20T Mettler Tolledo's Analytical Balance – used for weighing coupons.
- Elcometer 112 – used for measuring WFTs of the coupons.
- PosiTector 200d1 used for measuring DFTs of the coupons.

Table 1: Chemical compositions and carbon equivalence of the coupons

% Fe	% C	% Mn	% Cr	% M_o	% V	% Cu	Ni	% CE
98.4800	0.2101	0.1800	0.0041	0.0026	0.0033	0.0024	0.0023	0.2427

2.2 Methods

There were basically four steps followed in this study. A specific task is performed at each step as presented in Figure 5.

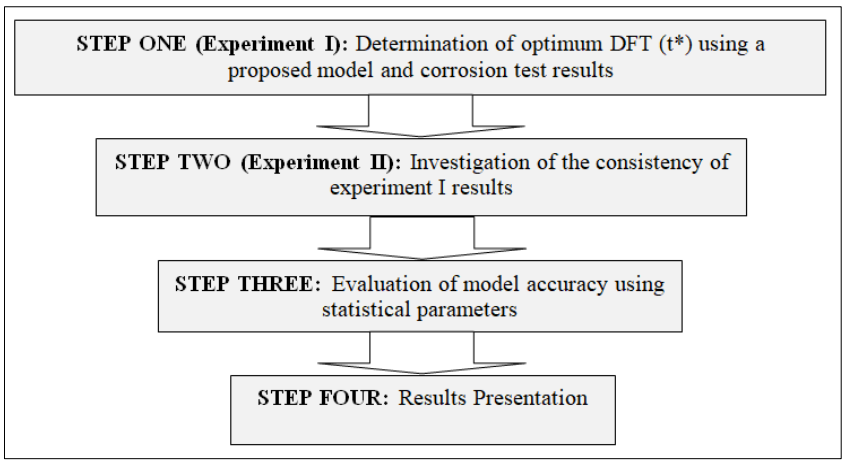


Fig 5: Illustration of the basic steps taken in this study

Preparation of coupons

Coupons were produced in accordance with ASTM G121-98 specifications using mild steel. The mild steel sheet was marked accordingly and cut to the appropriate dimensions using FwinCNC cutting machine. The coupons were ground with Boch angle grinder, using Expert grinding disc and polished accordingly with grades 60, 120, 220, 400, 600, 800 and 1000 emery cloth. Then, one 4mm diameter hole was drilled on each coupon. The coupons were produced at BINNA Engineering and Construction Limited, located at plot 67/68 Naze Industrial Cluster Owerri, Imo State.

Sample size

Seven (7) samples were taken for each set of coupons in accordance with ISO 12944-6. Also, coupons were exposed in the test medium and monitored on weekly basis for a total of 7 weeks (49 day). Table 2 shows sampling of coupons for experiment I, while Table 3 shows sampling of coupons for experiment II.

Table 2: Sampling of Coupons for Experiment I

DFT	DFT Value (µm)	Number of coupons
t_1	50	7
t_2	100	7
t_3	150	7

Table 3: Sampling of Coupons for Experiment II

Fractional DFT (t/t*)	0.25	0.625	1	1.375	1.75	-
Number of coated coupons	7	7	7	7	7	-
Number of uncoated coupons	-	-	-	-	-	7

t* = optimum DFT calculated from experiment I results

Application of coating

Dip coating was performed maintaining withdrawal speed of 6 mm/s to 8 mm/s, in line with the range recommended by Sutha *et al*. (2017). According to NATO AEP-61 specifications, the substrate/environmental temperature, and relative humidity of the coating bay were kept at 35 ºC and 75 % respectively. Furthermore, all through the coating application, the specimen temperature was maintained at 4 ºC to 6 ºC above the dew point. Figure 6 (A) shows the dimensions of coupon used (X = 4mm, Y = 16mm, Z = 50mm, Ø = 4mm). Figure 6 (B) is a picture of uncoated coupon, while Figure 6 (C) is a picture of coated polyurethane coated coupon. A total of 63 coupons were prepared for experiment I and experiment II as specified in Table 2 and Table 3.

Determination of volumes solid

To ensure that the DFTs of the coatings conform to the targeted values, "volume solid" was determined by making one coated samples. The WFTs and corresponding DFTs were measured at five different points in accordance to ISO 12944-6. The values obtained were used to estimate the expected WFTs and corresponding DFTs for 50µm, 100µm, and 150µm for experiment 1. The values obtained were used to estimate WFTs and DFTs for experiment II. However, sight differences were observed between targeted and actual DFTs and WFTs.

