CORROSION BARRIER AND FLAME RETARDANCY PROPERTIES OF EPOXY COATING MODIFIED WITH NANOFILLERS

SITI MAZNAH BINTI KABEB

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Faculty of Engineering
Universiti Teknologi Malaysia

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DEDICATION

To my mother, who gave to me the opportunities to develop a love of learning.
To my beloved husband and family for the love, continuous support and memories.

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ABSTRACT

Epoxy resin is widely used as coatings for corrosion protection of metals due to many advantages including good corrosion resistance, high mechanical strength and low shrinkage. Nevertheless, one of the major drawbacks of epoxy is it flammability which restricts the use in certain applications. Nanofillers has received great attention to increase the anticorrosive properties of the epoxy coating due to the ability to enhance the barrier properties. This study focused on the use of several types of nanofillers; graphene nanoplatelets (GNP), graphene oxide (GO), halloysite (HNT) and montmorillonite (MMT) in epoxy nanocomposite coating of mild steel plate. The effect of nanofillers content on corrosion resistance, flame retardancy, adhesion strength and thermal properties of the epoxy coating were studied. The effects of hybrid nanofillers on anticorrosion performance and flame retardancy of epoxy coatings were also evaluated. Electrochemical impedance spectroscopy, Tafel polarization and salt spray test were conducted to reveal the effect of nanofillers on corrosion protection performance. Besides that limiting oxygen index (LOI) and thermogravimetry analysis (TGA) were performed to evaluate the flame retardancy and thermal stability of epoxy filled coatings. Adhesion of the coating to its substrate and water absorption behavior were used to determine the time associated with the loss of adhesion and water permeability through the epoxy coating. The dispersion and interaction of the nanofillers with the matrix were characterized by transmission electron microscopy (TEM) and Fourier transform infrared (FTIR). The best anticorrosion performance of epoxy coating was exhibited by the incorporation of nanofillers into the epoxy matrix with 0.8 phr (for GNP and GO) and 1.5 phr (for MMT and HNT). For the hybrid nanofillers coatings some increment were observed at the ratio 0.6/0.3 phr of GO/HNT and was the best when compared to the other contents. The incorporation of nanofillers had increased the LOI values of epoxy coatings and the value was further improved in the presence of hybrid nanofiller. The maximum LOI value of 26 was observed for the epoxy coating with 1 phr ammonium polyphosphate in the intumescent flame retardant (IFR) formulation. TGA analysis showed that the incorporation of nanofillers and IFR formulation slightly enhanced the thermal stabilities and char formations of the coated samples. The water absorption results were fairly consistent with the data obtained from the corrosion studies. The water resistance had improved by 48.7 % and 52.4 % for EGO0.8 and EH1.5 coatings, respectively. The hybrid coating of EGO0.6H0.3 was more effective in repelling the water and durable. Adhesion strength for all coating samples decreased after 200 hours of exposure to 5 wt. % NaCl solution and more noticeable for neat epoxy coating. The positive effect of the nanofillers on the epoxy coating properties was attributed to the interaction between nanofillers and the epoxy matrix which was confirmed by FTIR and TEM, producing epoxy coatings with well-dispersed and great barrier properties. Therefore, the combination of hybrid GO/HNT as an additive may be considered as an efficient method to obtain good anticorrosion performance and flame retardancy properties for epoxy coating. The results demonstrated that the incorporation of hybrid GO/HNT nanofillers with IFR had further enhanced the flame retardancy with a slight decrease in anticorrosion properties.

