

# Towards A Novel, Non-Metal Graphene Nanoplatelet Hybrid Anti-Corrosive System for Tomorrow's Protective Coatings

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## Abstract

Graphene's two-dimensional structure in the nanoplatelet form results in very high aspect ratio, high surface area materials which are particularly suited for use as multi-functional additives in paints and coatings. The mechanism by which graphene delivers anticorrosion has been proposed to be a combination of physicochemical processes restricting uptake of water (combined with oxygen and salt) and electrochemical.

Previously, AGM has developed and reported meaningful anticorrosive performance gains in epoxy coatings for C3 (ISO12944) environments, against zinc phosphate systems, using a novel "green" primer solution incorporating graphene nanoplatelets. In this work, the performance on ASTM G85 adhesion test was extended from 1000 to 5000 hours when using graphene in combination with metal free active inhibitors [1]. This paper will discuss the extension of use of AGM's graphene nanoplatelets into C4 and C5 type environments, benchmarking against commercial zinc rich systems.

## 1. Introduction

Applied Graphene Materials UK Ltd. (AGM) produces a range of dispersions of graphene nanoplatelets (GNPs), enabling property introductions/enhancements such as electrical/thermal conductivity, mechanical e.g. fracture toughness, gas permeability and barrier type to be achieved. GNPs are manufactured using the company's patented proprietary "bottom up" process, yielding high specification graphene materials.

Coatings of various types such as inorganic [2], organic [3], hybrid [4], nano [5] and green [6] have been widely employed in the corrosion protection of metallic materials under high and very high risk environmental categories for corrosion. Such categories, as referred to in BS EN ISO 12944-2 [7], range from C4-C5, with exterior examples of these categories including industrial and coastal areas of moderate to high salinity. Due to growth within the offshore industry in emerging economies and an increased rate of shipbuilding, the marine coatings market is estimated to be worth USD 15 billion by 2024 [8].

Current organic coating systems designed for such harsh environments are typically comprised of a number of different types of coating layer, each providing a different set of properties. A basic system usually consists of three layers, which may include a primer coat, an intermediate coat and a final topcoat. Typical dry film thicknesses of these coats is around 50 to 150  $\mu\text{m}$  for the primer and intermediate coat and 50  $\mu\text{m}$  for the top coat.

Primer coats are typified by epoxy-based formulations containing a relatively high loading of a more anodic metal such as zinc (zinc rich), which provides a sacrificial protection to the metal substrate. Intermediate coats are usually formulated around a solvent/epoxy base with a pigment blend containing a relatively large fraction of micaceous iron oxide. The intermediate coat or tiecoat serves to promote adhesion between the primer coat and the top coat layers; such layers which may otherwise be incompatible. The intermediate coat may also provide a barrier type protection against corrosive species such as water, ions or oxygen, slowing their diffusion to and from the metal surface, although it is recognised that there are some limitations to these barrier properties due to the permeability of organic coatings to such corrosive species [9]. Finally, the top coat of the system is normally composed of a polyurethane or polysiloxane. These materials usually offer UV resistance in addition to any glossy finish required for aesthetic purposes.

It has been demonstrated that GNPs, both as prepared and chemically functionalised, when incorporated into an organic coating system or host matrix, provide a highly tortuous pathway which acts to impede the movement of corrosive species towards the metal surface [9], a passive corrosion protection mechanism. In support of this, previous work has also shown that very small additions of GNPs decreased water vapour transmission rates [10], indicating a barrier type property, while some authors also report an electrochemical activity provided by graphene within coatings [11].

For the initial part of this work we look to study the coating performance benefit when GNPs are incorporated into an epoxy prototype primer/intermediate layer, studied as a single coat entity. GNPs will be incorporated into this layer via commercially available graphene dispersion products. We then look to assess the coating system performance when the GNP-included single layers are integrated into typical coating systems aimed at C4/C5 type environments. For this work, graphene coatings were tested direct to substrate and in the intermediate layer, applied over a zinc rich primer. The graphene enhanced intermediate layer should prevent water ingress, while the zinc rich coating provides sacrificial protection for the steel substrate. The majority of the prior work cited in the literature connected to GNP organic coatings relates to the study of simple single layer coatings; to the best of the authors' knowledge, this is the first reporting of the use of GNPs in fully formulated C4/C5 anticorrosive coating systems. Along with any anticorrosion performance benefits offered by these graphene-enhanced coating systems, we also report on other aspects such as overcoat-ability and compatibility between coating layers. Ultimately, this work seeks to determine if the operational lifetime of the zinc rich primer layer can be extended through the use of an intermediate layer with GNP-enhanced barrier properties, potentially reducing the amount of zinc required in the primer layer. The authors are also interested in the possibility that GNPs within the intermediate layer may act to reduce the release of zinc ions, essentially acting as a moderator to further increase the lifetime of the zinc rich primer layer.

