Comparative Analysis of The Normal Splitting Stresses of Bio-Based Coated Reinforcements Using Experimental Studies and Finite Element Simulations

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Abstract: - The Philippines has been moderately vulnerable to corrosion; surface coating should be applied to prevent this problem. The main objective of this research was to develop and optimize a bio-based mixture of Pili Resin and Lime as Coating Materials. Three (3) factors were considered in choosing the best coating material: Chemical adhesion, friction, and the bearing/shear against the steel bar-concrete interface. Fortunately, both proportions of the Bio-based coating materials (50:50 and 65:35) do not have red rust formation complying with ASTM B117 but failed in terms of ASTM D 3359. Splitting failures of concrete were observed in the Unconfined Reinforced Concrete Samples. All of the steel bars (uncoated and coated) surpassed the Minimum Bond strength (NSCP 2015) by about 203% to 285%. The experiments were about 1% to 3% of the results from the ANSYS Simulations with and without the Salt Spray Test. The normal splitting strength using the bio–based and epoxy coatings were declined. However, there was no significant difference between the **results**. Thus, bio-based coating materials can be used as an alternative to epoxy coating materials and it was highly recommended for low-rise buildings only.

Key Words: - ***Canarium Luzonicum, Calcium Oxide, Corrosion, Finite Element Simulations, Epoxy Coated Steels.***

I. Introduction

Reinforced concrete is a commonly used construction material in the Philippines. It has greater durability compared to wood. 1However, steel can deteriorate when the reinforcements are exposed to harsh environments which include exposure or contact with metal with the air (oxygen) and moisture. Soil, soluble salts, water resistivity, and water pH are also some factors that cause the deterioration of steel. Changes in the appearance of the metal surface such as color change, rust, and tarnish can be identified when corrosion occurs.

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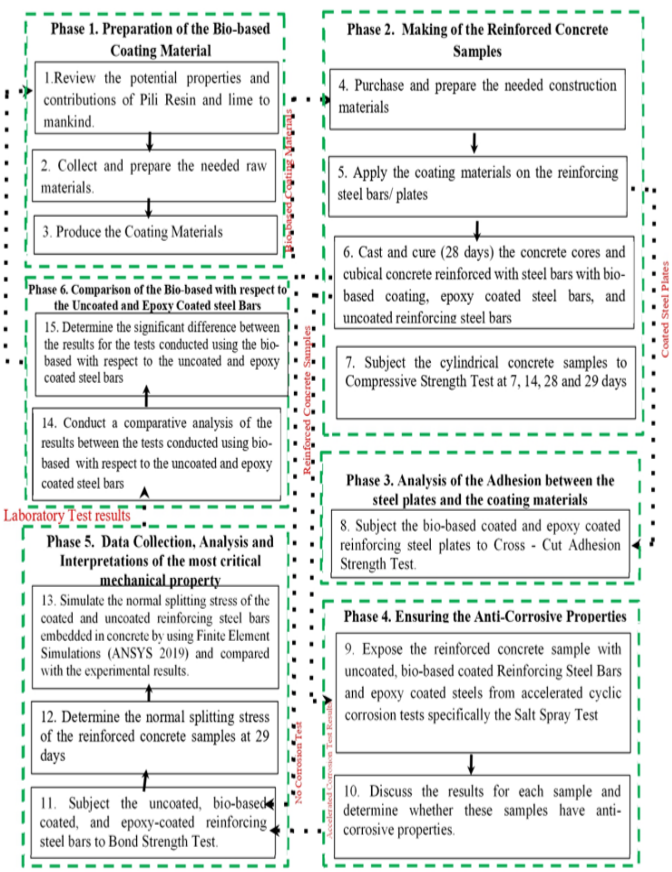
Swelling, spalling, galling, and seizure are also potential results of the deterioration. However, manufactured coated steels are available that can eliminate corrosion like epoxy-coated steels. 2Epoxy Coating is commonly used to protect reinforcing steel from corrosion but using epoxy decreases the bond strength between concrete and the reinforcing steel bars. Also, a large cost may be required to purchase such a number of steel bars. Also, 3the Philippines is moderately vulnerable to corrosion, with corrosion causing losses of about 1 million USD in 2010 and is projected to increase to about 5 million USD in 2030. Due to this tremendous cost of corrosion, there is a need to prevent the deterioration of reinforced concrete structures. The penetration of chlorides from seawater causes the rusting of the reinforcements. Cracks on the concrete surface can be observed and this is a result of the corrosion inside the concrete core.

