UNIVERSITI PUTRA MALAYSIA

PREPARATION AND CHARACTERIZATION OF ANTI-CORROSIVE COATINGS BASED ON SILANE FUNCTIONALIZED GRAPHENE OXIDE/ EPOXY RESIN NANOCOMPOSITES

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By

AUJARA KABIRU MUSA

Thesis Submitted to the school of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the degree of Doctor of Philosophy

December 2020

DEDICATION

I hereby dedicate this thesis to the Almighty Allah, who has been my help, sustainer, provider, guide, encouragement, keeper, and my all in all throughout the course of my studies and also to my parents (Alhaji Musa Ibrahim and Hajiya Fatima Bintu Usman), My wife Fauziyya Musa and my beloved and beautiful daughters (Rabi‘at, Fatima, Amina, and Nana Aisha) whose prayers and support have kept me going. Finally, to my brothers and sisters who are always by my side and ready to render any kind of support and assistance

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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Chairman : **Associate Professor Nor Azowa binti Ibrahim, PhD**
Faculty : **Science**

Epoxy resins are generally used to protect metal substrates, however, there is a need for improvement of anti-rust performance and mechanical properties. The addition of nano-sized fillers such as graphene to produce nanocomposites can overcome the shortage of polymeric materials and has remarkable mechanical, electrical, and gas barrier properties. In this study, graphene oxide and functional-GO were incorporated into epoxy resins to provide a protective layer of the metal substrate. Functional-GO is synthesized using environmentally friendly gamma irradiation techniques, which are a simple and clean alternative approach to alter the structural and physicochemical properties of graphene oxide (GO). Graphene oxide obtained by Hummer method was modified by incorporating 3-Aminopropyltriethoxysilane (APTES) and 3-Glycidyloxypropyltrimethoxy silane (GPTMS) to its surface by radiation from gamma ray. The nature of GO and functional-GO is characterized by various techniques such as Fourier transform infrared spectroscopy (FT-IR), X-ray diffraction spectroscopy (XRD), field release scanning electron microscope (FESEM), Raman spectroscopy, and thermogravimetric analysis (TGA). The FT-IR spectrum reveals chemical interactions between the cross section which shows significant weakening of the -OH, COOH and C-O-C with the appearance of chemical bonds due to the withdrawal of oxygen functional groups on the GO surface where crystal surface changes and surface defects due to modification are determined by XRD which shows the gradual weakening with simultaneous disappearance of graphite peak as the oxidation process proceeds with the corresponding appearance of diffraction peak at about $2\theta=9.8$ leading to an increased in the interlayer spacing from 0.34nm to 0.90nm. Similarly, the Raman spectroscopy indicate an increase in I_D/I_G from 0.90 for GO to 1.21 and 1.18 for AGO-150 and GGO-150 respectively. The TGA thermograms showed peaks at various temperature regions (i.e. 30-120°C, 120-300°C and 300-650°C) which can be attributed to the degradation oxygen functional groups and chemically bonded silane on the GO surface. Within these temperature regions the AGO-150 exhibits highest thermal stability with the lowest water evaporation (5.5%), lowest decomposition of unreacted silanes (9.36%) and thermal-oxidative decomposition of grafted silane (32.17%). Preparation of the protective material of the steel substrate begins by ultrasonically dispersing the 1 wt.% GO in the solvent before mixing it by shearing it into an epoxy matrix and adding a hardener. XRD showed the existence of GO morphology, functional-GO intercalation and exfoliation throughout the matrix shown by the existence of broad diffraction peak of epoxy between 2θ=5-28° centered at 2θ=18° indicating the dispersion of functionalized-GO in the matrix. SEM on the sample surface layer determined during the tensile test showed microscopic and homogeneous functional-GO dispersion in the matrix. Thermogravimetric analysis (TGA) through the analysis of some thermodynamic parameters such as T_{on}, $W_{350°C}$, T_{max} and $T_{500°C}$ all revealed improved thermal stabilities of nanocomposites coatings fabricated with functionalized-GO. The dynamic mechanical analysis (DMA) was used to investigate the thermomechanical properties of nanocomposite coatings. Thermodynamic parameters such E' and T_g of the nanocomposites coatings showed a significant increase in storage modulus and a gradual increase in glass transition temperature with the dispersion of functionalized-GO, where EAG-150 exhibits highest E' of 3414.90 MPa and T_g of 90.49°C.

The physical properties of coatings such as adhesion, hardness, flexibility, and chemical properties are also assessed. Corrosion resistance of nanocomposite layers in NaCl solution (3.5% by mass) was also assessed using Open Circuit Potential (OCP), potentiodynamic polarization, and Electrochemical Impedance Spectroscopy (EIS). The results showed that the functional nanocomposite layer-GO is capable to block the penetration of electrolytes between the metal surface and the coating. This study shows that Functional-GO /epoxy nanocomposites provide better corrosion protection and can act as an excellent corrosion barrier on lightweight steel substrates due to improvement of some electrochemical properties such as shifting of E_{corr} to more positive value i.e., from -0.853554V for EP to -0.18488 for EAG-150 and decreasing of I_{corr} value from 8.349×10^{-7} for EP to 5.281×10^{-8} for EAG-150. This improvement in corrosion protection behavior can be attributed to the GO two-dimensional (2D) structure and outstanding performance, which can hinder the penetration of corrosive media to a certain extent, thereby enhancing the anti-corrosion properties of the coatings.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai
memenuhi keperluan untuk ijazah Doktor Falsafah

PENYEDIAAN DAN PENCIRIAN LAPISAN ANTI KARAT BERASASKAN GRAPHEN BERFUNGSIONAL SILAN/EPOKSI NANOKOMPOSIT

Oleh

AUJARA KABIRU MUSA

Disember 2020

Pengerusi : Profesor Madya Nor Azowa binti Ibrahim, PhD
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Resin epoksi secara amnya digunakan untuk melindungi substrat logam, namun, terdapat keperluan untuk peningkatan prestasi anti karat dan sifat mekanikalnya. Tambahan pengisi bersaiz nano seperti grafin untuk menghasilkan nanokomposit dapat mengatasi kekurangan bahan polimer dan mempunyai sifat mekanikal, elektrik, dan gas yang utuh. Pada kajian ini, grafin oksida dan fungsional-GO dimasukkan ke dalam resin epoksi bagi menyediakan lapisan pelindung substrat logam. Fungsional-GO disintesis dengan menggunakan teknik penyinaran gamma yang mesra alam, dimana merupakan pendekatan alternatif mudah dan bersih untuk mengubah sifat struktur dan fizikokimia grafin oksida (GO). Grafin oksida yang diperoleh melalui kaedah Hummer telah diubahsuai dengan mencantumkan 3-Aminopropiltrietoksi silana (APTES) dan 3-glisidiloksipropiltrimetoksi silana (GPTMS) ke atas permukaan grafin oksida menggunakan radiasi dari penyinaran sinar gamma. Sifat GO dan fungsional-GO dicirikan melalui pelbagai teknik seperti spektroskopi inframerah transformasi Fourier (FT-IR), spektroskopi difraksi sinar-X (XRD), mikroskop elektron pengimbasan pelepasan medan (FESEM), spektroskopi Raman, dan analisis termogravimetrik (TGA). Spektrum FT-IR mendedahkan interaksi kimia antara keratan rentas yang menunjukkan kelemahan ketara -OH, COOH dan C-O-C dengan kemunculan ikatan kimia kerana tarikan kumpulan fungsional oksigen pada permukaan GO yang membawa perubahan permukaan kristal dan kerosakan permukaan disebabkan untuk pengubahsuaian ditentukan oleh XRD yang menunjukkan kelemahan secara beransur-ansur dengan hilangnya puncak grafit secara serentak ketika proses pengoksidaan diteruskan dengan penampilan puncak difraksi yang sepadan pada sekitar 2θ = 9,8 yang menyebabkan peningkatan jarak antara lapisan dari 0.34nm kepada 0.90nm. Seterusnya, spektroskopi Raman juga menunjukkan peningkatan I_D/I_G dari 0.90 untuk GO ke 1.21 dan 1.18 untuk AGO-150 dan GGO-150g. Termogram TGA menunjukkan puncak julat bagi suhu (30-120 °C, 120-300 °C dan 300-650 °C) yang dikaitkan dengan degradasi kumpulan fungsi oksigen dan ikatan kimia silan pada permukaan GO. Pada kawasan suhu ini, AGO-150 menunjukkan kestabilan terma tertinggi dengan penyejatan air terendah (5.5%), penguraian terendah silan yang tidak berinteraksi (9.36%) dan penguraian terma-oksidatif silan cantuman (32.17%). Penyediaan bahan pelindung substrat keluli dimulakan dengan penyebaran ultrasonik GO seberat 1% ke dalam pelarut sebelum mencampurkannya dengan mengkikis ke dalam matriks epoksi dan menambahkan bahan pengeras. XRD menunjukkan adanya morfologi GO dan interkalasi dan pengelupasan GO-fungsional di seluruh matriks yang ditunjukkan oleh adanya puncak difraksi epoksi luas antara $2\theta = 5\text{-}28°$ berpusat pada $2\theta = 18°$ menunjukkan penyebaran fungsional-GO dalam matriks. SEM pada lapisan permukaan sampel yang ditentukan semasa ujian tegangan menunjukkan penyebaran fungsional-GO mikroskopik dan homogen dalam matriks. Analisis termogravimetri (TGA) melalui analisis beberapa parameter termodinamik seperti T_{on}, $W_{350°C}$, T_{max} dan $T_{500°C}$ semuanya menunjukkan peningkatan kestabilan terma lapisan nanokomposit yang dibuat dengan fungsional-GO. Analisis mekanikal dinamik (DMA) digunakan untuk menyiasat sifat termomekanik pelapis nanokomposit. Parameter termodinamik seperti pelapisan nanokomposit E' dan T_g menunjukkan peningkatan modulus penyimpanan yang ketara dan peningkatan suhu peralihan kaca secara beransur-ansur dengan penyebaran fungsional-GO, di mana EAG-150 menunjukkan E' tertinggi 3414.90 MPa dan T_g 90.49 °C.

Sifat fizikal lapisan seperti kelekatan, kekerasan, kelenturan, dan sifat kimia juga dinilai. Ketahanan kakisan lapisan nanokomposit dalam larutan NaCl (3.5% jisim) juga dinilai menggunakan Potensi Litar Terbuka (OCP), polarisasi potensiodinamik, dan Spektroskopi Impedansi Elektrokimia (EIS). Hasil kajian menunjukkan bahawa lapisan nanokomposit berfungsi-GO mampu menyekat penembusan elektrolit antara permukaan logam dan lapisan. Kajian ini menunjukkan bahawa nanokomposit fungsional-GO/epoksi memberikan perlindungan hakisan yang lebih baik dan dapat bertindak sebagai penghalang hakisan yang sangat baik pada substrat keluli ringan kerana peningkatan beberapa sifat elektrokimia seperti peralihan E_{corr} ke nilai yang lebih positif iaitu dari -0.853554V untuk EP ke -0.18488 untuk EAG-150 dan penurunan nilai I_{corr} dari 8.349×10^{-7} untuk EP kepada 5.281×10^{-8} untuk EAG-150. Peningkatan tingkah laku perlindungan hakisan ini dapat dikaitkan dengan struktur dua dimensi (2D) GO dan prestasi luar biasa, yang dapat menghalang penembusan bahan hakisan kepada tahap tertentu, sehingga meningkatkan sifat anti-karat permukaan.