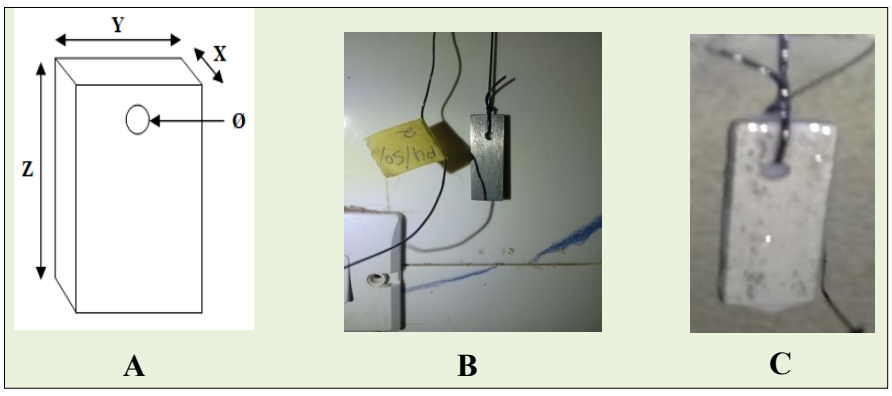


Fig 6: Showing geometry of the coupons (A), uncoated coupon (B), and coated coupon (C)

Experiment I: One of the plastic containers provided was used for experiment I. The container was thoroughly washed with distilled water, and thereafter exposed to dryness under atmospheric conditions. It was filled with 25 litres of 0.2 M dilute HCl solution. The coupons were submerged accordingly into the containers of to about half of the liquid depth, maintaining uniform coupons spacing. This set up was kept in laboratory under normal atmospheric condition. On weekly basis, one coupon was withdrawn accordingly from the container for a total of 7 weeks. The coupons were carefully delaminated, and thoroughly washed with acetone to clear off corrosion products from the surface of the coupons. The washed coupons were sun dried and reweighed. Weight losses obtained were recorded accordingly and used to calculate the corrosion rates of the coupons and the optimum DFT (t*) of the coating following the proposed parabolic model. The model was also used to estimate the corrosion rates of the uncoated coupons.

Experiment II: For experiment II, 7 coupons each of DFTs 0.25t*, 0.625t*, t*, 1.375t*, and 1.75t* were used, which is in line with ISO 9227, where t* is the optimum DFT determined from experiment I results. The dilute HCl solution used for experiment I was evacuated from the plastic container. The empty containers were washed with distilled water and again rinsed with acetone. The container was then exposed to dryness under atmospheric conditions. The container was used for setting up for coated coupons while the second container was used for setting up for uncoated coupons. Each of these containers was filled with 25litres of the dilute HCl solution. Coupons were submerged accordingly into the containers to about half of the depth of the solution. Then, the set up were kept in laboratory under normal atmospheric condition. The corrosion rates of the coupons were evaluated accordingly on weekly basis for duration of seven weeks. Average corrosion rates were calculated for each DFT. Graph of corrosion rates versus exposure times was plotted. Also, the average corrosion rate for each DFT was plotted against the corresponding DFTs. The model was also used to estimate the corrosion rates of the coupons. Results obtained from the model were compared with those obtained directly from experimentations.

Statistical analysis

Micro Soft Excel was used for computations. Version 29.0 of Statistical Package for Social Science (SPSS) was used to conduct Chi-square test at (p<0.05) level of significance, to evaluate the association between coating thickness and corrosion rate of the substrate. In accordance to ISO 5725, the performance of the proposed model was evaluated using the following statistical parameters: Spearman's rank Correlation Coefficient (R), Root mean squared error (RMSE), Scatter Index (SI), and Nash-Sutcliffe Efficiency Coefficient (E). All these were calculated using Microsoft Excel spread sheet. These parameters have been used for evaluation of model performance in a data driven assessment of corrosion in reinforced concrete structures embedded in clay dominated soils (Shahbaz *et al*., 2025) [22].