4Pili resin is insoluble in water and, thus, will not contribute to the deterioration of the steel. Canarium Luzonicum tree naturally produces a valuable resin or elemi from its bark. Also, Pili resin or elemi is considered an important raw material that is utilized in the production of paints, adhesives, waterproof and fireproof materials, plastics, and printing inks. This is why the researcher utilized Pili resin as one of the components in optimizing bio-based coating materials.

In fact, lime or calcium oxide has high alkaline content and will result in higher pH values. It will passivate the steel surface and no corrosion will occur. 4Concrete contains a hydrated cement paste that will also contribute to the alkalinity of the steel and will protect it from sudden corrosion. Also, Calcium Oxide can improve the resistance of steel. Likewise, 5lime was used as one additive in the production of wood binders. Due to its high melting point of 2752oC, it was mixed with the Pili resin to facilitate the hardening of the resin.

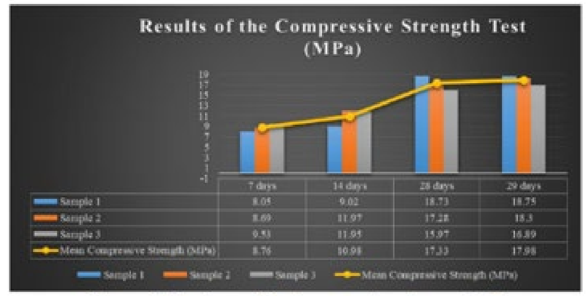
Thus, the mixture of these two materials prevented the possible corrosion of the reinforced concrete.

II. Methodology



III. Results And Discussion

3.1 Compressive Strength



	7 days	14 days	28 days	29 days
Sample 1	8.05	9.02	18.73	18.75
Sample 2	8.69	11.97	17.28	18.3
Sample 3	9.53	11.95	15.97	16.89
Mean Compressive Strength (MPa)	8.76	10.98	17.33	17.98

Figure 1: Results of the Compressive Strength Test

A series of three (3) cylindrical samples for each day of curing (7th, 14th, 28th, and 29th day) was made to determine compressive strength in accordance with Specification C 39. Based on the results conducted in the Department of Public Works and Highways in the province of Marinduque, there was no concrete strength data below their respective mean f'c more than 3.5 MPa.

Thus, these conformed to the Compliance Report of NSCP 2015: Section 426.12.3.1 which assesses the acceptability of lower concrete strength. Also, it satisfies Section 426.12.4 of NSCP 2015, which states that no single core should be less than 75% of 20.5 MPa. However, the mean compressive of the three core samples was 84% of the Design Compressive Strength (20.7 MPa). Despite having a low concrete strength of 17.33 MPa at 28 days, the compressive strength satisfies the specifications of NSCP 2015, Section 419.3.2.1, that the minimum compressive strength for normal weight and lightweight concrete should be 17 MPa. It also shows the percentage increase of the mean compressive strength from the test conducted at 7 days, 14 days, 28 days, and 29 days. It was found that the compressive strength increases as the curing of concrete increases. The strength escalated to 25% for the period of 7 days. There was a great increase in concrete strength of about 58% when 28 days of curing was reached. However, after 28 days, there was a minimal increase in strength one day after the 28th day of curing, which is a 4% increase.