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

0D	0 Dimensional
^{135}Cs	Cesium-137
1D	1 dimensional
2D	2 dimensional
3D	3 dimensional
^{60}Co	Cobolt-60
APTES	3-Aminopropyltriethoxysilane
ASTM	American Society for Testing and Materials
BISE	1,3-bis[3-(4,5-epoxy-1,2,3,6-tetrahydrophthalimido)propyl] tetramethyldisiloxane
BPA	Bisphenol A
CAE	Cycloaliphatic epoxy
CNT	Carbon nanotube
CR	Corrosion rate
CVD	Chemical Vapor Deposition
DETA	Diethylenetriamine
DGEBPA	Diglycidyl Ether of Bisphenol-A
DMA	Dynamic Mechanical Analysis
DMF	Dimethylformamide
DTA	Deferential Thermal Analysis
DWCNT	Double-walled carbon nanotube
EAG	APTES functionalized-GO/Epoxy coatings
ECH	Epichlorohydrin
E_{corr}	Corrosion potential

EG	Expanded graphite
EGG	GPTMS functionalized-GO/Epoxy coatings
EGO	GO/Epoxy coatings
eV	Electron volts
EVA	Ethylene-vinyl acetate
FESEM	Field Emission Scanning Electron Microscopy
f-GO	Functionalized-GO
FRA	Frequency Response Analysis
FT-IR	Fourier-transform infrared spectroscopy
GDP	Gross Domestic Product
GGO	GPTMS functionalized-GO
GNP	Graphene Nano Platelets
GO	Graphene Oxide
GPTMS	3-glycidyloxypropyltrimethoxy silane
Gy	Gray
$H_{12}MDI$	4,4’-dicyclohexylmethene diisocyanates
HDI	Hexamethylene diisocyanates
HHPA	Hexahydrophthalic anhydride
I_{corr}	Corrosion current density
IPDI	Isophorone diisocyanates
ISO	International Organisation for Standardization
KBr	Potassium Bromide
KGy	Kilo Gray
LDH	Layered Double Hydroxide

MEK	Methyl Ethyl Ketone
MHHPA	Methyl hexahydrophthalic anhydride
MMT	Montmorillonite
IMPACT	International Measures and Prevention, Application and Economics of Corrosion Technologies
MTHPA	Methyl Tetrahydrophthalic Anhydride
MWCNT	Multi-walled carbon nanotube
NACE	National Association of Corrosion Engineers
OCP	Open Circuit Potential
PA	Phthalic Anhydride
PDI	Pentamethylene diioscyanates
PDP	potentiodynamic polarization
PE-g-MA	polyethylene-grafted maleic anhydride
PMMA	polymethylmethacrylate
PNC	Polymer Nanocomposites
PS	Polystyrene
PVP	polyvinylpyrrolidone
rGO	Reduced Graphene Oxide
RM	Ringgit
R_p	polarization resistance
RT	Room Temperature
SCE	Saturated Calomel Electrode
SEM	Scanning Electron Microscopy
SRI	Standard research institute
SWCNT	Single-walled carbon nanotube

TEM	Transmission electron microscope
TETA	triethylenetetramine
T_g	Glass transition temperature
THF	tetrahydrofuran
THPA	tetrahydrophthalic anhydride
TMXDI	tetramethyl xylylene diisocyanates
US	United States
UV	Ultra violet
XDI	xylylene diisocyanates
XRD	X-ray diffraction
γ-ray	Gamma-ray

CHAPTER 1

INTRODUCTION

1.1 Research Background

Corrosion is a process that leads to the deterioration of the performance of a material; it is a physicochemical interaction leading to a significant reduction of the functional properties of either the material or/and the environment in which it has interacted (Marcus and Maurice,2009). Corrosion is more commonly understood to involve a chemical or electrochemical process that involved the typical transfer of electron due to the natural tendency for most metals to return to their natural state. Typically, metals are produced by extracting them from nature by applying energy to the mineral and ore. In an open environment, these metals are not thermodynamically stable and therefore tend to return to their lower Gibbs free energy forms as hydroxides, oxides, etc. These chemical and electrochemical processes through which metals go back to their lower Gibbs free energy states are termed corrosion. Corrosion tends to deteriorate metal surface through charge transfer reaction at an ambient environment (Cai et al., 2016).

Corrosion is a spontaneous process, and just like any other natural phenomenon, it drives the material to its lowest possible energy state. Metals and alloys have a natural tendency to combine with oxygen and water in the surrounding environment and return to their most stable form. When iron and steel interact with the environment, they return to their native and stable oxide. Like any other natural disaster such as weather change and earthquake, corrosion results in an unprecedented and economic challenge. National Association of Corrosion Engineers (NACE) International established the International Measures and Prevention, Application, and Economics of Corrosion Technologies (IMPACT) in October 2014. The NACE-IMPACT report is regarded to be the first assessment of global corrosion costs. Its report published in 2016 estimates the cost of corrosion at US$2.5 trillion, equivalent to 3.4% of global GDP (Prasad et al., 2020). To make a global assessment, classification was made based on economic region to represent the total economy according to the World Bank’s economic status for the countries. The economic regions comprised of the United States (US), China, European region, India, the Arab world, Russia, Japan, the four Asian tigers + Macau, and the rest of the world.

Furthermore, the industrial economic sector, services, and agricultural sectors in each of these countries were considered. A substantial economic impact was logged for the Arab world, sacrificed 5% of GDP for corrosion costs in different economic sectors. The least affected economic region is Japan, with total corrosion cost equivalent to 1% of GDP. The report, however, excludes the cost associated with individual safety and environmental consequences even though its essential in a real sense for implementing effective corrosion management strategies (Koch et al., 2016). The lifetime of products containing metallic components is often limited by the corrosion of their metallic parts. This cost could be saved with a better understanding and control of corrosion phenomena (Marcus and Maurice, 2009). Loss of production, inefficient operation, high maintenance are among the expensive problem associated with metal corrosion (Karthik et al., 2015). Its therefore imperative to note that total elimination of the corrosion process is impossible; hence, various techniques are utilize in multiple fields such as marine equipment, pipelines, and construction to attenuate the intensity and severity of corrosion. These techniques include anodic or cathodic protection (Shen et al., 2005), corrosion inhibitors (Zheludkevich et al., 2006), and protective coatings (Hong, 2018).

Coatings are usually applied to improve the surface properties of a substrate, corrosion resistance, wettability, and adhesion. Applications of these coatings is a smart way to combine the mechanical properties of metals with the surface characteristics of the coatings (Ammar et al., 2016). The coating industry has been driven to seek new technologies and materials to improve the efficiency of coatings by economic benefits and growing environmental concerns. Several factors affect the effectiveness of a coating against all the possible damaging sources: they are the quality of the coating, the substrate characteristics, the properties of the coating/substrate interface, and the corrosiveness of the environment (Kiran et al., 2017). Organic coatings are widely used in the protection of the metallic structures against corrosion due to their high barrier and superior mechanical properties (Alam et al., 2013).

Various organic coating systems such as polyurethane, acrylic coatings, vinyl-based coatings, epoxy coatings, etc., are available in the market as it is generally assumed that these polymeric coatings play as a physical barrier between the metal substrate and corrosive environment. Among these polymeric coatings, Epoxy coatings have been widely used for protecting metal structures from environmental and corrosion attacks due to their outstanding toughness and durability (Brostow et al., 2010)

Epoxies are noted for their versatility, high resistance to chemicals, outstanding adhesion to a variety of substrates, toughness, high electrical resistance, durability at high and low temperatures, low shrinkage upon cure, flexibility, and the ease with which they can be poured or cast without forming bubbles and relatively cheap (Wang et al., 2018). These properties make them eligible for use in various applications such as protective coatings that can reduce the corrosion of metal/alloy substrates by acting as an excellent physical barrier layer because it also effectively prevents the invasion of aggressive chloride ion, hydrogen ion, and oxygen in a wet environment (Jin et al., 2017). But pure epoxy coatings have some deficiencies, which include micro-pores, bubbling, poor resistance to cracks propagation. Also, epoxies have hydrophilic hydroxyl groups and free volumes in their structure, which make them permeable to aggressive agents (i.e., water, oxygen, Cl^-), which consequently accelerates the corrosion of the metallic substrate over time (Ji et al., 2006). To overcomes this problem, various efforts were made by researchers to improve the properties of the epoxy by the addition of various types of additives such as carbon-based nanofillers (Frigione and Lettieri, 2020), thereby enhancing barrier performance. The incorporations of these additives that are miscible into the resin occupy cavities, thereby reducing the porosity and zigzagging the diffusion path for the deleterious species and consequently enhancing the integrity and durability of the coating (Chen et al., 2017). Apart from increasing the length of the diffusion pathways for the corrosive agents, these additives also offer electrochemical anodic or cathodic protection effects. Also, properties of the coating such as UV blocking, scratch and abrasion resistance, hardness, and other mechanical properties were reported to be improved by the addition of these fillers (Rahman et al., 2015).

Graphene related materials have attracted tremendous attention and have been employed in various field, especially in the improvement of the properties of polymeric coatings, due to its two-dimensional structure, high aspect ratio and specific surface area, superior gas barrier properties, and permeability to small ions and molecules (Xia et al., 2016). This property consequently makes the reinforced composites coatings to have an excellent anti-corrosive performance in a severely corrosive environment.

However, the electrostatic interaction, π-π stacking, and high specific surface area make graphene aggregates easily, thereby resulting in heterogeneous dispersion in the polymer matrix. The tendency of graphene to agglomerate and its subsequent stacking resulted in graphite-like with low surface area pose a challenge in obtaining homogeneous dispersion and efficient interfacial interaction of graphene in organic coating and subsequent nanocomposites with optimal properties (Wang et al., 2012).

However, one of the approaches to improve the dispersion of graphene sheets in organic coatings is utilizing graphene oxide (GO), which has functional groups including hydroxyls, epoxides, and carboxyl on its structure that alter the van der Waals interactions, making them easily dispersed in the polymer matrix. Recently, researchers show that graphene oxide (GO) as a two-dimensional nanofiller of sp^2-hybridized carbon atoms, remarkably improves the corrosion resistance of polymeric coatings via increasing the diffusion path of corrosive agents as well as decreasing the coating porosity (Mo et al., 2015). However, to ensure adequate dispersion of GO in polymer coatings and its subsequent strengthening of the interfacial bonding between GO and polymer matrix, surface modification of GO is an alternative choice to prevent GO agglomeration and hence improved corrosion resistance of the coating. The functional groups at the basal plane and edges of GO provide the reactive sites for covalent functionalization. Amongst various functionalization methods considered for improving GO dispersion in a polymer matrix, silane modification is a promising method for enhancing the properties of the composites due to its bifunctional structure (Zhang et al., 2018). The coupling process is accomplished via a chemical reaction between the silane molecules alkoxy groups and the hydroxyl group’s presence on the surface of the graphene, at the same time, the other functional groups of silane molecules, which are generally amine, ethylene, epoxy, trihydroxy, etc. remained. These surviving functional groups can provide a chemical bonding site of graphene with the polymer matrix, leading to enhanced properties (Li et al., 2015). Thus, the performance of epoxy coatings will ultimately be enhanced by utilizing the advantages of functionalized-GO (f-GO).

So far, there have been several methods for the functionalization of GO, one of which is chemical techniques that typically require a long reaction time, toxic reagent, strict reaction conditions that restrict large-scale production (Ahmad et al., 2017). Hence, a new route combining the economic advantage and convenience of chemical synthesis with excessive reduction efficiency has therefore been an import goal for the preparation of functionalized GO. Gamma-ray irradiation has recently been investigated as a safe, clean and simple way to alter the nanostructure and properties of carbon materials and facilitate chemical reactions on their surface (Ansón-Casaos et al., 2014). Not only because it is an environmentally friendly procedure, but also because it is practical, cost-effective and can be performed at room temperature, the method has attracted interest among researchers. However, the study of inducing grafting onto the surface of GO using gamma-ray irradiation is still an emerging field.

1.2 Problems statement

Corrosion is a disturbing phenomenon in which chemical or electrochemical reactions occur that lead to the deterioration of metals materials. Apart from economic losses associated with corrosion, the process is a threat to the safety of industrial production. However, various corrosion protection methods have been developed which includes protective coatings, environmental modifications, cathodic and anodic protection, application of inhibitors or any combination of these. Protection of metallic surface from corrosion employing polymeric coatings are the commonest approach due to their excellent anti-corrosion performance coupled with their low cost. Among them, epoxy coatings have captivated the interest of researchers due to their excellent mechanical properties and adhesion to metallic substrates. Nevertheless, epoxy coatings fail over prolong exposure to permeable aggressive corrosive media, in addition to its low resistance to crack propagation; epoxy contains hydrophilic hydroxyl groups in their cured network leading to poor resistance in humid condition. Hence, the initiation and propagation of cracks in the coating allow the penetration of corroding agents through the defect thus reduces adhesion and enhancing corrosion.

To overcome this problem, nanoparticles such as graphene oxide is incorporated as a nanofiller. Nonetheless, graphene oxide sheet agglomeration due to the strong van der Waals forces among their sheets and its weak compatibility with most of the polymer matrices have been fundamental roadblocks that restrict its potentials. Surface modification by adding functional groups such as organo silane compounds is an effective way to reduce the tendency to agglomerate. Also, functionalization increases the graphene compatibility with specific polymers thereby improving the reinforcing effect. Previous studies focus on the functionalization of graphene derivatives through various techniques that are often complex with long reaction time, toxic reagents with specific reaction conditions. However, this study focus on the γ-irradiation method of graphene functionalization, which is cost-effective, environmentally friendly, and can be conducted at low temperatures.