The testing of the coatings takes a dual approach: the more traditional visual accelerated technique of neutral salt spray testing (NSS) combined with electrochemical AC impedance spectroscopy (EIS), with shared test panels across both experiments. These combined tests are complimentary to each other since EIS can determine relatively small changes within the coating e.g. with respect to water uptake prior to any visible changes noted from the examination of the test panels, providing quantitative data. In addition, the test conditions of NSS are more realistic and accelerative compared to simply submerging the sample in NaCl solution, under ambient conditions, as is usually done during prolonged EIS studies within the paint test cell. Test data from EIS and salt spray test results may also be used to corroborate coating performance.

## **2. Experimental**

### **2.1 Material and Sample Preparation**

A GNP-free epoxy prototype base (control) coating (part A) was initially prepared, formulated to be representative of a standard commercial primer/intermediate coating layer, as outlined in Table 1. This was prepared by charging formulation component numbers 1, 2, 3, 4, 5 and 6 to a vessel and then processing these components at 2000 rpm, for 10 minutes, using a standard laboratory over-head stirrer. Formulation component numbers 7 and 8 were then added to the resultant gel before the mixture was again processed at 2000 rpm for 15 minutes, or until the grind had reached 25 microns. Finally, formulation component 9 was added at 10 wt. %. Prior to applying the coating, an amine slow cure hardener was added as the part B.

	Number	Component	Epoxy Prototype Base (control)	D1	D2	D3
Part A	1	Epoxy (EEW 190 g/eq)	15.119	15.119	15.119	15.119
	2	Amino Resin	0.244	0.244	0.244	0.244
	3	Dispersant	0.402	0.402	0.402	0.402
	4	Xylene	15.376	15.376	15.376	15.376
	5	Bentonite thixotrope	0.366	0.366	0.366	0.366
	6	Butanol	1.986	1.986	1.986	1.986
	7	Titanium dioxide	10.966	10.966	10.966	10.966
	8	Blanc Fixe	43.619	43.619	43.619	43.619
	9	<b>Epoxy (EEW 190 g/eq)</b>	<b>10</b>	<b>0</b>	<b>0</b>	<b>0</b>
	10	<b>Commercial GNP dispersion</b>	<b>0</b>	<b>10</b>	<b>10</b>	<b>10</b>
Part B	11	Amine slow cure hardener	1.922	1.922	1.922	1.922
		<b>Total</b>	100	100	100	100
		<b>Final GNP loading (wt.%)</b>	0	1	0.1	0.5

Table 1: Formulation outline of the epoxy prototype base and GNP-incorporated epoxy prototype base (variable components are highlighted in blue)

Three different GNP-containing variants of the control were then prepared (D1-D3) using the same initial preparation route as for the epoxy prototype base, by substituting commercially available GNP-containing dispersion additives (AGM) (formulation component 10) for epoxy in the final step (formation component 9). The GNP dispersion additives were effectively treated as masterbatches and were added in varying amounts according to their prior graphene content and the final GNP content specified in the end coating (Table 1). The dispersion used in the preparation of D1 and D3 contained reduced graphene oxide type GNPs. The dispersion used in the preparation of D2 contained GNPs of a 'crumpled sheet' type morphology with a relatively low density and high surface area. In addition, dispersion D3 contained an active corrosion inhibitor alongside the GNPs.

Prior to coating application, all substrates were degreased using acetone. Each first coat was applied to grit blasted mild steel CR4 grade panels (Impress North East Ltd.), of dimensions 150 x 100 x 2mm, by means of a gravity fed conventional spray gun. For multi coat samples the over coating interval was 3 hours with all panels permitted a final curing period of 7 days at 23°C (+/-2°C).

Dry film thickness of the prepared coatings were in the range of 50-60 microns for single coat samples and 150-160 microns for multi coat samples. Full details of the coating systems prepared can be seen in Table 2. All substrates were backed and edged prior to testing.