3.2 Adhesion, Cross–Cut Tape Test

Three (3) pieces of epoxy painted panels, 5" x 3" in size, were subjected to Adhesion, Crosscut Tape Test in accordance with ASTM D 3359 – Standards, Paints – Tests for Formulated

Products and Applied Coatings, Volume 06.01, 1992. The Adhesion Test was done at the DOST- Industrial Technology Development Institute, Standard Testing Division.

Based on the results, the epoxy painted passed in terms of the Cross–Cut Adhesion Test, it was classified as 5B and none of the cuts has been detached. The edges of the cuts were completely smooth. On the other hand, the steel plates with bio-based coating with the two proportions (65:35) and (50:50) failed in terms of ASTM D3359. Based on the test reports, bio-based coatings were classified as 0B, which means that there was worse flaking and detachment compared to the grade.

3.3 Salt Spray Test

Figure 2: Set-up of Reinforced concrete samples in the corrosion chamber

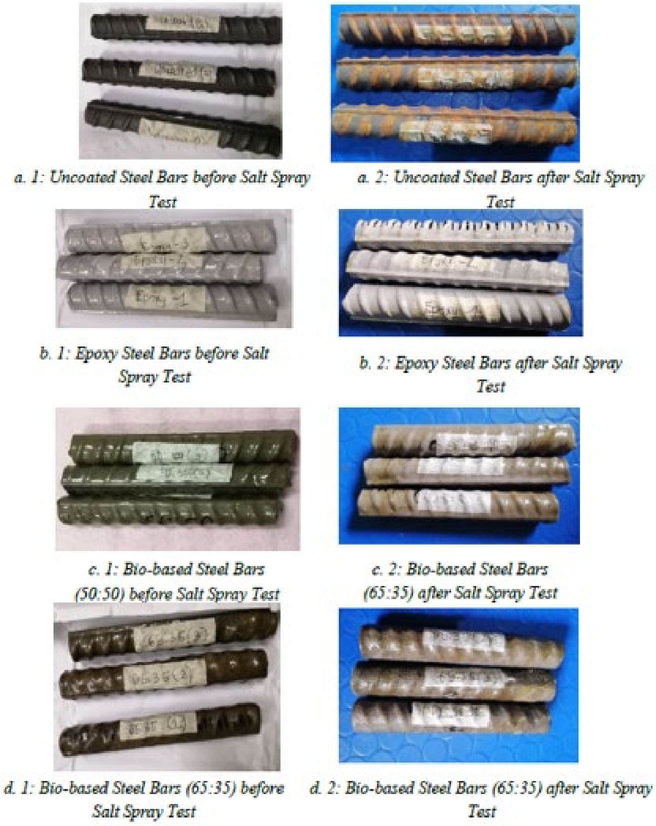
A series of twenty-four (24) cubic concrete samples (150mm) with embedded bio-based coated were utilized in Pull-out Test (with and without Corrosion Test). The researcher utilized twelve (12) reinforced concrete samples which were cured for about 28 days in accordance with specification ASTM C511. Then, these were subjected to Accelerated Corrosion Test (Salt Spray Test) before being subjected to Pull-out Test. This test is standard practice for operating Salt Spray (Fog) Apparatus with the use of a cyclic corrosion chamber (ATLAS CCX 2000, S/N: 25131

The samples were evaluated through visual inspection with the aid of a magnifying glass. The method of evaluation was based on PNS ISO 10289:2004. This is a method for Corrosion Testing of metallic and other inorganic coatings on metallic substrates. The method looks into the rating of the test specimens and manufactured articles subjected to corrosion tests.