1.3 Objective of the study

To prepare and characterized an anti-corrosive coating based on silane functionalized Graphene Oxide (f-GO) / Epoxy resin nanocomposites
Specific Objectives:

- To prepare, functionalized and characterized Graphene oxide with Organosilane, i.e. 3-Aminopropyltriethoxysilane (APTES) and 3-

Glycidyloxypropyltrimethoxy (GPTMS) via radiation assisted process using gamma-ray irradiation at various radiation doses.

- To prepare and characterize nanocomposites coatings for morphology, coatings surface performance and chemical resistance performance

- To investigates thermomechanical properties of the nanocomposites coatings via Thermogravimetric Analysis (TGA) and Dynamic Mechanical Analysis (DMA).

- To investigate the anti-corrosion performance of the AGO/Epoxy coatings (EAG's) and GGO/Epoxy coatings (EGG's) via Electrochemical Impedance Spectroscopy (EIS) and Potentiodynamic polarization.

1.4 Significance of the Study

Several studies in this field have been inspired by the excellent properties of graphene. Up till now, the performance of polymer/graphene nanocomposites have been extensively investigated so far in applications such as solar cells, supercapacitors, lithium-ion batteries, electrochemical sensing, and membrane-based separation applications. Currently, most of the research of graphene/Epoxy nanocomposites is largely focusing on their electrical conductivity features in fuel cells, transistors, and photocatalytic applications. Up till now, no research is being reported on the incorporation of gamma-irradiation functionalized-GO nanomaterials as nanofillers in the fabrication of epoxy nanocomposites for anti-corrosion coatings. Since various researches findings have shown that graphene exhibited anti-corrosion properties, the present study would concentrate on the functionalization of GO with hydrophobic silane molecules such as APTES and GPTMS to increase the properties of GO. This can, in turn, heighten the performance of GO as a coating material.

REFERENCES

Abdel Rehim, M., and Turky, G. (2019). Silane-functionalized graphene oxide/epoxy resin nanocomposites: Dielectric and thermal studies. *Journal of Applied Polymer Science*, *136*(47), 1–11.

Abdelmouleh, M., Boufi, S., Belgacem, M. N., Dufresne, A., and Gandini, A. (2005). Modification of cellulose fibers with functionalized silanes: Effect of the fiber treatment on the mechanical performances of cellulose-thermoset composites. *Journal of Applied Polymer Science*, *98*(3), 974–984.

Abdullah, S. I., and Ansari, M. N. M. (2015). Mechanical properties of graphene oxide (GO)/epoxy composites. *HBRC Journal*, *11*(2), 151–156.

Adetayo, A., and Runsewe, D. (2019). Synthesis and Fabrication of Graphene and Graphene Oxide: A Review. *Open Journal of Composite Materials*, *09*(02), 207–229.

Ahmad Daud, N., Chieng, B., Ibrahim, N., Talib, Z., Muhamad, E., and Abidin, Z. (2017). Functionalizing Graphene Oxide with Alkylamine by Gamma-ray Irradiation Method. *Nanomaterials*, *7*(6), 135.

Ahmadi-Moghadam, B.M., M. S., Shadlou, S., and Taheri, F. (2014). Effect of functionalization of graphene nanoplatelets on the mechanical response of graphene / epoxy composites. *JOURNAL OF MATERIALS&DESIGN*.

Ahmadi, Y., and Ahmad, S. (2020). Polymeric nanocomposite coatings. *Corrosion Protection at the Nanoscale*, 363–378.

Ahmed, T., Das, S., and Irin, F. (2012). *High performance polymer-stabilized pristine graphene based epoxy composites with enhanced mechanical and electrical properties*. *February 2015*.

Al-Kaseasbeh, Q., Lin, Z., Wang, Y., Azarmi, F., and Qi, X. (2018). Electrochemical Characterization of Steel Bridge Welds under Simulated Durability Test. *Journal of Bridge Engineering*, *23*(10), 1–13.

Alam, M. A., Sherif, E. S. M., and Al-Zahrani, S. M. (2013). Mechanical properties and corrosion behavior of different coatings fabricated by diglycidyl ether of bisphenol-A epoxy resin and Aradur®-3282 curing agent. *International Journal of Electrochemical Science*, *8*(6), 8388–8400.

Alhumade, H., Yu, A., Elkamel, A., Simon, L., and Abdala, A. (2016). Enhanced protective properties and UV stability of epoxy/graphene nanocomposite coating on stainless steel. *Express Polymer Letters*, *10*(12), 1034–1046.

Aljeaban, N. A., Goni, L. K. M. O., Alharbi, B. G., Jafar, M. A., Ali, S. A., Chen, T., Quraishi, M. A., and Al-Muallem, H. A. (2020). Polymers Decorated with Functional Motifs for Mitigation of Steel Corrosion: An Overview. *International Journal of Polymer Science*, *2020*.

Alkhouzaam, A., Qiblawey, H., Khraisheh, M., Atieh, M., and Al-Ghouti, M. (2020). Synthesis of graphene oxides particle of high oxidation degree using a modified Hummers method. *Ceramics International*, *May*, 1–11.

Allen, J. M., Vincent, T. C., and Richard, K. B. (2010). Honeycomb carbon : A Review of Graphene What is graphene ? *Chemical Reviews*, *110*, 132–145.

Almeida, E. (2001). Surface treatments and coatings for metals. A general overview. 1. Surface treatments, surface preparation, and the nature of coatings. *Industrial and Engineering Chemistry Research*, *40*(1), 3–14.

Ammar, S., Ramesh, K., Vengadaesvaran, B., Ramesh, S., and Arof, A. K. (2016). Amelioration of anticorrosion and hydrophobic properties of epoxy/PDMS composite coatings containing nano ZnO particles. *Progress in Organic Coatings*, *92*, 54–65.

Ansón-Casaos, A., Puértolas, J. A., Pascual, F. J., Hernández-Ferrer, J., Castell, P., Benito, A. M., Maser, W. K., and Martínez, M. T. (2014). The effect of gamma-irradiation on few-layered graphene materials. *Applied Surface Science*, *301*, 264–272.

Aslam, S., Sagar, R. U. R., Kumar, H., Zhang, G., Nosheen, F., Namvari, M., Mahmood, N., Zhang, M., and Qiu, Y. (2020). Mixed-dimensional heterostructures of hydrophobic/hydrophilic graphene foam for tunable hydrogen evolution reaction. *Chemosphere*, *245*, 125607.

Ataei, S., Yahya, R., and Gan, S. N. (2011). Fast physical drying, high water and salt resistant coatings from non-drying vegetable oil. *Progress in Organic Coatings*, *72*(4), 703–708.

Balaraju, J.N., Radhakrishnan, P., V.Ezhilselvi, Kumar, A. A., Chen, Z., and K.P.Surendran. (2016). Studies on electroless nickel polyalloy coatings over carbon fibers/CFRP composites. *Surface and Coatings Technology*, *302*, 389–397.

Bandyopadhyay, P., Park, W. B., Layek, R. K., Uddin, E., Kim, N. H., Kim, H., and Lee, J. H. (2015). Author ' s Accepted Manuscript. *Journal of Membrane Science*.

Bao, C., Guo, Y., Song, L., Kan, Y., Qian, X., and Hu, Y. (2011). In situ preparation of functionalized graphene oxide/epoxy nanocomposites with effective reinforcements. *Journal of Materials Chemistry*, *21*(35), 13290–13298.

Berhanuddin, N. I. C., Zaman, I., Rozlan, S. A. M., Karim, M. A. A., Manshoor, B., Khalid, A., Chan, S. W., and Meng, Q. (2017). Enhancement of mechanical properties of epoxy/graphene nanocomposite. *Journal of Physics: Conference Series*, *914*(1). https://doi.org/10.1088/1742-6596/914/1/012036

Bertuoli, P. T., Piazza, D., Scienza, L. C., and Zattera, A. J. (2014). Preparation and characterization of montmorillonite modified with 3-aminopropyltriethoxysilane. *Applied Clay Science*, *87*, 46–51.

Bouibed, A., and Doufnoune, R. (2019). Synthesis and characterization of hybrid materials based on graphene oxide and silica nanoparticles and their effect on the corrosion protection properties of epoxy resin coatings. *Journal of Adhesion Science and Technology*, *33*(8), 834–860.

Brostow, W., Dutta, M., and Rusek, P. (2010). Modified epoxy coatings on mild steel: Tribology and surface energy. *European Polymer Journal*, *46*(11), 2181–2189.

Buchheit, R. G., Mamidipally, S. B., Schmutz, P., and Guan, H. (2002). Active corrosion protection in Ce-modified hydrotalcite conversion coatings. *Corrosion*, *58*(1), 3–14.

Bunaciu, A. A., Udriştioiu, E. gabriela, and Aboul-Enein, H. Y. (2015). X-Ray Diffraction: Instrumentation and Applications. *Critical Reviews in Analytical Chemistry*, *45*(4), 289–299.

Cai, K., Zuo, S., Luo, S., Yao, C., Liu, W., Ma, J., Mao, H., and Li, Z. (2016). Preparation of polyaniline/graphene composites with excellent anti-corrosion properties and their application in waterborne polyurethane anticorrosive coatings. *RSC Advances*, *6*(98), 95965–95972.

Camargo, P. H. C., Satyanarayana, K. G., and Wypych, F. (2009). Nanocomposites: Synthesis, structure, properties and new application opportunities. *Materials Research*, *12*(1), 1–39.

Cambridge, E., and Science, N. C. (2012). *Overvew of Corrosion Science , Engineering and Technology Chapter 1 : Overview of Corrosion Science*.

Campbell, B., and Manning, J. (2018). The rise of victimhood culture: Microaggressions, safe spaces, and the new culture wars. *The Rise of Victimhood Culture: Microaggressions, Safe Spaces, and the New Culture Wars*, 1–265.

Carreira, L. G., Mendes, L. C., Ribeiro, M. R. G., and Sebastião, P. J. (2013). Organically-Expanded Graphite/Octadecylamine: Structural, Thermal and Relaxation Evaluation. *Materials Sciences and Applications*, *04*(05), 281–286.

Chang, C. H., Huang, T. C., Peng, C. W., Yeh, T. C., Lu, H. I., Hung, W. I., Weng, C. J., Yang, T. I., and Yeh, J. M. (2012). Novel anticorrosion coatings prepared from polyaniline/graphene composites. *Carbon*, *50*(14), 5044–5051.

Chang, K. C., Ji, W. F., Li, C. W., Chang, C. H., Peng, Y. Y., Yeh, J. M., and Liu, W. R. (2014). The effect of varying carboxylic-group content in reduced graphene oxides on the anticorrosive properties of PMMA/reduced graphene oxide composites. *Express Polymer Letters*, *8*(12), 908–919.

Chattopadhyay, D. K., Panda, S. S., and Raju, K. V. S. N. (2005). Thermal and mechanical properties of epoxy acrylate/methacrylates UV cured coatings. *Progress in Organic Coatings*, *54*(1), 10–19.

Chen, C., Qiu, S., Cui, M., Qin, S., Yan, G., Zhao, H., Wang, L., and Xue, Q. (2017). Achieving high performance corrosion and wear resistant epoxy coatings via incorporation of noncovalent functionalized graphene. *Carbon*, *114*, 356–366.

Chen, D., Wang, X., Liu, T., Wang, X., and Li, J. (2010). Electrically conductive poly(vinyl alcohol) hybrid films containing graphene and layered double hydroxide fabricated via layer-by-layer self-assembly. *ACS Applied Materials and Interfaces*, *2*(7), 2005–2011.

Chen, F., Clough, A., Reinhard, B. M., Grinsta, M. W., Jiang, N., Koga, T., and Tsui, O. K. C. (2013). *Glass Transition Temperature of Polymer − Nanoparticle Composites : E ff ect of Polymer − Particle Interfacial Energy*.

Chen, J., Li, Y., Huang, L., Li, C., and Shi, G. (2015). High-yield preparation of graphene oxide from small graphite flakes via an improved Hummers method with a simple purification process. *Carbon*, *81*(1), 826–834.

Chen, J., Yao, B., Li, C., and Shi, G. (2013). An improved Hummers method for eco-friendly synthesis of graphene oxide. *Carbon*, *64*(1), 225–229.