	Coating System	System Composition		
		Coat 1	Coat 2	Coat 3
Single coat samples	Epoxy Prototype Base	Epoxy prototype base	N/A	N/A
	D1	D1	N/A	N/A
	D2	D2	N/A	N/A
	D3	D3	N/A	N/A
Three coat system samples	Control	Zinc rich primer	Epoxy prototype base	Polyurethane topcoat
	ZRP/D1/PU	Zinc rich primer	D1	Polyurethane topcoat
	ZRP/D2/PU	Zinc rich primer	D2	Polyurethane topcoat
	ZRP/D3/PU	Zinc rich primer	D3	Polyurethane topcoat

Table 2: Coating systems sample summary

## 2.2 Neutral Salt Spray (NSS) Testing

The panels were placed in a corrosion chamber, running ISO 9227 for a period of up to 720 hours. This test method consists of a continuous salt spray mist at a temperature of 35°C. Panels were assessed at 10 day (240 hour intervals) for signs of blistering, corrosion, and corrosion creep in accordance with ISO4628. These assessments were complimented with electrochemical measurements, carried out at the same intervals.

There are three test methods identified in ISO 12944 to demonstrate performance in C4 and C5 atmospheric conditions [7]. These include Water Condensation, Neutral Salt Spray and a Cyclic Ageing test (Table 3). As a preliminary piece of work to identify systems with the potential to deliver extended performance lifetime, Neutral Salt Spray was selected as the initial screening method. Water condensation and cyclic ageing tests will be carried out on graphene formulations that have demonstrated performance equivalent or better than a zinc rich epoxy primer.

Corrosivity category as defined in ISO 12944-2	Durability ranges according to ISO 12944-1	Test regime 1			Test regime 2
		ISO 2812-2 (water immersion) (h)	ISO 6270-1 (water condensation) (h)	ISO 9227 (neutral salt spray) (h)	Annex B (cyclic ageing test) (h)
C2	Low	-	48	-	-
	Medium	-	48	-	-
	high	-	120	-	-
	Very high	-	240	480	-
C3	Low	-	48	120	-
	Medium	-	120	240	-
	High	-	240	480	-
	Very high	-	480	720	-
C4	Low	-	120	240	-
	Medium	-	240	480	-
	High	-	480	720	-
	Very high	-	720	1440	1680
C5	Low	-	240	480	-
	Medium	-	480	720	-
	High	-	720	1440	1680
	Very high	-	-	-	2688

Table 3: ISO 12944 Test Procedures [7]

## 2.3 Electrochemical Measurements

Prior to electrochemical/NSS testing, a small amount of the panel backing material was removed with a knife blade to provide an electrical connection point for the working electrode connectors. Upon completion of electrochemical testing, the removed section of backing material was covered with electrical insulation tape to reduce any possibility of corrosion whilst the sample was under NSS conditions. An additional prior step was to mark out the test area with a permanent marker to aid in relocating the test area for subsequent electrochemical measurements.

All electrochemical measurements were recorded using a Gamry 1000E potentiostat in conjunction with a Gamry ECM8 multiplexer to permit the concurrent testing of up to 8 samples per run. Each individual channel was connected to a Gamry PCT-1 paint test cell, specifically designed for the electrochemical testing of coated metal substrates.

Within each paint test cell, a conventional three-electrode system, the coated steel samples represented the working electrodes, a graphite rod served as a counter electrode and a saturated calomel electrode (SCE) served as the reference electrode. The test area of the working electrode was 14.6 cm<sup>2</sup>. All tests were run using a 3.5 wt% NaCl electrolyte.

During all EIS experiments, an AC voltage of 10 mV was applied across the sample, with a zero volt DC bias, over a frequency range of 1 MHz to 0.05 Hz. Ten measurements were recorded for every decade in frequency. An integration time of 1 second per measurement was used with a delay time of 0.2 seconds between each measurement. Equivalent circuit fitting to the obtained data was performed using the proprietary Gamry Echem Analyst software package in order to obtain coating capacitance values.

In the first instance, the samples, as described in Table 2, were tested before being placed under NSS. The samples were then retrieved from NSS every 10 days, where electrochemical measurements were conducted.