ABSTRAK

Resin epoksi digunakan secara meluas sebagai salutan bagi melindungi kakisan logam kerana banyak kebaikannya termasuk rintangan kakisan yang baik, kekuatan mekanikal yang tinggi dan pengecutan yang rendah. Walau bagaimanapun, salah satu daripada kelemahan epoksi adalah kebolehbakaran yang menghadkan penggunaannya di dalam aplikasi tertentu. Pengisi nano telah mendapat perhatian luas bagi meningkatkan sifat antikakisan salutan epoksi kerana kebolehannya untuk meningkatkan sifat-sifat halangan. Kajian ini tertumpu kepada penggunaan pelbagai jenis pengisi nano; platlet nano grafin (GNP), grafin oksida (GO), haloisit (HNT) dan montmorilonit (MMT) di dalam salutan epoksi berpengisi nanopartikel pada plat keluli. Kesan kandungan pengisi nano terhadap rintangan kakisan, rintangan api, kekuatan pelekatan dan sifat-sifat termal salutan epoksi dikaji. Kesan pengisi nano hibrid ke atas prestasi antikakisan dan rintangan api salutan epoksi juga dinilai. Spektroskopi impedans elektrokimia, polarisasi Tafel dan ujian semburan garam telah dijalankan untuk menunjukkan kesan pengisi nano ke atas prestasi perlindungan kakisan. Disamping itu, indeks penghadan oksigen (LOI) dan analisis termogravimetri (TGA) telah dilakukan bagi menilai rintangan api dan kestabilan termal salutan epoksi berpengisi. Pelekatan salutan ke atas substrat dan kelakuan penyerapan air digunakan untuk menentukan masa kehilangan lekatan dan ketelapan air menerusi salutan epoksi. Penyebaran dan interaksi pengisi nano ke dalam matrik dicirikan oleh mikroskop elektron transmisi (TEM) dan inframerah jelmaan Fourier (FTIR). Prestasi antikakisan salutan epoksi terbaik telah dipamerkan dengan penyatuan pengisi nano ke dalam epoksi matrik pada 0.8 phr (bagi GNP dan GO) dan 1.5 phr (bagi MMT dan HNT). Bagi salutan berpengisi nano hibrid sedikit peningkatan telah diperhatikan pada nisbah 0.6/0.3 phr GO/HNT dan menunjukkan prestasi yang terbaik berbanding kandungan yang lain. Penyatuan pengisi nano telah meningkatkan nilai LOI salutan epoksi dan nilainya telah dipertingkatkan dengan kehadiran pengisi nano hibrid. Nilai maksimum LOI sebanyak 26 diperhatikan untuk salutan epoksi dengan 1 phr ammonium polifosfat di dalam formulasi rintangan api intumesen (IFR). Analisis TGA menunjukkan, penyatuan pengisi nano dan fomulasi IFR meningkatkan sedikit kestabilan haba dan pembentukan arang sampel salutan. Keputusan penyerapan air hampir konsisten dengan data yang diperolehi daripada ujian kakisan. Rintangan air meningkat sebanyak 48.7% dan 52.4 % masing-masing bagi salutan EGO0.8 dan EH1.5. Salutan hibrid EGO0.6H0.3 adalah lebih efektif menghalang air dan tahan lama. Kekuatan pelekatan bagi semua sampel salutan menurun selepas 200 jam pendedahan kepada larutan 5 wt. % NaCl dan lebih nyata bagi salutan epoksi tanpa pengisi. Kesan positif pengisi nano ke atas sifat-sifat salutan epoksi adalah disebabkan oleh interaksi antara pengisi nano dan matrik epoksi yang telah dibuktikan oleh FTIR dan TEM, menghasilkan salutan epoksi yang terserak dengan baik dan sifat-sifat halangan yang baik. Oleh itu, penggabungan hibrid GO/HNT sebagai bahan tambah mungkin dipertimbangkan sebagai kaedah yang berkesan untuk mendapatkan prestasi antikakisan dan sifat rintangan api yang baik dalam salutan epoksi. Keputusan menunjukkan bahawa penyatuan hibrid GO/HNT nano dengan pengisi IFR terus meningkatkan rintangan api dengan sedikit penurunan dalam sifat antikakisan.

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LIST OF ABBREVIATIONS

ACM - Applied Corrosion Monitoring
APP - Polyphosphate
ASTM - American Society for Testing and Materials
ATH - aluminium trihydrate
BF_3 - Boron trifluoride
BPA - Bisphenol-A
BPF - Bisphenol-F
C - Capacitance
CEC - Cation exchange capacity
Cl^- - Chloride ion
CN - Cerium nitrate
CNFs - Carbon nanofibers
CNT - Carbon nanotubes
CP - Cathodic protetcion
CTBN - Carboxyl-terminated butadiene-acrylonitrile
Cu - Cuprum
DCH - Diaminocyclohexane
DGEBA - Diglycidylether bisphenol-A
DMM - Diaminodiphenyl methane
DTA - Differential Thermal Analysis
DTA - Diethylenetriamine
ECH - Epichlorohydrin
EEDS - Energy Dispersive Spectroscopy
EG - Expanded graphite
EGC - Epoxy/graphene composites
EIS - Electrochemical impedance spectroscopy
ESEM - Environmental scanning electron microscope
f-(PVA) - Functionalised poly(vinyl alcohol)
Fe_2O_3 - Iron (III) oxide