2.3 Calculations

a) Volume solid (VS)

$$VS = \left(\frac{WFT}{DFT}\right)100\% \quad (7)$$

Where:
VS = volume solid
WFT and DFT have their usual meaning

b) Total surface area of coupon (A)

$$A = 2\left(xy + xz + yz + \pi rx - \pi r^2\right) \quad (8)$$

Where:
X = thickness of coupon,
Y = width of coupon,
Z= length of coupon and
r = radius of hole on the coupon.

c) Corrosion rate (CR)

$$CR = \frac{365\Delta m}{\rho A t} \quad (9)$$

Where:
$\Delta m = m_o - m$ = mass loss (g)
m_o = initial mass (g)
m = final mass (g)
ρ = density of the steel (g/mm^3)
t = exposure time (days)
A = surface area of coupon (mm^2)

d) Optimum DFT (t*)

The optimum DFT was calculated using Eq. (6)

e) Constant (a)

$$a = \frac{CR_1 - CR_2}{\left(t_1^2 - t_2^2\right) - 2t^*\left(t_1 - t_2\right)} \quad (10)$$

f) Minimum corrosion rate (CR*)

$$CR^* = \frac{1}{3}\left[\left(CR_1 + CR_2 + CR_3\right) + 2at^*\left(t_1 + t_2 + t_3\right) - a\left(t_1^2 + t_2^2 + t_3^2\right) - 3at^{*2}\right] \quad (11)$$

g) Corrosion rate of the uncoated (CR^o)

$$CR^o = at^{*2} + CR^* \quad (12)$$

h) Product moment correlation coefficient (R)

$$R = \frac{\sum_{i=1}^{n}(A_i - \overline{A})(M_i - \overline{M})}{\sqrt{\sum_{i=1}^{n}(A_i - \overline{A})^2 \sum_{i=1}^{n}(M_i - \overline{M})^2)}} \quad (13)$$

Where:
A = Actual value

$\overline{A}$ = Mean of actual values

M = Model value

$\overline{M}$ = Mean of model values

R = Product moment correlation coefficient

i) Root Mean Squared Error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(A_i - M_i)^2}{n}} \quad (14)$$

j) Scatter Index

$$SI = \frac{RMSE}{\overline{A}} \times 100\% \quad (15)$$

k) Nash-Sutcliffe Efficiency Coefficient (E)

$$E = 1 - \frac{\sum_{i=1}^{n}(A_i - M_i)^2}{\sum_{i=1}^{n}(A_i - \overline{A})^2} \quad (16)$$

3. Results and Discussions

3.1 Results

The results obtained from this study include: volume solid (VS) of the polyurethane coating, optimum DFT (t*), minimum corrosion rate (CR*), minimum DFT allowable corrosion rate, CR (t_{min}), maximum DFT allowable corrosion rate, CR (t_{max}), and parabolic equation of corrosion of the coating. Actual DFTs: t_1, t_2 and t_3 in Table 5 and the corresponding corrosion rates were substituted into Eq. (6) to get the optimum DFT (t* = 110 µm). The result of Experiment I was validated using Experiment II, take DFTs in the range 0.25t* to 1.75t* as shown in Table 6. The results are presented as follows.

Table 4: Thicknesses and volumes solid measured at various points

Test Points	WFT (µm)	DFT (µm)	VS (%)
1	150.00	120.40	80.30
2	151.00	120.20	79.60
3	149.80	121.90	81.40
4	151.01	121.41	80.40
5	149.69	120.20	80.30
AVG.	150.30	120.80	80.40

Table 5: Showing WFTs and DFTs recorded for Experiment I

Parameter	t1	t2	t3
Targeted DFT (µm)	50	100	150
Estimated WFT (µm)	62.20	124.40	186.60
Actual WFT (µm)	61.91	123.93	187.10
Actual DFT (µm)	49.51	99.68	149.48
CR (mm/yr)	0.1155	0.0921	0.1000

Table 6: Showing WFTs and DFTs recorded for Experiment II

Fractional DFT (t/t*)	0.25	0.625	1	1.375	1.75
Targeted DFT (µm)	27.50	68.75	110.00	151.25	192.50
Estimated WFT (µm)	34.20	85.51	136.82	188.12	239.43
Actual WFT (µm)	37.43	68.53	138.12	195.65	249.37
Actual DFT (µm)	30.10	55.10	111.06	157.30	200.50
Model CR (mm/yr)	0.1279	0.1086	0.0914	0.1042	0.1382
Actual CR (mm/yr)	0.1307	0.1165	0.0911	0.1097	0.1325