## 3. Results & Discussion

### 3.1 Single Layer Coats

Water uptake in organic coatings can be studied and quantified using a variety of different methods such as the more traditional gravimetric methods [12] and capacitance methods [13]. Capacitance methods rely on the creation of a capacitor over time due to water uptake in the organic coating. Water has a dielectric constant around 30 times that of most organic coatings, and the change of capacitance as water enters the coated substrate is related to the level of water uptake. Such dielectric type capacitance information can also be derived from EIS data, although there are several additional advantages of using EIS.

When applied to the study of organic-based protective anticorrosive coatings, impedance values, in their straight form, provide an indication of corrosion protection. Such values may be used as an initial screening for coating barrier type performance. In addition, through the appropriate equivalent circuits modelling of EIS data, additional critical information can be obtained such as pore resistance and coating capacitance along with interfacial properties, where a coating is breached, such as double layer capacitance.

The main contribution of the coating towards impedance occurs within the lower frequency region, at a frequency close to 0.1 Hz. This feature may be used as a type of screening method in the selection of suitable organic coatings. In a review paper concerning the performance of fast-cure epoxies for pipe and tank linings, O'Donoghue et al describe the use of EIS as such a screening tool [14], where the coating impedance measured at a frequency of 0.1 Hz can be used for screening materials. O'Donoghue et al assign impedance values of 10<sup>4</sup> Ohm.cm<sup>2</sup> to poor coatings and impedance values of 10<sup>10</sup> ohm.cm<sup>2</sup> to excellent coatings. In between these values, a relatively good coating is assigned an impedance value in the order of 10<sup>8</sup> Ohm.cm<sup>2</sup>, with barrier protection beginning at 10<sup>6</sup> Ohm.cm<sup>2</sup>. Since the O'Donoghue paper, several others have also employed this screening method to measure coating performance [15, 16].

Figure 1 shows the progression of impedance modulus for single coat samples, measured at 0.1 Hz, over the time during which all samples had been placed under NSS test conditions. Since these are single coat samples, and are therefore of reality low thickness (50-60 micron range) compared to thicker multi-layered systems, it is observed that impedance values in general are relatively low; performance is judged on relative values not overall impedance values. The epoxy prototype base coating shows relatively low impedance values, and a fast rate of change of impedance, indicating poor barrier properties. When any of the commercial graphene containing dispersions are added to epoxy prototype base, impedance values are increased by varying amounts, suggesting that in all cases, the inclusion of graphene nano platelets is acting to increase the barrier performance properties of the base coating.

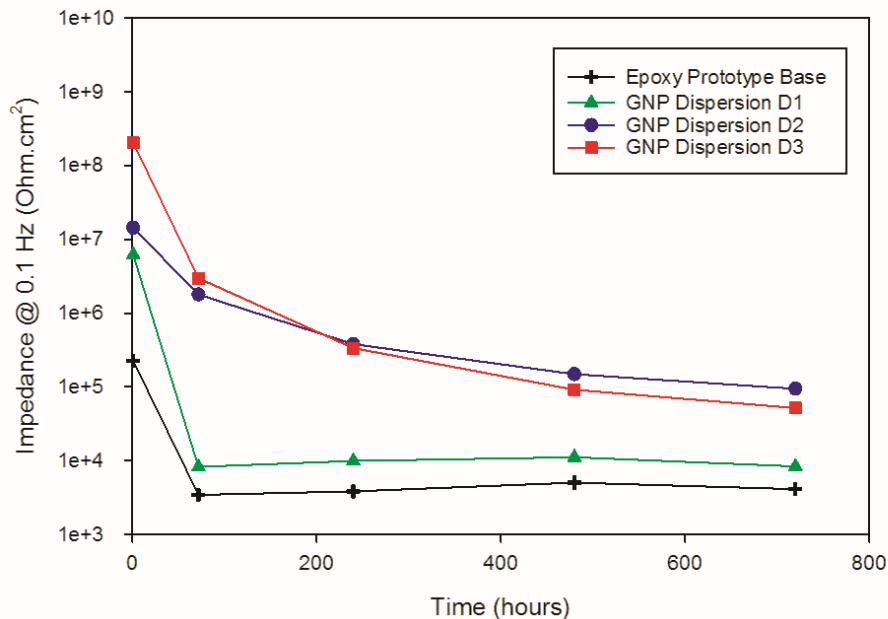


Fig. 1: EIS data - single coat samples

Coating	Creep (mm)	Blistering	Adhesion	Degree of corrosion
Epoxy Prototype Base	3	-	Good	Excessive corrosion
GNP Dispersion D1	1	-	Good	Heavily corroded
GNP Dispersion D2	1	1s1	Good	Mild corrosion
GNP Dispersion D3	1	1s1	Good	Mild corrosion