In terms of the Salt Spray Test, the reinforcing steel bars (15 cm in length) both coated with bio-based and epoxy coating materials had no observable defects after being subjected to a cyclic corrosion test. Meanwhile, a moderate amount of red rust developed in the uncoated steel bars. The reinforcing steel bars were submerged by the researcher in salt water at 1, 7, 35, and 55 days. The same results were observed in the uncoated steel bars with severe deterioration. Slight formations of rust were present in the epoxy-coated steel bars and no formation in the bio–based coated steel bars. Meanwhile, for the corrosion test conducted in the reinforcing steel bars embedded in unconfined concrete, the same results were observed in the uncoated steel bars. It was shown that there was a moderate amount of red rust developed having a 20% area of defects in uncoated steel bars. The bio-based coating materials with 50% Pili resin and 50% lime did not have red rust formation. However, there was an excessive deterioration of color. The brown color of the coating materials turned white due to the reaction of the 5% NaCl into the coating materials.

Meanwhile, the two samples of the steel bars with a bio-based coating (65:35) had no red rust. However, one of the samples was observed with a slight amount of red rust. A slight amount of red rust at the reinforcing steel bars coated with epoxy coating materials. One of the samples of the epoxy-coated steel bars had excessive deterioration of color. It was noticeable that most of the samples (2 out of 3 samples) coated with bio-based coating materials passed the Salt Spray Test (ASTM B117) compared to the commercially available epoxy coating materials. Then, there was a great difference in the results of uncoated steel bars. Thus, the proposed bio-based mixture of Canarium Luzonicum and Calcium Oxide can be said to have the potential to resist corrosion.

Figure 3: Bio-based Coated Reinforcing Steel Bars (65:35)



a. 1: Uncoated Steel Bars before Salt Spray Test

a. 2: Uncoated Steel Bars after Salt Spray Test

b. 1: Epoxy Steel Bars before Salt Spray Test

b. 2: Epoxy Steel Bars after Salt Spray Test

c. 1: Bio-based Steel Bars (50:50) before Salt Spray Test

c. 2: Bio-based Steel Bars (65:35) after Salt Spray Test

d. 1: Bio-based Steel Bars (65:35) before Salt Spray Test

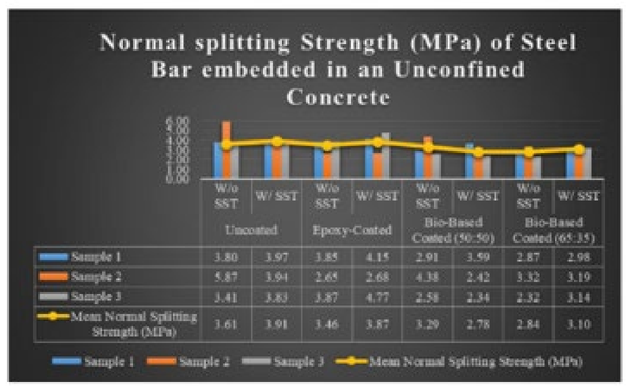
d. 2: Bio-based Steel Bars (65:35) after Salt Spray Test

Figure 4: Results of the reinforced concrete samples subjected to Salt Spray Test

Figure 5: Rust Formation in the Reinforced Concrete Samples after the Salt Spray Test

3.4 Normal – Splitting Strength

Figure 6: Concrete Splitting with (a) Uncoated Steel Bars; (b) Epoxy Coated Steel Bars; (c) Bio –based Coated Steel Bars, 50:50; (d) , 65:35



	Uncoated		Epoxy-Coated		Bio-Based Coated (50:50)		Bio-Based Coated (65:35)	
	W/o SST	W/ SST	W/o SST	W/ SST	W/o SST	W/ SST	W/o SST	W/ SST
Sample 1	3.80	3.97	3.85	4.15	2.91	3.59	2.87	2.98
Sample 2	5.87	3.94	2.65	2.68	4.38	2.42	3.32	3.19
Sample 3	3.41	3.83	3.87	4.77	2.58	2.34	2.32	3.14
Mean Normal Splitting Strength (MPa)	3.61	3.91	3.46	3.87	3.29	2.78	2.84	3.10