3.2 Discussions

Percentage volume solid, otherwise referred to as volume solid (VS) of corrosion protective coatings is the ratio of its dry volume of coating to its wet volume (Joshi, Patil, Gite, 2025) [16]. It is used to estimate the WFT of a coating of known DFT. On the other hand, it can also be used to estimate the DFT of a coating of known WFT. It is expressed mathematically by Eq. (7). Table 4 shows volumes solid measured at various points for the polyurethane coating used for this study. Average value of 80.40 % was realized. This volume solid was use to estimate the WFTs given in Table 5 and Table 6. The optimum DFT, t*, of the polyurethane coating was calculated using the results of Experiment I presented in Table 5, which shows t_1 = 49.51 µm, t_2 = 99.68 µm, t_3 = 149.48 µm; CR_1 = 0.1155 mm/yr, CR_2 = 0.0921 mm/yr, and CR_3 = 0.1000 mm/yr. These variables were substituted accordingly into Eq. (6) to give optimum DFT (t* = 110 µm). Furthermore, the optimum DFT obtained was substituted into Eq. (10), which gives (a = 5.7177 /mm.yr). Minimum corrosion rate was then calculated using Eq. (11), which gives (CR* = 0.0914 mm/yr). Minimum corrosion rate, optimum DFT, and coating constant, a, were substituted accordingly into Eq. (12) to estimate average corrosion rate of the uncoated coupons, which gives (CR^o = 0.1611 mm/yr). Model parameters (t* = 110 µm; a = 5.7177 /mm.yr, and CR* = 0.0914 mm/yr) were substituted into Eq. (1) get Eq. (17).

$$CR = 5.7177(t - 0.11)^2 + 0.0914 \quad (17)$$

Following SSPC PA 2, standard, corrosion rates of the curve were investigated at minimum allowable DFT (t_{min} = 0.8t* = 88 µm), optimum DFT (t* = 110 µm), and maximum allowable DFT (t_{max} = 1.2t* = 132 µm), the results obtained are 0.0942 mm/yr, 0.0914 mm/yr, and 0.0942 mm/yr respectively. The

lowest corrosion rate occurred with coatings with optimum DFTs, suggesting that the curve is parabolic. Furthermore, the gradients of the curve were determined at t_{min}, t*, and t_{max}; the results obtained are -0.2517 yr^{-1}, 0, and +0.2517 yr^{-1}. These results also depicts that the curve is parabolic. Eq. (17) was solved to determine the limits within which the model applies. The roots obtained are 0 and 221µm, which implies that for polyurethane coating, the model applies between 0 and 221µm DFTs. Figure 7 is the graphical presentation of corrosion rates versus exposure time obtained from Experiment II. This graph was plotted to investigate the effects of DFT and duration of exposure on the corrosion behaviour of samples. It is observed that for all the samples, the corrosion rates are quite high between the week 1 and week 3, but gradually fall between the week 3 and week 7. A similar trend has been shown in a previous study by Anyanwu *et al* (2022) [6].

The gradual fall in corrosion rate over time might be due to formation of corrosion product (Fe_2O_3) on the surface of the coupons, which tends to lower the rate of further oxidation of the coupons. It is also notable that at all points in time, the corrosion rate of the uncoated coupons is relatively higher than those of coated samples; this is evidence that polyurethane coating is corrosion protective. Dramatic rise in corrosion rate was observed between the week 3 and the week 4, for coupons with 0.25t*, 1.375t*, and 1.75t*. However, the rise in corrosion rate is less significant with 0.65* and t*. For the coating of 0.25t* DFT, the rise in corrosion rate between week 3 and week 4 might be due to premature failure of coatings as a result of insufficient DFT, whereas for the coating of 1.75t* DFT, the rise in corrosion rate between week 3 and week 4 might have resulted from premature failure of coating due to excessive DFT, complimenting Raghvendra (2024) [20], who stated that the performance of corrosion protective coatings strongly depends of the dry film thickness of the coatings. For coatings of 0.625t*, the rise in corrosion rate between week 3 and week 4 of is appreciably low compared to 0.25t* and 1.75t*. This might be because 0.625t* is much closer to optimum thickness. It is interesting to note that at all points, the corrosion rates corresponding to t* are relatively less than those whose coating thickness are more or less.