Table 4: NSS assessment (720 hours) single coats

Table 4 displays the visual results from NSS testing of the single coat samples. The observations appear to be in agreement with the EIS data; the relatively low impedance epoxy prototype base (control) sample shows the highest degree of corrosion with the dispersion D1 sample showing heavy corrosion (slightly higher impedance). Both dispersion D2 and D3 samples show a mild level of corrosion, corresponding to similar elevated levels of impedance over the control sample.

### 3.1 Three Coat Systems

Figure 2 shows the progression of impedance modulus for the three coat system samples, measured at 0.1 Hz, over the time period during which the samples were subjected to NSS conditions. Initial impedance values (recorded at t=0) range from the orders of 10<sup>8</sup> to 10<sup>10</sup> Ω.cm<sup>2</sup>. Overall, these values are higher than the initial values observed in the single layer samples, as expected, due to the increased thickness of the three coat systems. The control sample, consisting of a zinc rich primer coat, a layer of epoxy prototype base and polyurethane topcoat, displays the lowest overall impedance values in addition to one of the higher rates of decrease of impedance from the t=0 point. When tested as a single

entity, the epoxy prototype base coat also gave the lowest impedance throughout the duration of the test; also observed when incorporated into a full coating system. When GNPs are introduced into the intermediate layer, the impedance modulus is increased by varying amounts over the course of the experiment, suggesting that, once again, the inclusion of GNPs is acting to increase the barrier performance properties of the system as a whole. The smallest increase in overall impedance is observed when D1 dispersion is incorporated into the intermediate layer, and this is also the case when D1 is tested as a single coat entity. In the case of the D1 intermediate layer, the impedance is approximately one order of magnitude greater than the control when tested as part of the three coat system, similar to the observations of D1 as a single coat entity. In the single coat testing, dispersions D2 and D3 gave approximately the same level of impedance uplift over the control sample. When these dispersions are incorporated into the intermediate layer of three coat systems, the D3 intermediate layer gave a final uplift of close to 2 orders of magnitude above the control and the D2 intermediate layer gave a final uplift of 5 orders of magnitude above the control. In addition, the D2 incorporated sample (ZRP/D2/PUTC) showed little change in impedance, compared to the other samples, during the course of the experiment. This suggests that the D2 intermediate layer sample offers good to excellent barrier performance throughout the entire experiment, where the control ends just above the poor region ( $\Omega \cdot \text{cm}^2$ )

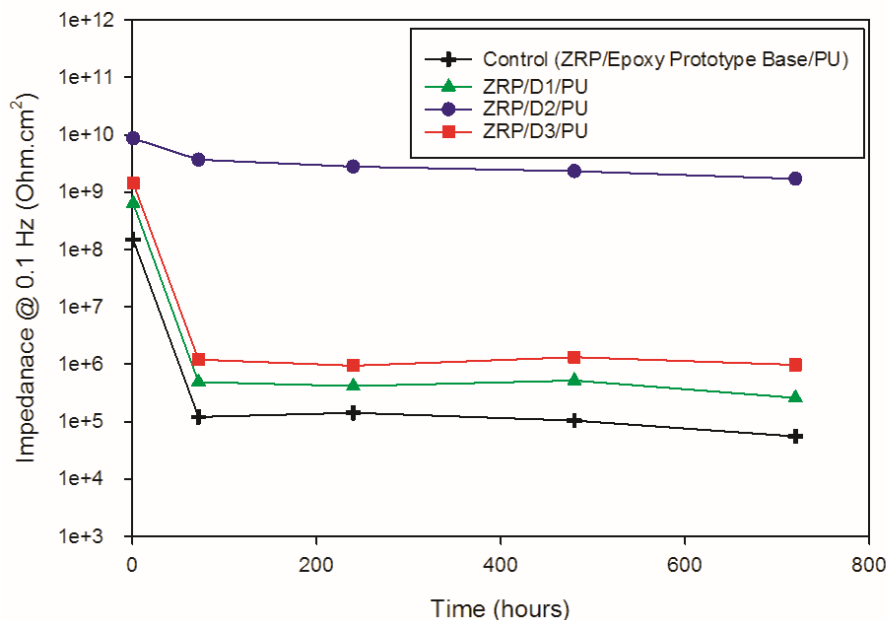


Fig. 2: EIS data - three coat systems

Coatings of relatively high thickness with superior barrier properties, such as those designed for use in C4/C5 type environments, will typically be of high impedance, both at the onset of exposure and, ideally, beyond as the coating is exposed to harsh environments for extended periods. Coatings of lower performance, either due to a thinner application or inferior barrier properties, may also display a high impedance, if only for a relatively short period of time.