Chen, W., Weimin, H., Li, D., Chen, S., and Dai, Z. (2018). A critical review on the development and performance of polymer/graphene nanocomposites. *Science and Engineering of Composite Materials*, *25*(6), 1059–1073.

Chieng, B. W., Ibrahim, N. A., Daud, N. A., and Talib, Z. A. (2019). Functionalization of Graphene Oxide via Gamma-Ray Irradiation for Hydrophobic Materials. In *Synthesis, Technology and Applications of Carbon Nanomaterials*. Elsevier Inc.

Chmielewski, A. G., and Haji-Saeid, M. (2004). Radiation technologies: Past, present and future. *Radiation Physics and Chemistry*, *71*(1–2), 17–21.

Chmielewski, Andrzej G., Haji-Saeid, M., and Ahmed, S. (2005). Progress in radiation processing of polymers. *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms*, *236*(1–4), 44–54.

Cho, J. S., Jang, W., Mun, S. C., Yi, M., Park, J. H., and Wang, D. H. (2018). Tuning surface chemistry and morphology of graphene oxide by γ-ray irradiation for improved performance of perovskite photovoltaics. *Carbon*, *139*, 564–571.

Choi, W., Lahiri, I., Seelaboyina, R., and Kang, Y. S. (2010). Synthesis of graphene and its applications: A review. *Critical Reviews in Solid State and Materials Sciences*, *35*(1), 52–71.

Chua, C. K., and Pumera, M. (2014). Chemical reduction of graphene oxide: A synthetic chemistry viewpoint. *Chemical Society Reviews*, *43*(1), 291–312.

Corrosion, E. (2009). Introduction and Aim. *Acta Medica Scandinavica*, *166*(S349), 7–9.

Čubová, K., and Čuba, V. (2020). Synthesis of inorganic nanoparticles by ionizing radiation – a review. *Radiation Physics and Chemistry*, *169*(February 2019), 108774.

Cui, G., Bi, Z., Zhang, R., Liu, J., Yu, X., and Li, Z. (2019). A comprehensive review on graphene-based anti-corrosive coatings. *Chemical Engineering Journal*, *373*(66), 104–121.

Cui, Y., Kundalwal, S. I., and Kumar, S. (2016). Gas barrier performance of graphene/polymer nanocomposites. *Carbon*, *98*, 313–333.

Damian, C. M., Vulcan, M. A., and Iovu, H. (2016). Graphene oxide functionalization with silanes for advanced compatibility in epoxy nanocomposites. *UPB Scientific Bulletin, Series B: Chemistry and Materials Science*, *78*(1), 79–88.

Dante, V. (2010). *2 . 07 Galvanic Corrosion*. 828–856.

Dawes, K., Glover, L. C., and Vroom, D. A. (2007). The Effects of Electron Beam and g-Irradiation on Polymeric Materials. *Physical Properties of Polymers Handbook*, 867–887.

de Wit, J. H. W., van der Weijde, D. H., and Ferrari, G. (2011). Organic coatings. *Corrosion Mechanisms in Theory and Practice: Third Edition*, 863–906.

Dimiev, A. M., Shukhina, K., and Khannanov, A. (2020). Mechanism of the graphene oxide formation. The role of water, "reversibility" of the oxidation, and mobility of the C–O bonds. *Carbon*, *166*, 1–14.

Drobny, J. G. (2013). Fundamentals of Radiation Chemistry and Physics. *Ionizing Radiation and Polymers*, 11–26.

Dugas, V., and Chevalier, Y. (2003). Surface hydroxylation and silane grafting on fumed and thermal silica. *Journal of Colloid and Interface Science*, *264*(2), 354–361.

Dugas, V., and Chevalier, Y. (2011). Chemical reactions in dense monolayers: In situ thermal cleavage of grafted esters for preparation of solid surfaces functionalized with carboxylic acids. *Langmuir*, *27*(23), 14188–14200.

Dumée, L. F., Feng, C., He, L., Allioux, F. M., Yi, Z., Gao, W., Banos, C., Davies, J. B., and Kong, L. (2014). Tuning the grade of graphene: Gamma ray irradiation of free-standing graphene oxide films in gaseous phase. *Applied Surface Science*, *322*, 126–135.

Dumée, L. F., Feng, C., He, L., Yi, Z., She, F., Peng, Z., Gao, W., Banos, C., Davies, J. B., Huynh, C., Hawkins, S., Duke, M. C., Gray, S., Hodgson, P. D., and Kong, L. (2014). Single step preparation of meso-porous and reduced graphene oxide by gamma-ray irradiation in gaseous phase. *Carbon*, *70*, 313–318.

Eliyan, F. F., and Alfantazi, A. (2014). Mechanisms of corrosion and electrochemical significance of metallurgy and environment with corrosion of iron and steel in bicarbonate and carbonate solutions - A review. *Corrosion*, *70*(9), 880–898.

Espiritu, R., Mamlouk, M., and Scott, K. (2016). Study on the effect of the degree of grafting on the performance of polyethylene-based anion exchange membrane for fuel cell application. *International Journal of Hydrogen Energy*, *41*(2), 1120–1133.

Fan, M., Liu, J., Li, X., Cheng, J., and Zhang, J. (2013). Curing behaviors and properties of an extrinsic toughened epoxy/anhydride system and an intrinsic toughened epoxy/anhydride system. *Thermochimica Acta*, *554*, 39–47.

Fayomi, O. S. I., Akande, I. G., and Odigie, S. (2019). Economic Impact of Corrosion in Oil Sectors and Prevention: An Overview. *Journal of Physics: Conference Series*, *1378*(2).

Fayomi, O. S. I., Akande, I. G., and Sode, A. A. (2019). Corrosion Prevention of Metals via Electroless Nickel Coating: A review. *Journal of Physics: Conference Series*, *1378*(2).

Fayomi, O. S. I., Oluwadare, G. A., Fakehinde, O. B., Akande, I. G., Nwachia, W., Oziegbe, U., and Russell, A. J. (2019). Evolution of physical and mechanical characteristics of deposited composite coatings on A356 mild steel. *International Journal of Advanced Manufacturing Technology*, *103*(5–8), 2621–2625.

Ferrari, A. C., Meyer, J. C., Scardaci, V., Casiraghi, C., Lazzeri, M., Mauri, F., Piscanec, S., Jiang, D., Novoselov, K. S., Roth, S., and Geim, A. K. (2006). Raman spectrum of graphene and graphene layers. *Physical Review Letters*, *97*(18), 1–4.

Ferreira, F. V., Brito, F. S., Franceschi, W., Simonetti, E. A. N., Cividanes, L. S., Chipara, M., and Lozano, K. (2018). Functionalized graphene oxide as reinforcement in epoxy based nanocomposites. *Surfaces and Interfaces*, *10*(December 2017), 100–109.

Finšgar, M., and Jackson, J. (2014). Application of corrosion inhibitors for steels in acidic media for the oil and gas industry: A review. *Corrosion Science*, *86*, 17–41.

Fiore, V., Scalici, T., Vitale, G., and Valenza, A. (2014). Static and dynamic mechanical properties of Arundo Donax fillers-epoxy composites. *Materials and Design*, *57*, 456–464.

Flores-Rojas, G. G., López-Saucedo, F., and Bucio, E. (2020). Gamma-irradiation applied in the synthesis of metallic and organic nanoparticles: A short review. *Radiation Physics and Chemistry*, *169*.

Frigione, M., and Lettieri, M. (2020). Recent Advances and Trends of Nanofilled/Nanostructured Epoxies. *Materials*, *13*(15), 3415.

Gao, N., Liu, W., Yan, Z., and Wang, Z. (2013). Synthesis and properties of transparent cycloaliphatic epoxy-silicone resins for opto-electronic devices packaging. *Optical Materials*, *35*(3), 567–575.

Gao W. (2015). *Synthesis, Structure, and Characterizations. Graphene Oxide Reduction Recipes, Spectroscopy and Applications*.

Ghanbari, A., and Attar, M. M. (2015). A study on the anticorrosion performance of epoxy nanocomposite coatings containing epoxy-silane treated nano-silica on mild steel substrate. *Journal of Industrial and Engineering Chemistry*, *23*, 145–153.

Gharibi, R., Yousefi, M., and Yeganeh, H. (2013). Synthesis, characterization and assessment of poly(urethane-co-pyrrole)s derived from castor oil as anticorrosion coatings for stainless steel. *Progress in Organic Coatings*, *76*(10), 1454–1464.

Ghodrati, S., Mahmoodi, A., and Mohseni, M. (2018). Modification and characterization of an Iranian montmorillonite as a corrosion/mechanical promoter for epoxy coatings. *Clay Minerals*, *53*(4), 603–620.

Ghoreishian, S. M., Kang, S. M., Seeta Rama Raju, G., Norouzi, M., Jang, S. C., Yun, H. J., Lim, S. T., Han, Y. K., Roh, C., and Huh, Y. S. (2019). γ-Radiolysis as a highly efficient green approach to the synthesis of metal nanoclusters: A review of mechanisms and applications. *Chemical Engineering Journal*, *360*, 1390–1406.

Gibson, G. (2017). Epoxy Resins. *Brydson's Plastics Materials: Eighth Edition*, 773–797.

Golaz, B., Michaud, V., and Månson, J. A. E. (2013). Photo-polymerized epoxy primer for adhesion improvement at thermoplastics/metallic wires interfaces. *Composites Part A: Applied Science and Manufacturing*, *48*(1), 171–180.

Golling, F. E., Pires, R., Hecking, A., Weikard, J., Richter, F., Danielmeier, K., and Dijkstra, D. (2019). Polyurethanes for coatings and adhesives – chemistry and applications. *Polymer International*, *68*(5), 848–855.

Gonçalves, P. A. D., and Peres, N. M. R. (2016). An Introduction to Graphene Plasmonics. *An Introduction to Graphene Plasmonics*, 1–431.

Grundmeier, G., Rossenbeck, B., Roschmann, K. J., Ebbinghaus, P., and Stratmann, M. (2006). Corrosion protection of Zn-phosphate containing water borne dispersion coatings. Part 2: Investigations of the corrosive de-adhesion of model latex coatings on iron. *Corrosion Science*, *48*(11), 3716–3730.

Gu, H., Ma, C., Gu, J., Guo, J., Yan, X., Huang, J., Zhang, Q., and Guo, Z. (2016). An overview of multifunctional epoxy nanocomposites. *Journal of Materials Chemistry C*, *4*(25), 5890–5906.

Guo, B., Jia, D., Fu, W., and Qiu, Q. (2003). Hygrothermal stability of dicyanate-novolac epoxy resin blends. *Polymer Degradation and Stability*, *79*(3), 521–528.

Guo, Z., Shin, K., Karki, A. B., Young, D. P., Kaner, R. B., and Hahn, H. T. (2009). Fabrication and characterization of iron oxide nanoparticles filled polypyrrole nanocomposites. *Journal of Nanoparticle Research*, *11*(6), 1441–1452.

Gupta, B., Kumar, N., Panda, K., Melvin, A. A., Joshi, S., Dash, S., and Tyagi, A. K. (2016). Effective Noncovalent Functionalization of Poly(ethylene glycol) to Reduced Graphene Oxide Nanosheets through γ-Radiolysis for Enhanced Lubrication. *Journal of Physical Chemistry C*, *120*(4), 2139–2148.

Gurzęda, B., Florczak, P., Kempiński, M., Peplińska, B., Krawczyk, P., and Jurga, S. (2016). Synthesis of graphite oxide by electrochemical oxidation in aqueous perchloric acid. *Carbon*, *100*, 540–545.

Hack, R., Correia, C. H. G., Zanon, R. A. D. S., and Pezzin, S. H. (2018). Characterization of graphene nanosheets obtained by a modified hummer's method. *Revista Materia*, *23*(1).

Hameed, K. W., Yaro, A. S., and Khadom, A. A. (2016). Mathematical model for cathodic protection in a steel-saline water system. *Journal of Taibah University for Science*, *10*(1), 64–69.

Hart, E. (2016). Corrosion inhibitors: Principles, mechanisms and applications. *Corrosion Inhibitors: Principles, Mechanisms and Applications*, 1–161.

Heiyantuduwa, R., Alexander, M. G., and Mackechnie, J. R. (2006). Performance of a penetrating corrosion nihibitor in concrete fafected by carbonation-induced corrosion. *Journal of Materials in Civil Engineering*, *18*(6), 842–850.