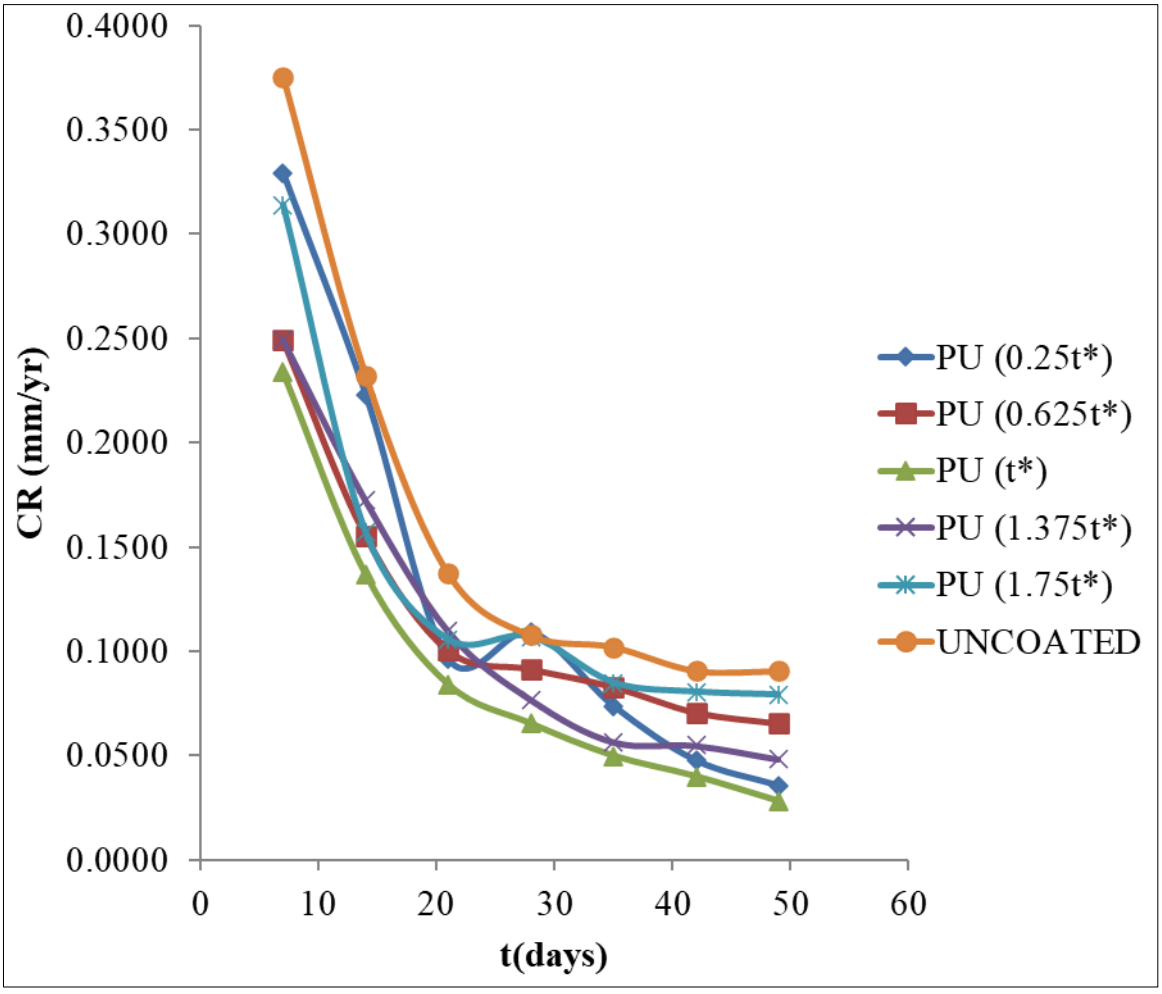


Fig 7: Corrosion rate versus exposure time for polyurethane coated samples, obtained from Experiment II

Figure 8 is graphical presentation of "model" and "actual" against the DFTs of the coatings in Table 6. This graph is presented to reveal how close model corrosion rates are to corresponding values obtained from experimentation. When the coating thickness is 30.10 µm, model corrosion rate was 0.1279 mm/yr, while actual corrosion rate was 0.1307 mm/yr. When the coating thickness is 55.10 µm, model corrosion rate is 0.1086mm/yr, while actual value is 0.1165 mm/yr. At turning point, coating thickness is 111.06 µm, model corrosion rate is 0.0914 mm/yr while the substrate was actually corroding

at 0.0911 mm/yr. It is also noted that when the coating thickness is 157.30 µm, model corrosion rate (0.1042 mm/yr) was observed against (0.1097 mm/yr) actual value. Lastly, when the coating thickness is 200.5 µm, model corrosion rate (0.1382 mm/yr) was recorded against rate (0.1325 mm/yr) actual value. It is interesting to note that in each case, higher corrosion rates occurred below and above 111.06 µm, suggesting a parabolic relationship between DFTs and corrosion rates. Slight variations in corrosion rate between the proposed model and experimental results might have resulted from approximations errors in calculations.