Figure 7: Normal Splitting Strength (MPa) of Steel Bar embedded in an unconfined concrete

After 28 days of curing, the concrete samples were subjected to accelerated corrosion techniques within twenty-four (24) hours. Then reinforced concrete samples were tested using the TORSEE Universal Testing Machine at Laboratory Testing Services in the DOST-ITDI, Standard Division to determine its residual bond/ normal splitting strength in accordance with CRD-C 24-01. It is a standard test that involves the comparison of concrete in terms of bond strength developed with steel bars. The concrete samples reinforced with both bio-based coating materials and with uncoated steel bars embedded in a 150mm piece of cubical unconfined concrete were utilized.

In terms of the Pull-out Test, splitting failures of concrete were observed in the reinforced concrete samples since the researcher used unconfined concrete. The compressive strength of the concrete design mix was determined to identify the normalized capacity of the reinforcing steel bars being pulled out in an unconfined concrete. The strength escalated to 25% for the period of 7 days. There was a great increase in concrete strength when it reached 28 days of curing about 58%. However, after 28 days, there was a minimal increase in strength one day after the 28th day of curing which is 4%.

It was also noticeable that the uncoated steel bars were able to resist the largest value of the applied load. The results of the Pull-out Test with epoxy-coated steel bars demonstrate that using epoxy coatings will decrease the bond strength between concrete and the reinforcing steel bars. Unfortunately, the bond strength also decreased when the reinforcing steel bars were coated with bio-based coating materials. However, the maximum applied load using the steel bars with a bio-based coating having a proportion of 50% Canarium Resin and 50% Calcium Oxide has a greater value compared with the results in 65:35.

Based also on the results, the steel bars with bio-based coating with 50% Canarium Luzonicum and 50% Calcium Oxide matched 95% of the normal splitting strength of epoxy-coated steel bars with the Salt Spray Test and matched 72% of the normal splitting strength of the epoxy coated steel bars without the Salt Spray Test. Bio-based coating materials (50:50 proportion) were also found to match 91% of the normal splitting strength of uncoated steel bars with the Salt Spray Test, and 71% of the normal splitting strength of uncoated steel bars without the Salt Spray Test.

Meanwhile, bio-based coating materials with a 65:35 proportion were found to match 82% of the normal splitting strength of epoxy-coated steel bars with the Salt Spray Test, and 80% of the normal splitting strength of epoxy-coated steel bars without the Salt Spray Test. According to the studies of [6]Kayyali (1995), the bond strength of the epoxy-coated steel bars was reduced to about 80% to 95% of the bond strength for uncoated steel bars. On the other hand, all of the steel bars (uncoated and coated) surpassed the minimum bond strength required by the NSCP 2015 about 203% to 285%.

Furthermore, the following specific observations were made: the bond / normal splitting strength of (1) uncoated steel bars increased by 8% because of the moderate amount of red rust developed and increased friction between the steel and concrete; (2) epoxy-coated steel bars increased by 12% due to slight amount of red rust developed; (3) steel bars with a bio-based coating (50:50) decreased by 15% due to the deterioration of coating which resulted to an excessive colour change. Since there was an equal amount of resin and lime in this proportion, the coating material did not adhere properly to the steel thus affecting its bond strength. The samples were subjected to cyclic corrosion; they underwent a Cyclic Wet and Dry Test; and (4) the steel bars with the bio-based coating materials (65:35) increased by 9%. There was a larger amount of Pili resin in the coating materials. The deterioration of the coating materials was also observed which resulted in excessive colour change. The resin in this coating was enough to adhere in the steel bars even though this was subjected to the Salt Spray Test and thus greater strength was attained.