The EIS response of such high impedance coatings, at the very beginning of exposure to harsh C4/C5 type environments is dominated by a capacitive behaviour; the coating is essentially acting a dielectric type capacitor, of either ideal or non-ideal type. Indeed, due to their very nature, complex multi-layered coatings are very likely to display a non-ideal type capacitance. When looking at the phase angle plot from the EIS data, values approaching -90 degrees (or close to if non-ideal) indicate the presence of a pure capacitive type behaviour. Following exposure to harsh environments, water may enter the coating. Depending on the intrinsic properties of the coating, the dielectric constant of water is in the region of 20 times that of the coating, leading to an increase in capacitance as water enters the coating. This change in capacitance is therefore related to water uptake in the coating.

Additionally, further deviation from a purely capacitive behaviour may arise as water or corrosive species penetrates within the coating pores, developing ionic pathways, creating a resistive contribution (pore resistance) to the overall impedance of the system. Figure 3(a) shows a selection of phase shift bode

plots for the three coat control sample, from before NSS exposure to 720 hours post NSS exposure. Whilst the T=0 measurement shows a value close to -90 degrees in the higher frequency range, there is some drift away from this value in the lower frequency range, suggesting some water uptake even at this early stage. Subsequent measurements in time show phase shift values relatively far removed from the ideal capacitor value, from 72 hours. The measurements from 72 hours and onwards sit fairly close together, suggesting the coating is nearing its saturation point. In contrast, the phase angle bode plot for the higher impedance sample, ZRP/D2/PU, shows relatively little deviation from close to the -90 degrees point, consistent with a coating which has taken up relatively little water. As previously discussed, the fact that the phase angle doesn't sit exactly on -90 degrees is due to the non-ideal capacitive behaviour of the system. Some increasing deviation is observed in the lower frequency domain, indicating that water is starting to enter the system, although the system is by no means fully saturated.