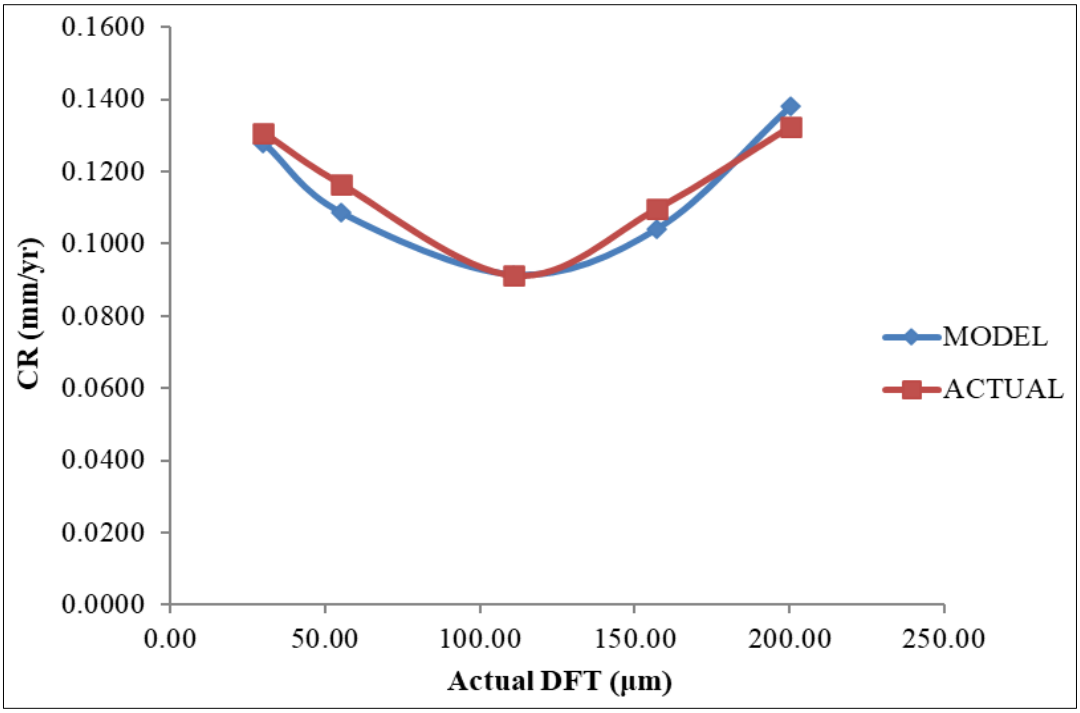


Fig 8: Plot of thickness ratio versus corrosion rate of polyurethane coated coupons

Yunhu Coating Co. (2026) [28] recommended DFT of 40 µm to 80 µm for polyurethane coated samples under ambient temperatures; 200 µm to 300 µm for moderate industrial environment; and 300 µm to 400 µm for sever industrial environments. Adrian (2025) [1] recommended coating thickness of 25 µm to 125 µm for polyurethane coatings under industrial and infrastructural environments. Herman *et al.* (2021) [13] recommended thickness of 60 µm to 100 µm for polyurethane coatings. Marlin Steel Co. (2026) recommended 0.032" (812µm) to 0.058" (1473.2µm) for polyurethane coating. Ferro-Clean (2026) recommended 50 µm to 150 µm, for polyurethane dry film coating thickness. Furthermore, David (2026) recommended 100 µm to 175 µm for polyurethane coatings. None of the cited publications stated the optimum value, and none showed how the recommended figures were arrived at. It is of interest that this study has covered the gap.

Minimum and maximum DFT allowable corrosion rates (CRa) were also deduced from Figure 8. The results obtained show that at minimum allowable DFT (tmin = 0.8t* = 88.85 µm), model corrosion rate was 0.0960 mm/yr, while actual value was 0.0988 mm/yr. At optimum DFT (t* = 111.06 µm), model corrosion rate was 0.0914 mm/yr, against 0.0911 mm/yr actual value. At maximum allowable DFT (tmax = 1.2t* = 133.3 µm), model corrosion rate of 0.0928 mm/yr was recorded against 0.0968 mm/yr actual value. These results compliment Raghvendra (2024) [20], saying that the performance of a coating strongly depends on the DFT of the coating. These results also suggest that the optimum DFT of polyurethane coating on mild steel substrate, at ambient temperature is (111.06 µm). Comparing with (t* = 110 µm) obtained from the proposed model with (t* = 111.06 µm) actual value, a difference of 1.06 µm is observed, which is negligible. The proposed model suggests equal corrosion rates at tmin and tmax, but results of experiment II has shown tmin and tmax exhibiting different corrosion rates. This underscores the need for statistical evaluation of model performance as to investigate the trueness of the results. Using "model" and "actual" corrosion rates in Table 6, the following statistical parameters were obtained: Root mean squared error (RMSE = 0.0045); scatter index (SI = 3.89); Product moment correlation coefficient (R = 0.96); Nash-Sutcliffe efficiency coefficient (E = 0.91). All the statistical parameters connote high model accuracy. However, result of Chi squared tests shows weak association between DFT and corrosion rate (p = 0.4742). This result suggests that some other factors may contribute significantly to premature failure coatings.