FG	-	Functionalized graphene
FGO	-	Functionalized graphene oxide
FR	-	Flame retardant
FRGO	-	Functionalized reduced graphene oxide
FTT	-	Fire Testing Technology
GNP	-	Graphene nanoplatelets
GNSS	-	Graphene nanosheets
GO	-	Graphene Oxide
GOPC	-	Graphene oxide-polymer composites
GPa	-	Gega pascal
H	-	Hour
H^+	-	Hydrogen ion
H_2	-	Hydrogen
H_2O	-	Water
HCl	-	Hydrochloric acid
HDT	-	Heat distortion temperature
HEGC	-	Hydrophobic epoxy/graphene composites
HNT	-	Halloysite
HRR	-	Heat release rate
i.e.	-	Id est (that is)
IFR	-	Intumescent flame retardant
IPDA	-	Isophorone diamine
ISO	-	International Organization for Standardization
ISP	-	In-situ polymerization
L/D	-	Length-to-diameter
LOI	-	Low oxygen index
LS	-	Layer silicate
MB	-	Melt blending
MCM	-	Mesoporous
MDA	-	Menthane diamine
MEL	-	Melamine
MF	-	Melamine formaldehyde
MH	-	magnesium hydroxide

mm	-	Millimeter
MMT	-	Montmorillonite
MPa	-	Mega Pascal
MPDA	-	Methaphenylene diamine
MPP	-	Melamine polyphosphate
mpt	-	Molten pentaerythritol
mV	-	Millivolts
MWCNT	-	Multiwall carbon nanotubes
Na^+	-	Sodium ion
NaCl	-	Sodium chloride
NaOH	-	Sodium hydroxide
NC	-	Nanocomposite coating
NH	-	Nitrogen-hydrogen
NH_3	-	Ammonia
Ni	-	Nickel
NIST	-	National Institute of Standards and Technology
n-SiC	-	Nano-silicon carbide
O_2	-	Oxygen
OH	-	Oxygen-hydrogen
OH^-	-	Hydroxyl ion
OMMT	-	Organically modified montmorillonite
PA6	-	Polyamine
PACCs	-	Polyaniline/clay composites
PAGCs	-	Polyaniline/graphene composites
PER	-	Pentaerythritol
PET	-	Poly(ethylene)terephthalate
PF	-	Phenol formaldehyde
PHRR	-	Peak heat release rate
PLS	-	Polymer/layer silicate
POSS	-	Polyhedral oligomeric silsesquioxane
PP	-	Poly(propylene)
PU	-	Polyurethane
PVC	-	Poly (vinyl) chloride

R - Resistance
R3N - Tertiary amines
RE - Reference Electrode
rGO - Reduced Graphene oxide
SACP - Sacrificial cathodic protection
SBS - Styrene-butadiene-styrene triblock
SC - Solution compounding
SEM - Scanning Electron Microscope
SHE - Standard hydrogen electrode
SiO_2 - Silicone dioxide
SO_2 - Sulfur dioxide
SO_3 - Sulfur trioxide
SST - Salt spray test
SWC-NT - Single-walled carbon nanotubes
TETA - Triethylenetetramine
TGA - Thermogravimetric analysis
THR - Total heat release
TiN - Thallium nitrate
TTA - Triethylenetetramine
TTI - Time to ignition
UF - Urea-formaldehyde
VOC - Volatile organic compounds
W - Weight
WE - Working electrode
wt. - Weight
XPS - X-ray Photoelectron Spectroscopy
XRD - X-ray Diffraction
Zn - Zinc
ZrN - Zirconium nitride
ZrO_2 - Zirconium dioxide