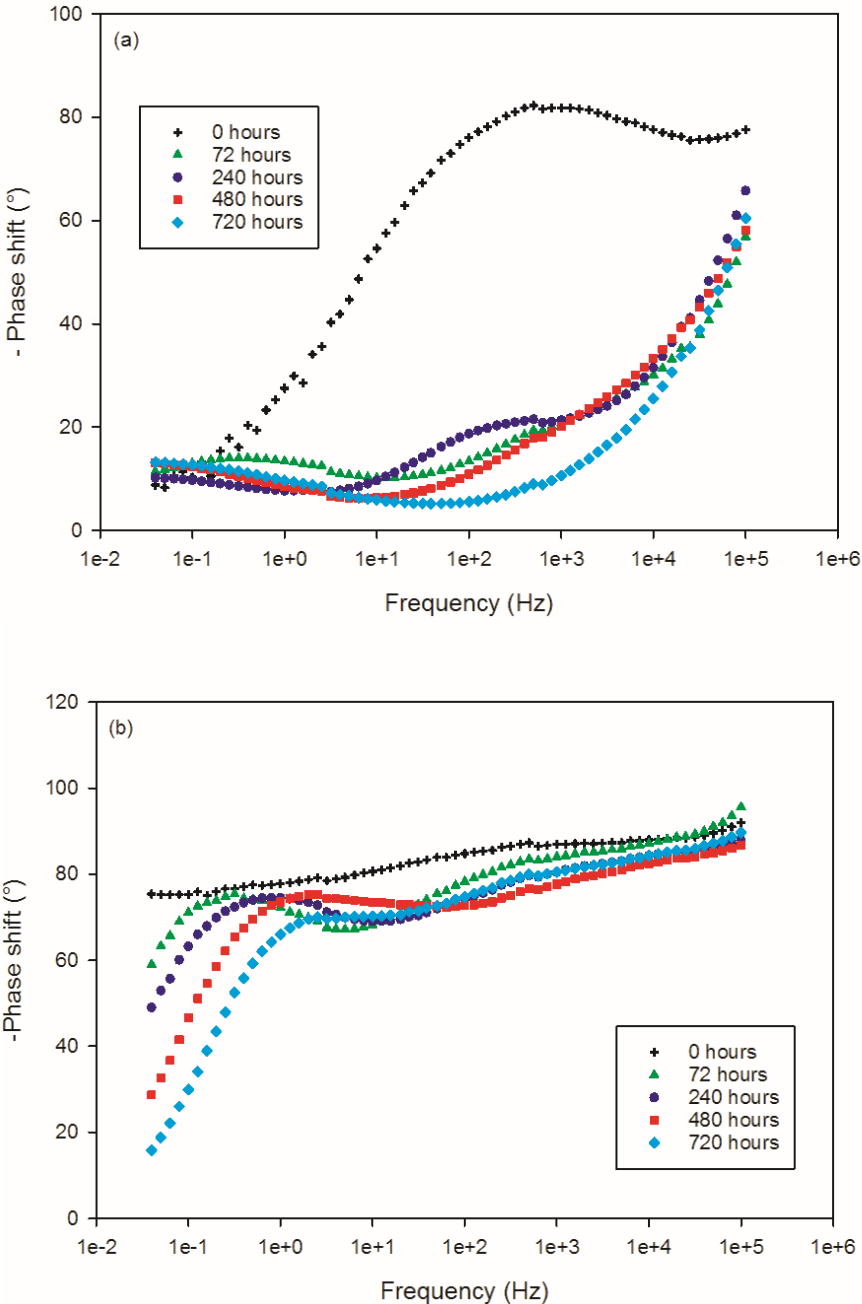


Fig. 3: Bode plots showing phase angle for (a) the 3 coat control sample and (b) the ZRP/D2/PU sample



Water uptake as a volume percent, %v, within a coating may be calculated as:

$$\%v = 100 \frac{\log\left(\frac{1}{C_0}\right) / \left(\frac{1}{C_x}\right)}{\log(80)}$$

Where  $C_0$  is the non-ideal coating capacitance at  $T=0$  and  $C_x$  is the non-ideal coating capacitance at  $T=72, 240, 480$  and  $720$  hours. Table 5 shows the water uptake values for the three coat system samples, calculated from the coating capacitance values obtained from equivalent circuit fitting of the EIS data, as per the water uptake equation above. The data suggests that, for the control sample, a saturation level is reached before the 72 hour point. This relatively high water uptake is concordant with the relatively low impedance values for this sample. In comparison, the graphene enhanced tie coat systems show far less water uptake, and appear stable during the test period; these low water uptake values correlate with the relatively high impedance values for the graphene enhanced samples.

Sample	Water uptake (%v)			
	72 hours	240 hours	480 hours	720 hours
Control (ZRP/Epoxy Prototype Base/PU)	61.75	63.00	62.97	66.41
ZRP/D1/PU	10.16	11.28	10.21	11.61
ZRP/D2/PU	4.54	4.23	4.03	4.93
ZRP/D3/PU	5.23	5.02	4.98	5.42

Table 5: Water uptake values for the three coat systems

Table 6 displays the visual outcome from NSS testing following 720 hours of exposure. At this point in time no visible corrosion was observed in any of the samples. It is anticipated that subsequent visual assessments will reveal differences between the samples with more corrosion evident on the control sample. The lack of visual signs of anticorrosion performance at this point in time highlights the relevance of EIS, where clear differences in sample performance can be observed.

Sample	Creep (mm)	Blistering	Degree of corrosion
Control (ZRP/Epoxy Prototype Base/PU)	0/<1	None	No visible corrosion
ZRP/D1/PU	<1	None	No visible corrosion
ZRP/D2/PU	<1	None	No visible corrosion
ZRP/D3/PU	<1	None	No visible corrosion