Limitations of the proposed model

The parabolic model proposed in this study is basically for determining the optimum dry film thickness of polymeric coatings. It is not applicable to metal coatings. It can be used to estimate coating thickness or corrosion rates between 0 and 221µm. The model is applicable only when the specimen is

exposed to corrosive medium at ambient temperatures. This is because the corrosion protective coatings may react differently in different exposure media. The model was proposed assuming a single layer coating system; therefore, the model is not suitable for multiple layers coating system where two or more different coatings may be applied. In the modeling, it was assumed that coating is not self-healing, and the defects are responsible for accelerated failure of coatings. Thus, the proposed model is not suitable for determining the optimum dry film thickness of self-healing corrosion protective coatings. Coating thickness is often recommended based on the specific function of the coating (Yunhu Coating, 2026; Adrian, 2025) [28, 1], but the specific function of the coating was not considered in the modeling, therefore the model is not applicable for heavy duty jobs where DFTs are required.

Conclusion

From the results of this study, the following conclusions may be drawn

- The mass losses of the coupons increase with the exposure time.
- Polyurethane coatings are effective for corrosion mitigation.
- The proposed parabolic model showed consistency of values comparing Experiment I and Experiment II.
- The optimum DFT (t*) of polyurethane coating falls between 110 µm and 111.06 µm.
- Minimum corrosion rate (CR*) of polyurethane coating falls between 0.0911 mm/yr and 0.0914 mm/yr.
- Minimum DFT (tmin) allowable corrosion rate falls between 0.0960 mm/yr and 0.0988 mm/yr.
- Maximum DFT (tmax) allowable corrosion rate falls between 0.0928 mm/yr and 0.0968 mm/yr.
- Based on SSPC-PA 2-2022 specification, DFT limits for polyurethane coating on mild steel at ambient temperature is (88µm – 133µm).
- Based on the results of statistical analysis, the proposed model is a suitable approach for investigating the optimum DFT of polyurethane coatings.

Recommendations

This study has opened the door for further researches on optimization of corrosion protective coatings, polymers in particular. However, the following recommendations are made:

- Further study is recommended, in which the chemical compositions of the coatings are considered. Such study will tend to address the issue of results differences due to chemical properties of the coatings.
- It is deemed interesting to conduct a further research in which temperature of the exposure medium will be varied. Such study will clear the air on how to mitigate corrosion with the coatings in environments of varying temperatures.
- It will also be interesting to investigate the optimum DFT of self-healing coating. Such studies will reveal the potentials of the coating that will enhance healing of the coating, and since the coating is self-healing, its performance will not depend mostly on DFT.
- The proposed model is focused on polymer resins, therefore; another study is recommended in which powder coatings are considered.
- In practical sense, corrosion protective coatings are often multiple layers, therefore, a future study that captures both single and multiple layer coatings is recommended.
- It will be delightful, to study optimization of corrosion protective coatings based on specifications other than SSPC-PA 2-2022.

Contribution to knowledge

- DFTs of corrosion protective coatings have been recommended in previous publications without specific rule for such recommendation, but this study has shown a mathematical model than can be used to determine the DFTs of corrosion protective coatings, using experiential results.
- Manufactures and researchers have often recommended DFTs of corrosion protective coatings as a range of values but this study has shown how a specific value of the optimum DFTs can be investigated.
- Findings of this study have also shown parabolic relationship between corrosion rate and DFT of mild steel coated with polyurethane, polyester, and epoxy resins coatings.

References

1. Adrian. The ultimate guide to conformal coating thickness measurement ensuring optimal PCB protection, 2025. Available from: https://share.google/2rMFvbJrTfTVrA5Ei. Accessed 2026 Jun 20.
2. Aisyah R. How to estimate optimum insulation thickness. Chemical Engineering Portal. 2020. Available from: https://missrifka.com/calculation/how-to-estimate-optimum-insulation-thickness.html.
3. Aljibori H, Al-Amiery A, Kadhum A. Advances in corrosion protection coatings: a comprehensive review. International Journal of Corrosion and Scale Inhibition. 2023;12:1476–1520. doi:10.17675/2305-6894-2023-12-4-6.
4. Amir S. Use of polyurethane coating to prevent corrosion in oil and gas pipelines transfer. International Journal of Innovation and Applied Studies, 2012, 1. Available from: http://www.issr-journals.org/ijias/. Accessed 2025 Jul 11.
5. Anand G, Anirbid S. Introduction to pigging & a case study on pigging of an onshore crude oil trunkline. IJLTEMAS, 2016, 5(2).
6. Anyanwu KO. Parabolic model for optimum dry film thickness (DFT) of corrosion protective coatings. International Research Journal of Multidisciplinary Technovation. 2022;4(4):8–13.
7. Baur J. Consequences of applying coatings outside of the recommended thickness range. KTA-Tator, 2001. Available from: https://kta.com/kta-university/recommended-coating-thickness/.