Hong Phan, D. T. (2018). CORROSION RESISTANCE AND MECHANICAL PROPERTIES OF TiO2 NANOTUBES / EPOXY COATING ON STEEL SPCC-JISG 3141. *Vietnam Journal of Science and Technology*, *55*(5B), 203.

Hsu, Y. G., Lin, K. H., Lin, T. Y., Fang, Y. L., Chen, S. C., and Sung, Y. C. (2012). Properties of epoxy-amine networks containing nanostructured ether-crosslinked domains. *Materials Chemistry and Physics*, *132*(2–3), 688–702.

Hu, H., Zhao, S., Sun, G., Zhong, Y., and You, B. (2018). Evaluation of scratch resistance of functionalized graphene oxide/polysiloxane nanocomposite coatings. *Progress in Organic Coatings*, *117*(June 2017), 118–129.

Hussain, A. K., Sudin, I., Basheer, U. M., and Yusop, M. Z. M. (2019). A review on graphene-based polymer composite coatings for the corrosion protection of metals. *Corrosion Reviews*, *37*(4), 343–363.

Inam, F., Heaton, A., Brown, P., Peijs, T., and Reece, M. J. (2014). Effects of dispersion surfactants on the properties of ceramic-carbon nanotube (CNT) nanocomposites. *Ceramics International*, *40*(1 PART A), 511–516.

Ionita, M., Pandele, M. A., and Iovu, H. (2013). Sodium alginate/graphene oxide composite films with enhanced thermal and mechanical properties. *Carbohydrate Polymers*, *94*(1), 339–344.

Javidparvar, A. A., Naderi, R., and Ramezanzadeh, B. (2020). L-cysteine reduced/functionalized graphene oxide application as a smart/control release nanocarrier of sustainable cerium ions for epoxy coating anti-corrosion properties improvement. *Journal of Hazardous Materials*, *389*(January), 122135.

Jegdić, B., Popić, J., Bobić, B., and Stevanović, M. (2016). Chemical corrosion of metals and alloys. *Zastita Materijala*, *57*(2), 205–211.

Ji, W. G., Hu, J. M., Zhang, J. Q., and Cao, C. N. (2006). Reducing the water absorption in epoxy coatings by silane monomer incorporation. *Corrosion Science*, *48*(11), 3731–3739.

Jin, F. L., Li, X., and Park, S. J. (2015). Synthesis and application of epoxy resins: A review. *Journal of Industrial and Engineering Chemistry*, *29*, 1–11.

Jin, F. L., and Park, S. J. (2008). Interfacial toughness properties of trifunctional epoxy resins/calcium carbonate nanocomposites. *Materials Science and Engineering A*, *475*(1–2), 190–193.

Jin, F. L., and Park, S. J. (2012). Thermal properties of epoxy resin/filler hybrid composites. *Polymer Degradation and Stability*, *97*(11), 2148–2153.

Jin, T., Han, Y., Bai, R., and Liu, X. (2017). Corrosion Protection Properties of Nano NH 2 -Reduced Graphene Oxide/Epoxy Composite Coatings Formed by Self-Curing on Magnesium Alloy . *Journal of Nanoscience and Nanotechnology*, *18*(7), 4971–4981.

Jing, Q., Liu, W., Pan, Y., Silberschmidt, V. V., Li, L., and Dong, Z. L. (2015). Chemical functionalization of graphene oxide for improving mechanical and thermal properties of polyurethane composites. *Materials and Design*, *85*, 808–814.

Jung, C., Hong, J., Jung, J., Hwang, I., Jung, C., and Choi, J. (2015). *Preparation of sulfonated reduced graphene oxide by radiation- induced chemical reduction of sulfonated graphene oxide*. *16*(1), 41–44.

Kadhim, M. G., and Ali, M. T. (2017). A Critical Review on Corrosion and its Prevention in the Oil Field Equipment. *Journal of Petroleum Research & Studies*, *14*, 1–28.

Kaliavaradhan, K., Rukmanikrishnan, B., and Muthusamy, S. (2018). Investigation of the effect of graphene oxide on the properties of epoxy-phthalonitrile nanocomposites. *Advances in Polymer Technology*, *37*(5), 1256–1267.

Karthik, D., Kalainathan, S., and Swaroop, S. (2015). Surface & Coatings Technology Surface modi fi cation of 17-4 PH stainless steel by laser peening without protective coating process. *Surface & Coatings Technology*, *278*, 138–145.

Kausar, A. (2019). Corrosion prevention prospects of polymeric nanocomposites: A review. *Journal of Plastic Film and Sheeting*, *35*(2), 181–202.

Khezri, T., Sharif, M., and Pourabas, B. (2016). Polythiophene-graphene oxide doped epoxy resin nanocomposites with enhanced electrical, mechanical and thermal properties. *RSC Advances*, *6*(96), 93680–93693.

Khodadadi Dizaji, A., Mortaheb, H. R., and Mokhtarani, B. (2016). Noncovalently functionalized graphene oxide/graphene with imidazolium-based ionic liquids for adsorptive removal of dibenzothiophene from model fuel. *Journal of Materials Science*, *51*(22), 10092–10103.

Kim, M., Kim, Y., Baeck, S. H., and Shim, S. E. (2015). Effect of surface treatment of graphene nanoplatelets for improvement of thermal and electrical properties of epoxy composites. *Carbon Letters*, *16*(1), 34–40.

Kiran, N. U., Dey, S., Singh, B. P., and Besra, L. (2017). Graphene coating on copper by electrophoretic deposition for corrosion prevention. *Coatings*, *7*(12).

Klunbud, P., Suktha, P., and Sawangphruk, M. (2017). Decoration of graphene oxide nanosheets with amino silane-functionalized silica nanoparticles for enhancing thermal and mechanical properties of polypropylene nanocomposites. *Journal of Applied Polymer Science*, *134*(2).

Koch, G., Brongers, M., Thompson, N., Virmani, P. (2002). Corrosion Cost and Preventive. In *Technical Report USA* (Issue March).

Koch, G., Varney, J., Thopson, N., Moghissi, O., Gould, M., and Payer, J. (2016). International Measures of Prevention , Application , and Economics of Corrosion Technologies Study. *NACE International*, 1–216.

Kondratova, I. L., Montes, P., and Bremner, T. W. (2003). Natural marine exposure results for reinforced concrete slabs with corrosion inhibitors. *Cement and Concrete Composites*, *25*(4-5 SPEC), 483–490.

Kuila, T., Bose, S., Mishra, A. K., Khanra, P., Kim, N. H., and Lee, J. H. (2012). Chemical functionalization of graphene and its applications. *Progress in Materials Science*, *57*(7), 1061–1105.

Kumar, M. P., Kesavan, T., Kalita, G., Ragupathy, P., Narayanan, T. N., and Pattanayak, D. K. (2014). On the large capacitance of nitrogen doped graphene derived by a facile route. *RSC Advances*, *4*(73), 38689–38697.

Kumar, N. A., Choi, H. J., Shin, Y. R., Chang, D. W., Dai, L., and Baek, J. B. (2012). Polyaniline-grafted reduced graphene oxide for efficient electrochemical supercapacitors. *ACS Nano*, *6*(2), 1715–1723.

Layek, R. K., and Nandi, A. K. (2013). A review on synthesis and properties of polymer functionalized graphene. *Polymer*, *54*(19), 5087–5103.

Lee, C., Wei, X., Kysar, J. W., and Hone, J. (2008). Measurement of the elastic properties and intrinsic strength of monolayer graphene. *Science*, *321*(5887), 385–388.

Lee, C. Y., Bae, J. H., Kim, T. Y., Chang, S. H., and Kim, S. Y. (2015). Using silane-functionalized graphene oxides for enhancing the interfacial bonding strength of carbon/epoxy composites. *Composites Part A: Applied Science and Manufacturing*, *75*, 11–17.

Lee, H.-S., Saraswathy, V., Kwon, S.-J., and Karthick, S. (2018). Corrosion Inhibitors for Reinforced Concrete: A Review. *Corrosion Inhibitors, Principles and Recent Applications*.

Lee, J. R., Jin, F. L., Park, S. J., and Park, J. M. (2004). Study of new fluorine-containing epoxy resin for low dielectric constant. *Surface and Coatings Technology*, *180–181*, 650–654.

Li, J., Cui, J., Yang, J., Li, Y., Qiu, H., and Yang, J. (2016). Reinforcement of graphene and its derivatives on the anticorrosive properties of waterborne polyurethane coatings. *Composites Science and Technology*, *129*, 30–37.

Li, W., Zhou, B., Wang, M., Li, Z., and Ren, R. (2015a). Silane functionalization of graphene oxide and its use as a reinforcement in bismaleimide composites. *Journal of Materials Science*, *50*(16), 5402–5410.

Li, W., Zhou, B., Wang, M., Li, Z., and Ren, R. (2015b). Silane functionalization of graphene oxide and its use as a reinforcement in bismaleimide composites. *Journal of Materials Science*, *50*(16), 5402–5410.

Li, Y., Huang, X., Zeng, L., Li, R., Tian, H., Fu, X., Wang, Y., and Zhong, W. H. (2019). A review of the electrical and mechanical properties of carbon nanofiller-reinforced polymer composites. *Journal of Materials Science*, *54*(2), 1036–1076.

Liu, H., Cooper, V. R., Dai, S., and Jiang, D. E. (2012). Windowed carbon nanotubes for efficient CO2 removal from natural gas. *Journal of Physical Chemistry Letters*, *3*(22), 3343–3347.

Liu, W., and Wang, Z. (2011). Silicon-containing cycloaliphatic epoxy resins with systematically varied functionalities: Synthesis and structure/property relationships. *Macromolecular Chemistry and Physics*, *212*(9), 926–936.

Liu, Y., Zhang, Y., and Yuan, J. (2014). Influence of produced water with high salinity and corrosion inhibitors on the corrosion of water injection pipe in Tuha oil field. *Engineering Failure Analysis*, *45*, 225–233.

Lling-Lling Tan, Wee-Jun Ong, Siang-Piao Chai, and Abdul Rahman Moha. (2013). Reduced graphene oxide-TiO 2 nanocomposite as a promising visible-light-active photocatalyst for the conversion of carbon dioxide. *Nanoscale Research Letters*, *8*(465), 1–9.

Ma, J., Meng, Q., Zaman, I., Zhu, S., Michelmore, A., Kawashima, N., Wang, C. H., and Kuan, H. C. (2014). Development of polymer composites using modified, high-structural integrity graphene platelets. *Composites Science and Technology*, *91*, 82–90.

Ma, P. C., Kim, J. K., and Tang, B. Z. (2007). Effects of silane functionalization on the properties of carbon nanotube/epoxy nanocomposites. *Composites Science and Technology*, *67*(14), 2965–2972.

Ma, W. S., Li, J., Deng, B. J., and Zhao, X. S. (2013). Preparation and characterization of long-chain alkyl silane-functionalized graphene film. *Journal of Materials Science*, *48*(1), 156–161.

Makuuchi, K., and Cheng, S. (2011). Trends in Applications and Future Prospect. *Radiation Processing of Polymer Materials and Its Industrial Applications*, 373–400.

Mandal, M., Maitra, A., Das, T., and Das, C. K. (2015). *Part 1 FUNDAMENTALS OF GRAPHENE AND GRAPHENE- Graphene and Related*.

Mansor, Y., Mansor, S., Zulhaidi, H., Rahman, A., and Isola, A. I. (2018). *INSTITUTE FOR DEFENCE (STRIDE) Nor Hafizah bt Mohamed*. *11*.

Mansouri, H. (2014). PH effect microbial corrosion of Corten steel and Carbon steel in oily waste water with Pseudomonas Aeruginosa. *IOSR Journal of Engineering*, *4*(1), 28–32.

Marcus, P., and Maurice, V. (2009). Fundamental aspects of corrosion of metallic materials. u: Material Science and Engineering, USA. *Encyclopedia of Life Support Systems*, *II*, 99–133.

Mathialagan, M., and Ismail, H. (2012). Optimization and Effect of 3-Aminopropyltriethoxysilane Content on the Properties of Bentonite-Filled Ethylene Propylene Diene Monomer Composites M. *Polymers and Polymer Composites*, *16*(2), 101–113.

Matinlinna, J. P., Vallittu, P. K., and Lassila, L. V. A. (2011). Effects of different silane coupling agent monomers on flexural strength of an experimental filled resin composite. *Journal of Adhesion Science and Technology*, *25*(1–3), 179–192.