LIST OF SYMBOLS

° - Degree

% - Percent

λ - Wavelength

°C - Degree Celsius

μm - Micrometre

$|Z|_{0.1\text{Hz}}$ - Impedance modulus at frequency 0.1 Hz

~ - Similarity

< - Less than

> - More than

± - Plus - minus

C_{dl} - Double layer capacitance

Cl^- - Chloride ion

I_{corr} - Corrosion current density

m - Weight of coating

R_{corr} - Corrosion rate

R_{ct} - Charge transfer resistance

R_p - Polarization resistance

T_g - Glass transition temperature

T_m - Melting temperature

W - Warburg impedance

x - Weight change rate

β_a - Anodic Tafel slope

β_c - Cathodic Tafel slope

D - Constant diffusion coefficient

C_c - Coating capacitance

T_{10} - Temperature at 10% weight loss

T_{max} - Temperature at a maximum mass loss

T - Temperature

g - Gram

R_c - Coating Resistance

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

Corrosion is a problem of great economic importance to industry and results in potential danger to humans. Deterioration due to corrosion is one of the major causes of metal component failures (Hasan et al., 2018). It cannot be fully prevented and thus, corrosion control strategies focus on slowing the kinetics and/or altering its mechanism. The widespread use of metals in corrosion prone environments initiate comprehensive research focused on developing coatings that protect against corrosion. Different strategies are utilized in various fields such as marine equipment, pipelines and construction to attenuate the intensity and severity of corrosion. Consideration of basic requirements such as durability, high performance, inexpensive, easy application and eco-friendly material is necessary for the selection of coating material (Gu et al., 2020). The uses of polymers which have long-chain carbon linkages can block large areas of the corroding metal surfaces upon adsorption.

Metallic materials are significant importance in industry and research because of their excellent mechanical and processing properties and are extensively used in various industries such as construction, transportation and marine (Xu et al., 2019). Unfortunately, metallic materials can be easily corroded as a result of environmental effects. The corrosion of metals involves a series of electrochemical reactions in oxygen-containing environments and deteriorates the performance of metallic components accordingly. In recent years, much more attention has been paid to metallic corrosion because of its adverse effect, including economic losses, environmental contamination and safety problems.

Aqueous corrosion represents the most troublesome forms of corrosion that exist in engineered structures when in contact with seawater as a destructive attack to structures, ships and other equipment used in seawater services (Zhang et al., 2019). Rising incidences of corrosion-induced premature degradation of metallic infrastructure make corrosion a pervasive issue across the industry. From the simplest fastener nail to huge underground pipes, all metallic substrates have a natural tendency to corrode in the presence of H_2O, O_2, Cl^-, etc. It is not prudent to quantify corrosion only in terms of gross domestic product loss, as it also leads to huge safety concerns, adverse health effects, loss of life, resources and more.

Although corrosion may be inevitable, but its protection can be possibly be done through cathodic protection (Qian et al., 2017), protective coatings (Moazeni et al., 2013), corrosion inhibitors (Goyal et al., 2018) or any combination thereof. The application of anticorrosive coatings seems to be a well-established approach for separating metals from an aggressive corrosive environment. For this purpose, ceramic coatings, metallic oxide coatings, graphene coatings, organic coatings and organic-inorganic hybrid coatings have been developed. Organic coatings have several advantages; high efficiency, easy operation and effective methods to protect metal surfaces by creating a physical barrier that retards the penetration of corrosive ions or oxygen into the coating (Montemor et al., 2012). However, owing to wide variations in environmental conditions or mechanical properties of the coatings, microcracks inevitably appear in the coatings usually after curing. The existence of microscopic defects in the protective coating accelerates the exfoliation and delamination of the coatings at the metal-coating interface and decreases the service life. Volatile organic compounds (VOC) and the high concentrations of pigments in organic coatings likely to cause tremendous harm to the environment. So, organic coatings composed of water-based polymers are attractive.

Epoxy resins are widely used in advanced composites coating due to its excellent chemical and electrical resistance, affinity to heterogeneous materials, great impregnation and adhesion to fibre reinforcement, resulting in an excellent mechanical performance, low shrinkage on a cure as well as ease processing. These technical benefits balance their relatively higher costs compared to other thermosetting polymers for a particular application (Toldy et al., 2011). Epoxy coatings generally used to protect the metal substrate against corrosion by two functions. First, they act as a physical barrier layer to control the ingress of deleterious species. Second, they can serve as a reservoir for corrosion inhibitors and other additives to protect the metal surface from the attack by different species such as chloride ions.