8. D&D Coating Industries Ltd. What is paint coating delamination. UK, 2024.
9. Ferrum SA. Extruded three-layer polypropylene coating on steel pipes. Ferrum SA. 2022. Available from: https://www.ferrum.com.pl/produkty/wytlaczana-trojwarstwowa-powloka-polipropylenowa-na-rurach-stalowych-lpp/?lang=en.
10. Forsgren A. Corrosion control through organic coating. CRC Press, 2006, p184.
11. For laboratory applications. MDPI. 6(4). doi:10.3390/automation6040075.
12. GZ Industrial Supplies. Understanding different types of professional surface coatings: applications and advantages, 2026.
13. Herman P, Felita W, Wimala L. Analysis of the effects of abrasive materials and polyurethane coating thickness variation on ASTM A36 steel towards corrosion rates in sea water environments. International Journal of Offshore and Coastal Engineering. 2021;5(1):10–17.
14. Hitchens L. Delamination. Nexus. 2017. Available from: https://www.conformalcoatinghelp.com/index.php/ebook/troubleshooting/delamination.
15. Ji H, Liu J, Ye H. Time-series prediction of steel corrosion in concrete using recurrent neural networks. Nondestructive Testing and Evaluation, 2025, 1–20. doi:10.1080/10589759.2025.2456668.
16. Joshi SS, Patil VJ, Gite VV. High performance coating formulation using multifunctional monomers and reinforcing functional filters for protecting metal substrate. Pigment & Resin Technology, 2025, 54(5). doi:10.1108/PRT-03-2024-0033.
17. Komalasari S, Utami M, Aziz Y, Irianti R. Corrosion control of carbon steel using banana peel extract as inhibitor in dilute acid solution. IOP Conference Series: Materials Science and Engineering, 2018. Available from: https://www.researchgate.net/publication/324494551_corrosion_control_of_carbon_steel_using_inhibitor_of_banana_peel_extract_in_acid_dilute_solutions. Accessed 2025 Mar 3.
18. Marlin Steel Wire. What is the average thickness for urethane coating? Marlin Steel Wire Products, 2013.
19. Onaifo J, Ofabar G, Onaiwu G, Edogun P, Ifijen I. Polyurethane foam: production processes and advanced material characterization. 2025. p. 31–36.
20. Raghvendra G. Dry film thickness (DFT). Corrosionpedia, 2024. Available from: https://www.corrosionpedia.com/contributors/raghvendra-gopal.
21. Sean H. Cracking in conformal coating: major causes and preventive strategies. Diamond-MT, 2017. Available from: https://blog.paryleneconformalcoating.com/cracking-conformal-coating/.
22. Shahbaz A, Siraj A, Sabih A, Faraz A, Majib A. Data driven assessment of corrosion in reinforced concrete structures embedded in clay dominated soils. Scientific Reports. 2025;15:22744. doi:10.1038/341598-025-08526-w.
23. Somarathna H, Raman S, Mohotti D, Mutalib A, Badri K. The use of polyurethane for structural and infrastructural engineering applications: a state-of-the-art review. Construction and Building Materials. 2018;190:995–1014.
24. SSPC-PA 2 2022: Procedure for determining conformance to coating thickness requirement. 2022.
25. Sutha S, Suresh S, Raj B, Ravi K. Transparent alumina based super-hydrophobic self-cleaning coating for solar cell cover glass applications. Solar Energy Materials and Solar Cells. 2017;165:128–137.
26. Winniki W, Malachowska A, Ambroziak A. Taguchi optimization of the thickness of a coating deposited by LPCS. Archives of Civil and Mechanical Engineering. 2014;14:561–568.
27. Ying Y, Ping Z, Shang-Xiong Z, Xiao Guang G, Dong-Ming G. Effect of substrate curvature on thickness distribution of polydimethylsiloxane thin film in spin coating process. Chinese Physics B, 2018, 27.
28. Yunhu Coating. Recommended dry film thickness for coatings, 2026. Available from: https://www.yuhhucoating.com/recommended-dry-film-thickness-industrial-coating/. Accessed 2026 Jun 20.