3.5 Simulation of the maximum applied load of the coated and uncoated reinforcing steel bars and the concrete by using Finite Element Simulations (ANSYS)

The results of the Bond Strength test of uncoated and coated steels embedded in concrete were analyzed using the Finite Element simulations (ANSYS 19.1) at Static Structural Analysis. In using the Finite Element model, the bond behavior of the steel and concrete can be treated as a contact problem if the contact properties or interaction were identified. The contact region between the two (2) geometries of the concrete was assigned as Bonded. Meanwhile, Frictional was assigned to the body contact of the steel and the concrete. Since the reinforced concrete samples were subjected to Accelerated Corrosion Tests, potential corrosion might occur if the coating materials failed to resist the corrosive environment. The interaction of the concrete and steel was assumed to be partially or perfectly compatible with nodes at its interface. The mesh was generated with an element size of 0.01 m and a total of 21840 Nodes and 4411 elements.

The coefficient of friction in uncoated steel bars increased from 0.6503 to 0.6879 by 8%. On the other hand, there was an increase of 6% for epoxy coated, a decrease of 12% for bio-based coating with a 50:50 proportion, and an increase of 5% for the other proportion of the proposed coating materials (65:35).

In relation to bond-splitting strength and normalized capacity, the same trend was observed. It was proven in the study of [7]Rabbat and Russell (1985) that the average effective coefficient of static friction varied between 0.57 and 0.70. The results of the simulations were compared to the results of experimental procedures. The results from the experiments were about 1% - 3% and 1% - 2% of the results from the ANSYS Simulations without and with Salt Spray Test respectively.

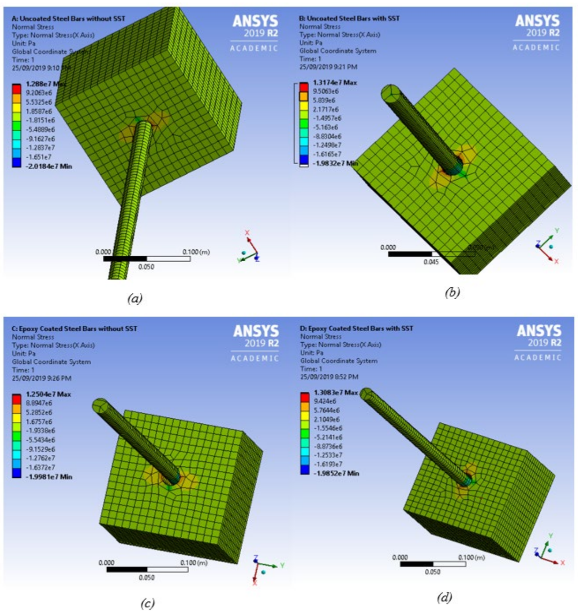


Figure 8 . Normal Splitting Stress of the reinforced concrete samples (a) Uncoated steel bars without SST: (b) Uncoated Steel bars with SST: (c) Epoxy Coated Steel Bars without SST: (d) Epoxy Coated Steel Bars with SST

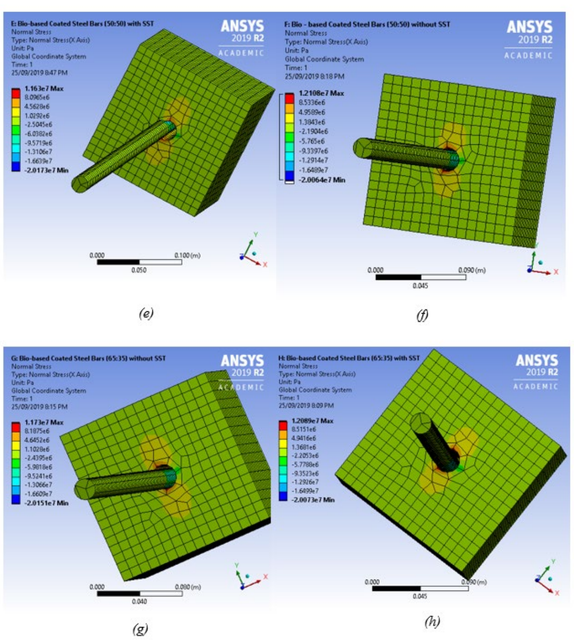


Figure 9 . Normal Splitting Stress of the reinforced concrete samples (e) Bio – based coated (50:50) steel bars with SST; (f) Bio – based coated (50:50) steel bars without SST; (g) Bio – based coated (65:35) steel bars without SST; (h) Bio – based coated (65:35) steel bars with SST