Although epoxy has many excellent characteristics, it has few drawbacks; brittleness, low fracture toughness and low flame retardancy Moreover, epoxy coatings thwart by their susceptibility to damage by surface abrasion and wear (Wang et al., 2019) and poor resistance to the initiation and propagation of cracks (Sapronov et al., 2019). These processes impair their appearance and mechanical strength as well as initiate localized defects which can also act as pathways accelerating the permeation of water, oxygen and aggressive species onto the metallic substrate, resulting in its localized corrosion.

Nanoparticles have been used to overcome the disadvantages of the epoxy coating due to its outstanding properties (Pourhashem et al., 2017; Rajitha et al., 2020). Nanoparticles filler tend to occupy tiny holes' defects formed from local shrinkage during curing of epoxy resin and they act as a bridge interconnecting more molecules. A decrease in total free volume and surface area of grain boundaries, as well as an increase in the cross-linking density of the epoxy resin matrix, can mitigate blister or delaminate of epoxy coating (Nguyen-Tri et al., 2018). Therefore, the durability of epoxy coatings can be further enhanced by the incorporation of nanoparticles filler when subjected to aggressive media.

The development of nanotechnology in the corrosion protection of metals has gained traction in recent years because the use of nanotechnology has proven to facilitate waste hazardous minimization which has been restricted by environmental regulations (Ijaola et al., 2020). The most crucial concern regarding anticorrosion coatings is finding an appropriate alternative to a toxic and environmentally harmful corrosion inhibitor. The use of natural resources and non-toxic inhibitive pigments, for instance, graphene and montmorillonite (MMT) spurred intense interest in industries to replace existing harmful and high toxicity inhibitive pigments such as strontium or zinc chromates (Bhattacharya, 2016; Krishnan et al., 2018). Therefore, nanocomposite coating has fascinated the number of consideration as a simple and cost-effective method of enhancing coating properties by the addition of a small amount of properly designed and dispersed nanoparticle fillers (TabkhPaz et al., 2018).

Nanoparticles filler such as graphene, nanoclay, carbon nanotubes (CNT) and carbon nanofibers (CNFs) enticing a lot of concerns in order to improve the mechanical properties and thermal stability of composite (Naz et al., 2016; Qi et al., 2014). Their eco-friendliness merit over conventional FR nanoparticles is being advantages to improve the FR through the formation of a protective network structure that acts as a heat shield for composites. Incorporation of nanofillers into polymeric coatings improved their corrosion resistance, transparency, color purity, resistance to organic solvents and reduce the tendency for the coating to blister or delaminate (Gul et al., 2016; Muralishwara et al., 2019; Nazari et al., 2016). Other property enhancements include the integrity and durability of coating polymeric composites through the minimization of detrimental effects of service and environmental factors over time (Chang et al., 2014).

The combination of different types of nanofillers or so-called as hybrid or binary system exploits the synergistic effect which can enhance various properties of the epoxy coatings (Di et al., 2016; Wang et al., 2012; Wang et al., 2018), hence harnessing desirable properties of each nanofillers and resulting in composites with multi-functionality. Great interfacial interactions between nanofillers and the epoxy coating offer environmental benign approach as well as reducing the production cost with balanced properties of mechanical, thermal and electrical (Maiti et al., 2013; Safdari et al., 2013; Yang et al., 2011). Wang et al. (2012) demonstrate the synergistic effect of 0.25 wt. % of MMT and 0.25 wt. % of mesoporous silica particles (MCM-41) on improving the barrier properties and corrosion resistance of an epoxy coating. It was proposed that the aforesaid findings were due to the formation of an interconnected network between the nanofillers. Therein, it is worth to point out that the inclusion of hybrid GO/MMT and GO/HNT in the epoxy matrix seems to be helpful in order to attain desired properties that could not be achieved by single nanofillers.

In addition, to enhance FR properties, the intumescent formulation was employed in combination with hybrid GO/HNT as effective passive fire protection coatings that offer great potential to coat structures in hazard regions (Ye et al., 2019). A suitable FR treatment might be able to retard the ignition by highly combustible materials and decrease flame spread, thereby obviating fire hazards and loss of life and destruction of property. It represents an increasingly used way to provide maximum fire protection to the structural steel in the construction industry, chemical plants and other facilities. The coating does not support combustion and expands once heated. It will form a thick insulation char around steelwork, protecting steel structure from the heat and retaining the structural integrity (Lucherini et al., 2020).