Mauro, M., Maggio, M., Cipolletti, V., Galimberti, M., Longo, P., and Guerra, G. (2013). Graphite oxide intercalation compounds with rotator hexagonal order in the intercalated layers. *Carbon*, *61*, 395–403.

Mcallister, M. J., Li, J., Adamson, D. H., Schniepp, H. C., Abdala, A. a, Liu, J., Herrera-alonso, O. M., Milius, D. L., Car, R., Prud, R. K., and Aksay, I. a. (2007). Expansion of Graphite. *Society*, *19*(4), 4396–4404.

McCafferty, E.(2010). Thermodynamics of Corrosion: Introduction to Corrosion Science. *Springer, New York, NY*, 328.

Mekki Abdelmouleh, Sami Boufi, Abdelhamid ben Salah, M. N. B. and A. G. (2002). Interaction of silane coupling agents with cellulose. *Langmuir*, *18*(8), 3203–3208.

Mittal, G., Dhand, V., Rhee, K. Y., Park, S. J., and Lee, W. R. (2015). A review on carbon nanotubes and graphene as fillers in reinforced polymer nanocomposites. *Journal of Industrial and Engineering Chemistry*, *21*, 11–25.

Mo, M., Zhao, W., Chen, Z., Yu, Q., Zeng, Z., Wu, X., and Xue, Q. (2015). Excellent tribological and anti-corrosion performance of polyurethane composite coatings reinforced with functionalized graphene and graphene oxide nanosheets. *RSC Advances*, *5*(70), 56486–56497.

Mohan, B., Bisht, S., Bhandari, H., Sambyal, P., Gairola, S. P., and Dhawan, S. K. (2016). *Highly Durable and Novel Anticorrosive Coating Based on Epoxy Reinforced with Poly (Aniline-co-Pentafluoroaniline)/ SiO 2 Composite*. *6*(3), 75–85.

Monetta, T., Acquesta, A., and Bellucci, F. (2015). Graphene/Epoxy Coating as Multifunctional Material for Aircraft Structures. *Aerospace*, *2*(3), 423–434.

Moriche, R., Sánchez, M., Jiménez-Suárez, A., Prolongo, S. G., and Ureña, A. (2016). Electrically conductive functionalized-GNP/epoxy based composites: From nanocomposite to multiscale glass fibre composite material. *Composites Part B: Engineering*, *98*, 49–55.

Mousaa, I. M., Ibrahim, S. M., and Radi, H. (2014). Coating Characteristics of UV Curable Epoxy Acrylate Oligomer Modified with Acrylated Sunflower Oil. *Arab Journal of Nuclear Science and Application*, *47*(1), 1–13.

Mousavi, M., and Fini, E. (2020). Silanization Mechanism of Silica Nanoparticles in Bitumen Using 3-Aminopropyl Triethoxysilane (APTES) and 3-Glycidyloxypropyl Trimethoxysilane (GPTMS). *ACS Sustainable Chemistry and Engineering*, *8*(8), 3231–3240.

Muradyan, V. E., Arbuzov, A. A., Sokolov, E. A., Babenko, S. D., and Bondarenko, G. V. (2013). The effect of addition of functionalized graphene oxide on the dielectric properties of epoxy composite. *Technical Physics Letters*, *39*(9), 798–800.

Mustafa, D. M. T., Rostam, S., and Aziz, S. B. (2020). A Comparative Study on Structural, Morphological, and Tensile Properties of Binary and Ternary Epoxy Resin-Based Polymer Nanocomposites. *Advances in Materials Science and Engineering*, *2020*, 1–11.

Naebe, M., Wang, J., Amini, A., Khayyam, H., Hameed, N., Li, L. H., Chen, Y., and Fox, B. (2014). Mechanical Property and Structure of Covalent Functionalised Graphene/Epoxy Nanocomposites. *Scientific Reports*, *4*, 1–7.

Naik, R. B., Jagtap, S. B., and Ratna, D. (2015). Effect of carbon nanofillers on anticorrosive and physico-mechanical properties of hyperbranched urethane alkyd coatings. *Progress in Organic Coatings*, *87*, 28–35.

Nasir, A., Raza, A., Tahir, M., and Yasin, T. (2020). Free-radical graft polymerization of acrylonitrile on gamma irradiated graphene oxide: Synthesis and characterization. *Materials Chemistry and Physics*, *246*(February), 122807.

Nguyen-Tri, P., Nguyen, T. A., Carriere, P., and Ngo Xuan, C. (2018). Nanocomposite Coatings: Preparation, Characterization, Properties, and Applications. *International Journal of Corrosion*, *2018*(ii), 1–19.

Nine, M. J., Cole, M. A., Tran, D. N. H., and Losic, D. (2013). Specifically Focuses on the Most Recent Advances in the Application of Graphene for Corrosion Resistant Coatings, Flame Retardant Coatings, Wear/Scratch Resistant Coatings, Anti-Fouling Coatings, Pollutant Adsorption Coatings and Anti-Septic Coatings. *J. Name*, *00*, 1–3.

Nuraje, N., Khan, S. I., Misak, H., and Asmatulu, R. (2013). The Addition of Graphene to Polymer Coatings for Improved Weathering. *ISRN Polymer Science*, *2013*, 1–8.

Nwabanne, J. T., and Okafor, V. N. (2012). Adsorption and Thermodynamics Study of the Inhibition of Corrosion of Mild Steel in H2SO4 Medium Using Vernonia amygdalina. *Journal of Minerals and Materials Characterization and Engineering*, *11*(09), 885–890.

Ogle, K., and Weber, S. (2000). Anodic Dissolution of 304 Stainless Steel Using Atomic Emission Spectroelectrochemistry. *Journal of The Electrochemical Society*, *147*(5), 1770.

Othman, N. H., Che Ismail, M., Mustapha, M., Sallih, N., Kee, K. E., and Ahmad Jaal, R. (2019). Graphene-based polymer nanocomposites as barrier coatings for corrosion protection. *Progress in Organic Coatings*, *135*(January), 82–99.

Ozcan, U. E., Karabork, F., Yazman, S., and Akdemir, A. (2019). Effect of Silica/Graphene Nanohybrid Particles on the Mechanical Properties of Epoxy Coatings. *Arabian Journal for Science and Engineering*, *44*(6), 5723–5731.

Papageorgiou, D. G., Kinloch, I. A., and Young, R. J. (2017). Mechanical properties of graphene and graphene-based nanocomposites. *Progress in Materials Science*, *90*(July), 75–127.

Park, M. H., Kim, H. J., Kim, Y. J., Moon, T., and Hwang, C. S. (2014). The effects of crystallographic orientation and strain of thin Hf 0.5Zr0.5O2 film on its ferroelectricity. *Applied Physics Letters*, *104*(7), 16–21.

Park, S. J., and Jin, F. L. (2004). Thermal stabilities and dynamic mechanical properties of sulfone-containing epoxy resin cured with anhydride. *Polymer Degradation and Stability*, *86*(3), 515–520.

Park, S. J., Jin, F. L., and Lee, J. R. (2004). Thermal and mechanical properties of tetrafunctional epoxy resin toughened with epoxidized soybean oil. *Materials Science and Engineering A*, *374*(1–2), 109–114.

Park, S., and Ruoff, R. S. (2009). Chemical methods for the production of graphenes. *Nature Nanotechnology*, *4*(4), 217–224.

Pehkonen, S. O., and Yuan, S. (2018). Self-Assembly Ultrathin Film Coatings for the Mitigation of Corrosion: General Considerations. *Interface Science and Technology*, *23*, 13–21.

Plueddemann, E. P. (2000). *5 5.1*. 115–116.

Popoola, A., Olorunniwo, O., and Ige, O. (2014). Corrosion Resistance Through the Application of Anti- Corrosion Coatings. *Developments in Corrosion Protection*.

Popov, B. N. (2015). Corrosion Engineering: Principles and Solved Problems. *Corrosion Engineering: Principles and Solved Problems*, 1–774.

Potts, J. R., Dreyer, D. R., Bielawski, C. W., and Ruoff, R. S. (2011). Graphene-based polymer nanocomposites. In *Polymer* (Vol. 52, Issue 1).

Pourhashem, S., Rashidi, A., Vaezi, M. R., and Bagherzadeh, M. R. (2017a). Excellent corrosion protection performance of epoxy composite coatings filled with amino-silane functionalized graphene oxide. *Surface and Coatings Technology*, *317*, 1–9.

Pourhashem, S., Vaezi, M. R., and Rashidi, A. (2017). Investigating the effect of SiO2-graphene oxide hybrid as inorganic nanofiller on corrosion protection properties of epoxy coatings. *Surface and Coatings Technology*, *311*, 282–294.

Pourhashem, S., Vaezi, M. R., Rashidi, A., and Bagherzadeh, M. R. (2017a). Distinctive roles of silane coupling agents on the corrosion inhibition performance of graphene oxide in epoxy coatings. *Progress in Organic Coatings*, *111*(October 2016), 47–56.

Pourhashem, S., Vaezi, M. R., Rashidi, A., and Bagherzadeh, M. R. (2017b). Exploring corrosion protection properties of solvent based epoxy-graphene oxide nanocomposite coatings on mild steel. *Corrosion Science*, *115*, 78–92.

Prasad, A. R., Kunyankandy, A., Joseph, A., and Munzer, A. J. (2020). *Corrosion Inhibition in Oil and Gas Industry : Economic Considerations*. 135–150.

Prichard, A. L. (2012). *North Dakota State University By*. *May*.

Prošek, T. (2017). Mechanisms of degradation of organic coatings. *Koroze a Ochrana Materialu*, *61*(4), 155–161.

Pu, X., Zhang, H. Bin, Li, X., Gui, C., and Yu, Z. Z. (2014). Thermally conductive and electrically insulating epoxy nanocomposites with silica-coated graphene. *RSC Advances*, *4*(29), 15297–15303.

Qian, M., Mcintosh Soutar, A., Tan, X. H., Zeng, X. T., and Wijesinghe, S. L. (2009). Two-part epoxy-siloxane hybrid corrosion protection coatings for carbon steel. *Thin Solid Films*, *517*(17), 5237–5242.

Qiao, B., Wang, T. J., Gao, H., and Jin, Y. (2015). High density silanization of nano-silica particles using γ-aminopropyltriethoxysilane (APTES). *Applied Surface Science*, *351*, 646–654.

Qiu, S., Hu, W., Yu, B., Yuan, B., Zhu, Y., Jiang, S., Wang, B., Song, L., and Hu, Y. (2015). Effect of functionalized graphene oxide with organophosphorus oligomer on the thermal and mechanical properties and fire safety of polystyrene. *Industrial and Engineering Chemistry Research*, *54*(13), 3309–3319.

Qiu, S. L., Wang, C. S., Wang, Y. T., Liu, C. G., Chen, X. Y., Xie, H. F., Huang, Y. A., and Cheng, R. S. (2011). Effects of graphene oxides on the cure behaviors of a tetrafunctional epoxy resin. *Express Polymer Letters*, *5*(9), 809–818.

Rad, E. R., Vahabi, H., de Anda, A. R., Saeb, M. R., and Thomas, S. (2019). Bio-epoxy resins with inherent flame retardancy. *Progress in Organic Coatings*, *135*(March), 608–612.

Rafiee, M. A., Rafiee, J., Wang, Z., Song, H., Yu, Z. Z., and Koratkar, N. (2009). Enhanced mechanical properties of nanocomposites at low graphene content. *ACS Nano*, *3*(12), 3884–3890.

Rahman, O. U., Kashif, M., and Ahmad, S. (2015). Nanoferrite dispersed waterborne epoxy-acrylate: Anticorrosive nanocomposite coatings. *Progress in Organic Coatings*, *80*, 77–86.

Raja, P. B., Ismail, M., Ghoreishiamiri, S., Mirza, J., Ismail, M. C., Kakooei, S., and Rahim, A. A. (2016). Reviews on Corrosion Inhibitors: A Short View. *Chemical Engineering Communications*, *203*(9), 1145–1156.

Rajitha, K., Mohana, K. N. S., Mohanan, A., and Madhusudhana, A. M. (2020). Evaluation of anti-corrosion performance of modified gelatin-graphene oxide nanocomposite dispersed in epoxy coating on mild steel in saline media. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *587*(December 2019), 124341.

Ramananda Singh, M., Gupta, P., and Gupta, K. (2019). The litchi (Litchi Chinensis) peels extract as a potential green inhibitor in prevention of corrosion of mild steel in 0.5 M H2SO4 solution. *Arabian Journal of Chemistry*, *12*(7), 1035–1041.