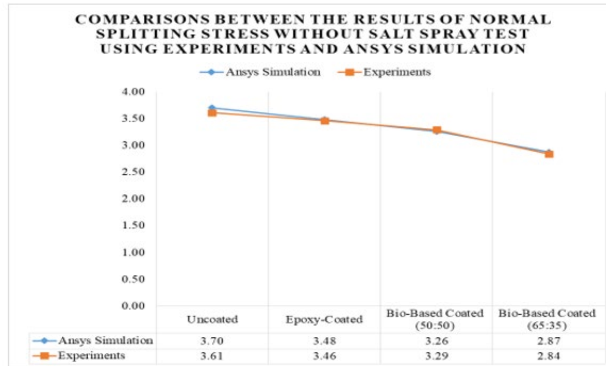


Figure 10. Comparisons between the results of Normal splitting strength without Salt spray test using experimental tests and ANSYS simulations

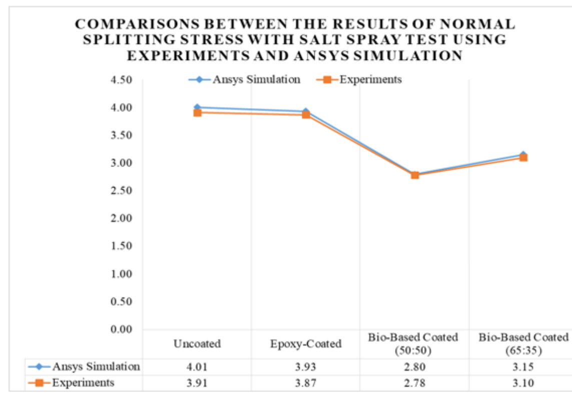


Figure 11. Comparisons between the results of Normal splitting strength with Salt spray test using experimental tests and ANSYS simulations

It was proven in this research study that there are three (3) factors that affect bond strength. These include chemical adhesion, friction, and the bearing/shear against the steel bar-concrete interface as stated by Shetty et al (2011) and were highlighted also in the study of [8]Tayeh (2017) and [9]Ramezani, Vilches, and Neitzert (2013). This is why the proposed bio-based coating materials were subjected to various testing procedures to determine its effectiveness as a replacement for commercially available coating materials.

IV. CONCLUSIONS

Based on the results, the epoxy paint passed but the bio–based coatings failed in terms of ASTM D 3359. The bio-based coating materials passed the Salt Spray Test (ASTM B117) since most of the samples had no rust formations unlike the commercially available epoxy coating materials and uncoated steel bars. The steel bars with a bio-based coating having a proportion of 50% Canarium Resin and 50% Calcium Oxide had greater strength compared with the results in 65:35.

However when the specimens were subjected to the Salt Spray Test, the coating material with a proportion of 65% resin and 35% lime was found to be more effective when subjected to the Bond strength Test than the other proportion (referring to 50%:50%).

The results of the simulations were compared to the results of experimental procedures. The results from the experiments were about 1% - 3% and 1% - 2% of the results from the ANSYS Simulations without and with Salt Spray Test respectively.

Meanwhile, based on the summary of the paired samples test on the normal splitting stress with a 5% significant level of confidence, it was seen that there was no significant difference between the proposed coating materials (bio-based coating materials) and the commercially available epoxy coating materials. The null hypothesis for the normal splitting stress was accepted. Thus, bio-based coating materials can be used as an alternative to epoxy coating materials. However, using the proposed coatings and epoxy coatings will decrease the bond strength between concrete and the reinforcing steel bars.

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