For environmental concerns, intumescent FR is considered as a promising halogen-free FR additive due to its advantages of low smoke, low toxicity, low corrosion and no molten dripping during a fire (Yasir et al., 2020). Intumescent fire protection has been used since about 50 years ago, whereas incorporating intumescent additives in polymeric materials is a relatively recent approach (Velencoso et al., 2018). Therefore, it will allow the products to penetrate the market demand and abide by current stringent aviation and other legislation to increase fire safety while maintenance of other important characteristics such as corrosion, mechanical and thermal properties without neglected an environmental issue.

1.2 Problem Statement

Coatings for the corrosion prevention of steel pipelines that transport oil/gas tend to suffer from premature failure and/or exhibit defects due to high ambient temperatures, resulting in corrosion issues. The coating system must be able to be applied in diverse environmental conditions and enable to protect the substrate from the destructive effects of rain, sunlight, wind, heat, cold, humidity, and oxygen while maintaining its integrity and often the aesthetic appearance. Epoxy coating is commonly used to overcome metal corrosion-related failures by preventing direct contact between the substrate and the corrosive environment that pipelines are usually exposed to such as severe abrasion and hydrothermal aging.

Epoxy coating is the most important engineered polymers which attract attention on account of their outstanding corrosion resistance, excellent adhesion properties, low shrinkage and good thermal and mechanical properties. Despite this versatility feature, epoxy resins are very brittle and have poor impact resistance and flexibility, which lead to the formation of abundant tiny pores and microcracks due to mechanical damage or generated during the curing process of epoxy resin. Moreover, long-term exposure to corrosive ions accelerated hydrolytic degradation of the epoxy matrix, which provide paths for the ingress of corrosive ions. Therefore, to enhance the durability of epoxy-based coatings, the incorporation of nanofiller as a protective barrier or inhibitor is inevitable. The inclusion of nanofiller into epoxy resin addresses the above bottleneck and further augments its anticorrosion performance.

Previous studies have shown that the barrier performance of epoxy coatings was enhanced by the incorporation of a second phase into the epoxy polymer, by decreasing the porosity and zigzagging the diffusion path for deleterious species (Nazari et al., 2016). However, there are limited studies available regarding the flammability characteristics of epoxy filled nanocomposite coating. Incorporation of inorganic filler has a significant influence on the final use properties because they can simultaneously improve the barrier performance and yield FR properties of the polymer due to its excellent thermal stability and gas barrier behavior.

However, nanofillers such as GNP tend to form agglomerates in the cured nanocomposite coating led to aggravated microcracks on the coating surface. Much research work has been done on hybrid composites with the incorporation of two or more fillers in improving the dispersion of hybrid nanofillers where they form a co-supporting network between the nanoparticles, thus causing improved properties (Bakhshandeh et al., 2014; Behzadnasab et al., 2013; Kumar et al., 2010). Synergistic effects of hybrid nanofillers produce an epoxy coating with balance properties that are difficult to attain with a single nanofiller (Li et al., 2014; Sari et al., 2017; Zuo et al., 2017).

Nevertheless, to the best of our knowledge, no effort has been put on a systematic examination that compares the effect of hybrid GO/HNT/epoxy and GO/MMT/epoxy to enhance anticorrosion properties and FR of epoxy coating has been reported in single study, which constitutes the novelty of the present study. Therefore, the present study raises an intriguing question on whether hybridization of GO/MMT and GO/HNT would give balance performance of an epoxy coating in terms of adhesion strength, thermal, corrosion and FR properties.

Intumescent flame retardant coatings were employed to meet fire safety requirements particularly for applications that require high flame resistance. The previous study showed that the addition of HNT and polydimethylsiloxane (PDMS) in the coating formulations based intumescent FR coatings (APP/MEL/BA/EG) resulted in better heat shielding developed silicate network over the char surface and the decreased thermal decomposition rate of residue carbon during the intumescent reaction (Gillania et al., 2018). However, the effect of GO, HNT and IFR on corrosion performance of epoxy coating has not been reported.