Ramanathan, T., Abdala, A. A., Stankovich, S., Dikin, D. A., Herrera-Alonso, M., Piner, R. D., Adamson, D. H., Schniepp, H. C., Chen, X., Ruoff, R. S., Nguyen, S. T., Aksay, I. A., Prud'Homme, R. K., and Brinson, L. C. (2008). Functionalized graphene sheets for polymer nanocomposites. *Nature Nanotechnology*, *3*(6), 327–331.

Ramezanzadeh, B., Haeri, Z., and Ramezanzadeh, M. (2016). A facile route of making silica nanoparticles-covered graphene oxide nanohybrids (SiO2-GO); fabrication of SiO2-GO/epoxy composite coating with superior barrier and corrosion protection performance. *Chemical Engineering Journal*, *303*, 511–528.

Ramezanzadeh, B., Niroumandrad, S., Ahmadi, A., Mahdavian, M., and Mohamadzadeh Moghadam, M. H. (2016). Enhancement of barrier and corrosion protection performance of an epoxy coating through wet transfer of amino functionalized graphene oxide. *Corrosion Science*, *103*, 283–304.

Ramon, E., Sguazzo, C., and Moreira, P. M. G. P. (2018). A review of recent research on bio-based epoxy systems for engineering applications and potentialities in the aviation sector. *Aerospace*, *5*(4).

Randviir, E. P., Brownson, D. A. C., and Banks, C. E. (2014). A decade of graphene research: Production, applications and outlook. *Materials Today*, *17*(9), 426–432.

Ray, S. C. (2015). Application and Uses of Graphene Oxide and Reduced Graphene Oxide. In *Applications of Graphene and Graphene-Oxide Based Nanomaterials* (Issue ii). Elsevier Inc.

Rd, X., Qu, H., and Shi, B. (2017). *Open Access Chemical and Electrochemical Mechanisms behind Aqueous CO 2 Corrosion of Mild Steel- a Basic Review ZhenGuo*. *2*(5), 182–185.

Reina A, Jia X, Ho J, N. D., Son H, Bulovic V, Dresselhaus MS, and Kong J. (2009). Large area, few-layer graphene films on arbitrary substrates by chemical vapor deposition. *Nano Letters* , *9*, 30.

Relosi, N., Neuwald, O. A., Zattera, A. J., Piazza, D., Kunst, S. R., and Birriel, E. J. (2018). Effect of addition of clay minerals on the properties of epoxy/polyester powder coatings. *Polimeros*, *28*(4), 355–367.

Rossky, P. J. (2010). Exploring nanoscale hydrophobic hydration. *Faraday Discussions*, *146*, 13–18.

Salunkhe, B., and Rane, S. (2016). Treatise on conducting polymers for corrosion protection–advanced approach. *Conducting Polymers*, *January*, 61–81.

Sánchez, Y., Albano, C., Perera, R., Karam, A., and Silva, P. (2007). Characterization of LDPE grafted with Diethylmaleate by gamma radiation: Application of FTIR, GPC and SSA techniques. *Macromolecular Symposia*, *257*, 139–146.

Sangaj, N. S., and Malshe, V. C. (2004). Permeability of polymers in protective organic coatings. *Progress in Organic Coatings*, *50*(1), 28–39.

Saravanan, N., Rajasekar, R., Mahalakshmi, S., Sathishkumar, T. P., Sasikumar, K., and Sahoo, S. (2014). Graphene and modified graphene-based polymer nanocomposites - A review. *Journal of Reinforced Plastics and Composites*, *33*(12), 1158–1170.

Schaefer, K., and Miszczyk, A. (2013). Improvement of electrochemical action of zinc-rich paints by addition of nanoparticulate zinc. *Corrosion Science*, *66*, 380–391.

Shamaila, S., Sajjad, A. K. L., and Iqbal, A. (2016). Modifications in development of graphene oxide synthetic routes. *Chemical Engineering Journal*, *294*(February), 458–477.

Shan, J., Ahmed, I., Ghazali, A., and Khairuddean, M. (2014). Novel poly (alkyd-urethane) s from vegetable oils : Synthesis and properties. *Industrial Crops & Products*, *52*, 74–84.

Shanmugharaj, A. M., Bae, J. H., Lee, K. Y., Noh, W. H., Lee, S. H., and Ryu, S. H. (2007). *SCIENCE AND Physical and chemical characteristics of multiwalled carbon nanotubes functionalized with aminosilane and its influence on the properties of natural rubber composites*. *67*, 1813–1822.

Sharin, S., Rahman, I. A., Ahmad, A. F., Mohd, H. M. K., Mohamed, F., Radiman, S., Yasir, M. S., Sarmani, S., Ayob, M. T. M., and Bastamam, I. S. A. (2015). Reduction of graphene oxide to graphene by using gamma irradiation. *Malaysian Journal of Analytical Sciences*, *19*(6), 1223–1228.

Sharmin, E., Rahman, O. U., Zafar, F., Akram, D., Alam, M., and Ahmad, S. (2015). Linseed oil polyol/ZnO bionanocomposite towards mechanically robust, thermally stable, hydrophobic coatings: A novel synergistic approach utilising a sustainable resource. *RSC Advances*, *5*(59), 47928–47944.

Shen, G. X., Chen, Y. C., and Lin, C. J. (2005). Corrosion protection of 316 L stainless steel by a TiO2 nanoparticle coating prepared by sol-gel method. *Thin Solid Films*, *489*(1–2), 130–136.

Sheng, X., Cai, W., Zhong, L., Xie, D., and Zhang, X. (2016). *Synthesis of Functionalized Graphene / Polyaniline Nanocomposites with Effective Synergistic Reinforcement on Anticorrosion*.

Shi, M., Lin, T., Hu, Y., Peng, J., Li, J., and Zhai, M. (2020). Functionalization of graphene oxide by radiation grafting polyhedral oligomeric silsesquioxane with improved thermal stability and hydrophilicity. *Journal of Materials Science*, *55*(4), 1489–1498.

Shi, X., Nguyen, T. A., Suo, Z., Liu, Y., and Avci, R. (2009). Effect of nanoparticles on the anticorrosion and mechanical properties of epoxy coating. *Surface and Coatings Technology*, *204*(3), 237–245.

Shokoohi, S., Arefazar, A., and Khosrokhavar, R. (2008). Silane coupling agents in polymer-based reinforced composites: A review. *Journal of Reinforced Plastics and Composites*, *27*(5), 473–485.

Shu Seki, Tsuneaki Sakurai, Masaaki Omichi, Akinori Saeki, D. S. (2015). *High-Energy Charged Particles Their Chemistry and Use as versatile Tools for Nanofabrication*.

Silva, C., Simon, F., Friedel, P., Pötschke, P., and Zimmerer, C. (2019). Elucidating the chemistry behind the reduction of graphene oxide using a green approach with polydopamine. *Nanomaterials*, *9*(6).

Sina Ebnesajjad. (2014). Surface Treatment of Materials for Adhesive Bonding Surface Treatment of Materials for Adhesive Bonding. *Adhesion Promoters*, 77-91/ 86.

Singh, B. P., Nayak, S., Nanda, K. K., Jena, B. K., Bhattacharjee, S., and Besra, L. (2013). The production of a corrosion resistant graphene reinforced composite coating on copper by electrophoretic deposition. *Carbon*, *61*, 47–56.

Singh, R. (2014). Coating for Corrosion Prevention. *Corrosion Control for Offshore Structures*, 115–129.

Soldano, C., Mahmood, A., and Dujardin, E. (2010). Production, properties and potential of graphene. *Carbon*, *48*(8), 2127–2150.

Solutions, A. (2020). *Durability of an Epoxy Resin and Its Carbon Fiber- Reinforced Polymer Composite upon Immersion in*.

Sørensen, P. A., Kiil, S., Dam-Johansen, K., and Weinell, C. E. (2009a). Anticorrosive coatings: A review. *Journal of Coatings Technology and Research*, *6*(2), 135–176.

Sørensen, P. A., Kiil, S., Dam-Johansen, K., and Weinell, C. E. (2009b). Influence of substrate topography on cathodic delamination of anticorrosive coatings. *Progress in Organic Coatings*, *64*(2–3), 142–149.

Srivatsan, T. S. (2014). Practical Raman Spectroscopy: An Introduction. *Materials and Manufacturing Processes*, *29*(5), 649–649.

Stankovich, S., Dikin, D. A., Piner, R. D., Kohlhaas, K. A., Kleinhammes, A., Jia, Y., Wu, Y., Nguyen, S. B. T., and Ruoff, R. S. (2007). Synthesis of graphene-based nanosheets via chemical reduction of exfoliated graphite oxide. *Carbon*, *45*(7), 1558–1565.

Stemmelen, M., Pessel, F., Lapinte, V., Caillol, S., Habas, J. P., and Robin, J. J. (2011). A fully biobased epoxy resin from vegetable oils: From the synthesis of the precursors by thiol-ene reaction to the study of the final material. *Journal of Polymer Science, Part A: Polymer Chemistry*, *49*(11), 2434–2444.

Sun, L. (2019). Structure and synthesis of graphene oxide. *Chinese Journal of Chemical Engineering*, *27*(10), 2251–2260.

Sun, L., and Fugetsu, B. (2013). Mass production of graphene oxide from expanded graphite. *Materials Letters*, *109*, 207–210.

Sun, W., Wang, L., Wu, T., Pan, Y., and Liu, G. (2014). Synthesis of low-electrical-conductivity graphene/pernigraniline composites and their application in corrosion protection. *Carbon*, *79*(1), 605–614.

Sun, W., Wang, L., Wu, T., Pan, Y., and Liu, G. (2015). Inhibited corrosion-promotion activity of graphene encapsulated in nanosized silicon oxide. *Journal of Materials Chemistry A*, *3*(32), 16843–16848.

Suresh Kumar, S. M., and Subramanian, K. (2018). Enhancement in Mechanical, Thermal, and Dielectric Properties of Functionalized Graphene Oxide Reinforced Epoxy Composites. *Advances in Polymer Technology*, *37*(2), 612–621.

Taimur, S., Hassan, M. I. ul, Yasin, T., and Ali, S. W. (2018). Synthesis of modified sepiolite-g-polystyrene sulfonic acid nanohybrids by radiation induced graft polymerization. *Radiation Physics and Chemistry*, *148*, 19–24.

Tait, W. S. (2018). Controlling corrosion of chemical processing equipment. In *Handbook of Environmental Degradation Of Materials: Third Edition* (Third Edit). Elsevier Inc.

Tan, F., Qiao, X., Chen, J., and Wang, H. (2006). Effects of coupling agents on the properties of epoxy-based electrically conductive adhesives. *International Journal of Adhesion and Adhesives*, *26*(6), 406–413.

Tao, Z., Yang, S., Chen, J., and Fan, L. (2007). Synthesis and characterization of imide ring and siloxane-containing cycloaliphatic epoxy resins. *European Polymer Journal*, *43*(4), 1470–1479.

Tee, D. I., Mariatti, M., Azizan, A., See, C. H., and Chong, K. F. (2007). Effect of silane-based coupling agent on the properties of silver nanoparticles filled epoxy composites. *Composites Science and Technology*, *67*(11–12), 2584–2591.

Tian, J., Xu, T., Tan, Y., Zhang, Z., Tang, B., and Sun, Z. (2019). *E ff ects of Non-Covalent Functionalized Graphene Oxide with Hyperbranched Polyesters on Mechanical*.

Tiwari, S. K., Hatui, G., Oraon, R., De Adhikari, A., and Nayak, G. C. (2017). Mixing sequence driven controlled dispersion of graphene oxide in PC/PMMA blend nanocomposite and its effect on thermo-mechanical properties. *Current Applied Physics*, *17*(9), 1158–1168.

Tkalya, E. E., Ghislandi, M., de With, G., and Koning, C. E. (2012). The use of surfactants for dispersing carbon nanotubes and graphene to make conductive nanocomposites. *Current Opinion in Colloid and Interface Science*, *17*(4), 225–232.

Tri, P. N., Nguyen, T. A., Rtimi, S., and Plamondon, C. M. O. (2019). Nanomaterials-based coatings: An introduction. In *Nanomaterials-Based Coatings: Fundamentals and Applications*. Elsevier Inc.

Trojanowicz, M., Bobrowski, K., Szreder, T., and Bojanowska-Czajka, A. (2018). Gamma-ray, X-ray and Electron Beam Based Processes. In *Advanced Oxidation Processes for Wastewater Treatment: Emerging Green Chemical Technology*. Elsevier Inc.