Table 6: NSS assessment (720 hours) multiple coat systems

## 4. Summary & Conclusions

### Single Layer Coats

- All impedance values for the single coat samples are generally low due to the single coat thickness (50-60 microns), but the data is comparable since the coating thicknesses are comparable
- The epoxy prototype base coating offers a relatively low impedance and, therefore, relatively low barrier performance compared with the GNP-enhanced samples when placed under NSS conditions over a period of 720 hours
- All graphene-containing variants of the prototype formulation appear to increase the barrier properties above the prototype base, by varying amounts
- The lowest graphene loading (0.1 wt.) of GNPs with a crumpled sheet morphology and relatively high surface area (dispersion D2) displayed the lowest overall rate of change of impedance over 720 hours where the final value was found to be 2 orders of magnitude higher than the epoxy prototype base
- Dispersions D1 and D3 contain the same reduced graphene oxide (RGO) type material with D3 offering a higher overall impedance than D1 despite containing half as much RGO type material
- The addition of an active inhibitor in the D3 dispersion may be acting in a synergistic manner to improve barrier performance
- The visual NSS results are in direct agreement with the EIS data: a high degree of corrosion for the prototype was observed with less overall corrosion coverage for dispersion D1 and even less [and roughly equal] corrosion coverage for dispersions D2 and D3

### Three Coat Systems

- The impedance values for the three coat systems were found to generally higher than for single coats due to the increased overall thicknesses, but the EIS data is comparable since the coating thicknesses are comparable
- The control sample offers a relatively low barrier performance when placed under NSS conditions over a period of 720 hours
- All systems containing graphene-enhanced tie coats offer a higher impedance and, therefore, improved barrier performance over the control sample
- The barrier performance ranking of each coating type (i.e. D2, D3, D1, Control) appears to be transferable across from single coat samples to multicoat systems
- The barrier properties of the single coat dispersions appear to be transferrable to the three coat systems, suggesting a good system compatibility
- The barrier performance of the dispersion D2 containing three layer system is relatively much higher than the corresponding control in comparison to the barrier performance of the D2 dispersion tested as a single layer entity
- A relatively low change in capacitive behaviour was observed for the ZRP/D2/PU system, suggesting relatively little water uptake for this sample
- This system has an impedance in the range of  $10^9$  Ohm.cm<sup>2</sup> after 720 hours of NSS (good to excellent barrier performance rating)
- There are no obvious visual differences between the samples after 720 hours, although EIS has shown to be capable of distinguishing performance differences
- All three coat samples meet the requirements for C4 high/C5 medium after 720 hours of testing
- Further NSS/EIS testing is required to reveal outright performance of the graphene-enabled three coat systems

### 5. References

- [1] G. Johnson, M. D. Sharp, W. Weaver and L. Chikosha, "Characterisation of a Novel Hybrid Anti-Corrosive System Comprising Graphene Nano Platelets and Non-Metal-containing Anti-Corrosive Pigments", The Oil & Colour Chemists' Association (OCCA) Centenary Conference, University of Leeds, 2018 (oral presentation)
- [2] L. Cheng et al: Journal of Alloys and Compounds Vol. 786 (2019), p. 791-797
- [3] A. Olajire: Journal of Molecular Liquids Vol. 269 (2018), p. 572-606
- [4] S. Pehkonen and S. Yuan: Interface Science and Technology Vol. 23 (2018), p. 115-132
- [5] T. Saravanakumar et al.: Progress in Organic Coatings Vol. 129 (2019), p.32-42
- [6] Z. Mahidashti, T. Shahrabi and B. Ramezanzadeh: Progress in Organic Coatings Vol. 114 (2018), p. 19.32
- [7] ISO 12944-2:2017: Paints and varnishes -- Corrosion protection of steel structures by protective paint systems -- Part 2: Classification of environments
- [8] Paint & Coatings Industry: PCIMAG.COM (October 2017)
- [9] P. Okafor et al.: Progress in Organic Coatings Vol. 88 (2015), p.237-244
- [10] K. Choi et al: ACS Nano Vol. 9 (2015), p. 5818 – 5824
- [11] S. Aneja et al: FlatChem Vo1. 1 (2017), p. 11-19
- [12] J. Crank and G. S. Park: Diffusion in Polymers, Academic Press, New York, NY, (1954)
- [13] D. M. Brasher and A.H. Kingsbury: J. Appl. Chem, (1954), p. 62
- [14] M. O'Donoghue et al: JPCL-PMC (1998), p. 36-51
- [15] A. Hussain et al: Engineering Failure Analysis Vol. 82 (2017), p. 765-775
- [16] G. Bouvet et al: Progress in Organic Coatings Vol. 77 (2014), p. 2045-2053