The present study scrutinizes and compares how additions of hybrid GO/MMT and GO/HNT into an epoxy matrix synergistically influence the anticorrosion performance and FR properties of epoxy coating. Determination of thermal stability and analysis of the microstructure of the coatings are also carried out in order to provide information and understanding of the overall influence of nanofillers addition in the epoxy matrix. To exploit the extraordinary beneficial properties of hybrid GO/HNT mainly in improving FR properties, hybrid GO/HNT based intumescent FR coating prepared using sonication and mechanical agitation technique was also investigated in the current study. The purposes of the present study are to obtain information regarding the potential of hybrid GO/HNT and IFR to further enhance the FR and barrier protection properties of an epoxy coating.

1.3 Aim and Objectives of Research

The aim of this research is to improve the corrosion resistance, flame retardancy property, adhesion strength and thermal stability of epoxy coatings. In order to achieve the aim, the following objectives are identified.

(a) To investigate the effect of different types of nanofillers i.e. GNP, GO, MMT and HNT content on the corrosion resistance, flame retardancy property, adhesion strength and thermal stability of epoxy coatings.
(b) To determine the effect of hybridization of GO/MMT and GO/HNT epoxy coating on the corrosion resistance, flame retardancy property, adhesion strength and thermal stability of epoxy coatings.
(c) To evaluate the effect of hybrid GO/HNT based intumescent flame retardant coating on the corrosion resistance, flame retardancy property, adhesion strength and thermal stability of epoxy coatings.

1.4 Scope of the Study

The scope of this study comprised the following:

(a) Preparation of epoxy coating filled nanofillers

    (i) Preparation of epoxy coating filled with different types of nanofillers i.e GNP, GO, MMT and HNT at different nanofillers loading.

- (ii) Preparation of hybrid GO/MMT and GO/HNT filled epoxy nanocomposites coating in ratio 0.6:0.2, 0.6:0.3 and 0.6:0.4, respectively.
- (iii) Preparation of hybrid GO/HNT based intumescent flame retardant coating with 1 to 3 phr APP content.

(b) Corrosion resistance, flame retardancy property, adhesion strength, thermal stability, morphological properties and structural characterization of epoxy coatings were done.

- (i) The entire sample is tested in order to study the corrosion resistance of coating samples
  - (a) Electrochemical Impedance Spectroscopy (EIS) ((ASTMG106-89(2015).
  - (b) Tafel polarization ((ASTM G59-97(2014).
  - (c) Salt Spray Test (SST) (ASTM B 117)
  - (d) Water Absorption Test (ASTM D570-98)
- (ii) Flame retardancy properties are evaluated by Limiting Oxygen Index (LOI) (ASTM D 2863)
- (iii) Thermogravimetry Analysis (TGA) is done to determine the thermal stability of the coating samples.
- (iv) Mechanical properties of nanoparticles filled epoxy coating is conducted by Adhesion Test (ASTM D3359-2)
- (v) Transmission electron microscopy (TEM) analysis is carried out to investigate the morphology and the actual structure or pattern of nanofillers dispersion in epoxy coating.
- (vi) Fourier Transform Infrared Spectroscopy is carried out to analyze the structural characteristic and identify any changes in the chemical structure.

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1. **Kabeb, S. M.**, Hassan, A., Mohamad, Z., Sharer, Z., Mokhtar, M. and Ahmad, F. Effect of Graphene Nanoplatelets on Flame Retardancy and Corrosion Resistance of Epoxy Nanocomposite Coating. Malaysian Journal of Fundamental and Applied Sciences. 2019. 15(4), pp. 543-547 https://doi.org/10.11113/mjfas.v15n4.1399

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1. **Kabeb, S. M.,** Hassan, A., Mohamad, Z., Sharer, Z., Mokhtar, M. and Ahmad, F. Exploring the Effects of Nanofillers of Epoxy Nanocomposite Coating for Sustainable Corrosion Protection. Chemical Engineering Transactions. 2019. 72, pp. 121-126 https://doi.org/10.3303/CET1972021 **(Indexed by SCOPUS)**
2. **Kabeb, S. M.,** Hassan, A., Mohamad, Z., Sharer, Z., Mokhtar, M. and Ahmad, F. Synergistic Effect of Graphene Oxide/Halloysite in Anticorrosion Performance and Flame Retardancy Properties of Epoxy Nanocomposite Coating. Chemical Engineering Transactions. 2020. 78, pp. 529-534 https://doi.org/10.3303/CET2078089 **(Indexed by SCOPUS)**