Ukaji, E., Furusawa, T., Sato, M., and Suzuki, N. (2007). The effect of surface modification with silane coupling agent on suppressing the photo-catalytic activity of fine TiO 2 particles as inorganic UV filter. *Applied Surface Science*, *254*(2), 563–569.

Vengatesan, M. R., Varghese, A. M., and Mittal, V. (2018). Thermal properties of thermoset polymers. In *Thermosets: Structure, Properties, and Applications: Second Edition* (2nd ed.). Elsevier Ltd.

Vennerberg, D., Rueger, Z., and Kessler, M. R. (2014). Effect of silane structure on the properties of silanized multiwalled carbon nanotube-epoxy nanocomposites. *Polymer*, *55*(7), 1854–1865.

Vignesh, R. B., and Sethuraman, M. G. (2014). Enhancement of corrosion protection of 3-glycidoxypropyltrimethoxysilane- based sol-gel coating through methylthiourea doping. *Journal of Coatings Technology and Research*, *11*(4), 545–554.

Vinod Babu, C., Yaradi, M., and Teja Thammineni, D. (2018). A Review on Recent Trends in Surface Coatings. *IOP Conference Series: Materials Science and Engineering*, *390*(1).

Vorrada, L., Krit, T., Passakorn, E., Wanchai, B., and Achanai, B. (2013). Preparation and Characterization of Reduced Graphene Oxide Sheets via Water-Based Exfoliation and Reduction Methods. *Advances in Materials Science and Engineering*, *2013*, 1–5.

Wan, Y.-J., Gong, L.-X., Tang, L.-C., Wu, L.-B., and Jiang, J.-X. (2014). Mechanical properties of epoxy composites filled with silane-functionalized graphene oxide. *Composites Part A: Applied Science and Manufacturing*, *64*, 79–89.

Wan, Y. J., Gong, L. X., Tang, L. C., Wu, L. Bin, and Jiang, J. X. (2014). Mechanical properties of epoxy composites filled with silane-functionalized graphene oxide. *Composites Part A: Applied Science and Manufacturing*, *64*, 79–89.

Wang, C., Liu, Z., Wang, S., and Zhang, Y. (2016). Preparation and properties of octadecylamine modified graphene oxide/styrene-butadiene rubber composites through an improved melt compounding method. *Journal of Applied Polymer Science*, *133*(4), 1–9.

Wang, N., Gao, H., Zhang, J., and Kang, P. (2018). Effect of graphene oxide/ZSM-5 hybrid on corrosion resistance of waterborne epoxy coating. *Coatings*, *8*(5).

Wang, R., Zhang, J., Chen, S., Wu, L., Zhuo, D., and Cheng, X. (2019). Green fabrication of graphene oxide/epoxy nanocomposite and its application in diamond abrasive tools. *Composites Part B: Engineering*, *177*(July), 107383.

Wang, Xin, Xing, W., Zhang, P., Song, L., Yang, H., and Hu, Y. (2012). Covalent functionalization of graphene with organosilane and its use as a reinforcement in epoxy composites. *Composites Science and Technology*, *72*(6), 737–743.

Wang, Xingyu, Qi, X., Lin, Z., and Battocchi, D. (2018). Graphene reinforced composites as protective coatings for oil and gas pipelines. *Nanomaterials*, *8*(12).

Wei, H., Ding, D., Wei, S., and Guo, Z. (2013). Anticorrosive conductive polyurethane multiwalled carbon nanotube nanocomposites. *Journal of Materials Chemistry A*, *1*(36), 10805–10813.

Wei, J., Vo, T., and Inam, F. (2015). Epoxy/graphene nanocomposites - processing and properties: a review. *RSC Advances*, *5*(90), 73510–73524.

Wie, J., Kim, K., and Kim, J. (2020). High thermal conductivity composites obtained by novel surface treatment of boron nitride. *Ceramics International*, *46*(11), 17614–17620.

Wu, G. (2018). Radiation sources and radiation processing. In *Radiation Technology for Advanced Materials: From Basic to Modern Applications*. Elsevier Inc.

Xia, W., Xue, H., Wang, J., Wang, T., Song, L., Guo, H., Fan, X., Gong, H., and He, J. (2016). Functionlized graphene serving as free radical scavenger and corrosion protection in gamma-irradiated epoxy composites. *Carbon*, *101*, 315–323.

Xu, Y. le, Dayo, A. Q., Wang, J., Wang, A. ran, Lv, D., Zegaoui, A., Derradji, M., and Liu, W. bin. (2018). Mechanical and thermal properties of a room temperature curing epoxy resin and related hemp fibers reinforced composites using a novel in-situ generated curing agent. *Materials Chemistry and Physics*, *203*, 293–301.

Yang, G., Song, N., Deng, F., Liang, J., Huang, Q., Dou, J., Wen, Y., Liu, M., Zhang, X., and Wei, Y. (2020). Direct surface functionalization of graphene oxide with ionic liquid through gamma ray irradiation induced radical polymerization with remarkable enhanced adsorption capacity. *Journal of Molecular Liquids*, *306*, 112877.

Yang, L. H., Liu, F. C., and Han, E. H. (2005). Effects of P/B on the properties of anticorrosive coatings with different particle size. *Progress in Organic Coatings*, *53*(2), 91–98.

Yang, X., Wang, X., Yang, J., Li, J., and Wan, L. (2013). Functionalization of graphene using trimethoxysilanes and its reinforcement on polypropylene nanocomposites. *Chemical Physics Letters*, *570*, 125–131.

Yaro, A. S., Khadom, A. A., and Wael, R. K. (2013). Apricot juice as green corrosion inhibitor of mild steel in phosphoric acid. *Alexandria Engineering Journal*, *52*(1), 129–135.

Yasein, M., Eissa, M. F., El-Fayoumi, M. A. K., Abood, A. A., Badawi, E. A., and Aly, A. H. (2020). Studying the effect of low doses of gamma and beta irradiations on graphene oxide samples. *Radiation Physics and Chemistry*, *173*(April), 108941.

Yoo, B. M., Shin, H. J., Yoon, H. W., and Park, H. B. (2014). Graphene and graphene oxide and their uses in barrier polymers. *Journal of Applied Polymer Science*, *131*(1), 1–23.

Young, R. J., Kinloch, I. A., Gong, L., and Novoselov, K. S. (2012). The mechanics of graphene nanocomposites: A review. *Composites Science and Technology*, *72*(12), 1459–1476.

Yousefi, N., Lin, X., Zheng, Q., Shen, X., Pothnis, J. R., Jia, J., Zussman, E., and Kim, J. K. (2013). Simultaneous in situ reduction, self-alignment and covalent bonding in graphene oxide/epoxy composites. *Carbon*, *59*, 406–417.

Yu, Y. H., Lin, Y. Y., Lin, C. H., Chan, C. C., and Huang, Y. C. (2014). High-performance polystyrene/graphene-based nanocomposites with excellent anti-corrosion properties. In *Polymer Chemistry* (Vol. 5, Issue 2).

Zaaba, N. I., Foo, K. L., Hashim, U., Tan, S. J., Liu, W. W., and Voon, C. H. (2017). Synthesis of Graphene Oxide using Modified Hummers Method: Solvent Influence. *Procedia Engineering*, *184*, 469–477.

Zaki, A., Chai, H. K., Aggelis, D. G., and Alver, N. (2015). Non-destructive evaluation for corrosion monitoring in concrete: A review and capability of acoustic emission technique. *Sensors (Switzerland)*, *15*(8), 19069–19101.

Zaman, I., Kuan, H. C., Dai, J., Kawashima, N., Michelmore, A., Sovi, A., Dong, S., Luong, L., and Ma, J. (2012). From carbon nanotubes and silicate layers to graphene platelets for polymer nanocomposites. *Nanoscale*, *4*(15), 4578–4586.

Zaman, I., Phan, T. T., Kuan, H. C., Meng, Q., Bao La, L. T., Luong, L., Youssf, O., and Ma, J. (2011). Epoxy/graphene platelets nanocomposites with two levels of interface strength. *Polymer*, *52*(7), 1603–1611.

Zarrin, H., Higgins, D., Jun, Y., Chen, Z., and Fowler, M. (2011). Functionalized graphene oxide nanocomposite membrane for low humidity and high temperature proton exchange membrane fuel cells. *Journal of Physical Chemistry C*, *115*(42), 20774–20781.

Zhang, L., Wu, H., Wei, M., Zheng, Z., Vu, D. D., Bui, T. T. X., and Huang, X. (2018). Preparation, characterization, and properties of graphene oxide/urushiol-formaldehyde polymer composite coating. *Journal of Coatings Technology and Research*, *15*(6), 1343–1356.

Zhang, T., and Tang, D. (2009). Current Research Status of Corrosion Resistant Coatings. *Recent Patents on Corrosion Science*, *1*(1), 1–5.

Zhang, Yan, Zhu, Y., Lin, G., Ruoff, R. S., Hu, N., Schaefer, D. W., and Mark, J. E. (2013). What factors control the mechanical properties of poly (dimethylsiloxane) reinforced with nanosheets of 3-aminopropyltriethoxysilane modified graphene oxide? *Polymer*, *54*(14), 3605–3611.

Zhang, Yongxing, Zhao, M., Zhang, J., Shao, Q., Li, J., Li, H., Lin, B., Yu, M., Chen, S., and Guo, Z. (2018). Excellent corrosion protection performance of epoxy composite coatings filled with silane functionalized silicon nitride. *Journal of Polymer Research*, *25*(5).

Zhang, Zhihao, Schniepp, H. C., and Adamson, D. H. (2019). Characterization of graphene oxide: Variations in reported approaches. *Carbon*, *154*, 510–521.

Zhang, Zhiyi, Zhang, W., Li, D., Sun, Y., Wang, Z., Hou, C., Chen, L., Cao, Y., and Liu, Y. (2015). Mechanical and anticorrosive properties of graphene/epoxy resin composites coating prepared by in-situ method. *International Journal of Molecular Sciences*, *16*(1), 2239–2251.

Zhao, J., Milanova, M., Warmoeskerken, M. M. C. G., and Dutschk, V. (2012). Surface modification of TiO2 nanoparticles with silane coupling agents. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *413*, 273–279.

Zhao, Y., Liu, Z., Sun, T., Zhang, L., Jie, W., Wang, X., Xie, Y., Tsang, Y. H., Long, H., and Chai, Y. (2014). Mass transport mechanism of Cu species at the metal/dielectric interfaces with a graphene barrier. *ACS Nano*, *8*(12), 12601–12611.

Zheludkevich, M. L., Serra, R., Montemor, M. F., Miranda Salvado, I. M., and Ferreira, M. G. S. (2006). Corrosion protective properties of nanostructured sol-gel hybrid coatings to AA2024-T3. *Surface and Coatings Technology*, *200*(9), 3084–3094.

Zheludkevich, M. L., Tedim, J., and Ferreira, M. G. S. (2012). “Smart” coatings for active corrosion protection based on multi-functional micro and nanocontainers. *Electrochimica Acta*, *82*, 314–323.

Zhou, T., Chen, F., Liu, K., Deng, H., Zhang, Q., Feng, J., and Fu, Q. (2011). A simple and efficient method to prepare graphene by reduction of graphite oxide with sodium hydrosulfite. *Nanotechnology*, *22*(4).

Zhou, X., Huang, H., Zhu, R., Sheng, X., Xie, D., and Mei, Y. (2019). Facile modification of graphene oxide with Lysine for improving anti-corrosion performances of water-borne epoxy coatings. *Progress in Organic Coatings*, *136*(July), 105200.

Zhu, K., and Li, J. (2019). Strong covalent bonding modulated graphene oxide/epoxy interfacial enhancement and advanced corrosion resistance. *Journal of Macromolecular Science, Part A: Pure and Applied Chemistry*, *56*(12), 1156–1167.

Zhu, Y., Murali, S., Cai, W., Li, X., Suk, J. W., Potts, J. R., and Ruoff, R. S. (2010). Graphene and graphene oxide: Synthesis, properties, and applications. *Advanced Materials*, *22*(35), 3906–3924.

Zong, P., Fu, J., Chen, L., Yin, J., Dong, X., Yuan, S., Shi, L., and Deng, W. (2016). Effect of aminopropylisobutyl polyhedral oligomeric silsesquioxane functionalized graphene on the thermal conductivity and electrical insulation properties of epoxy composites. *RSC Advances*, *6*(13), 10498–10506.