Flake-Filled Polymers for Corrosion Protection

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This article provides an overview of polymers reinforced with impermeable flakes that have long been used in the chemical process industry for protecting metal and concrete structures against corrosion. Reviewing the function of impermeable flakes in the anticorrosion performance of polymer composite coatings and linings could serve as a guiding perspective for future studies and extended applications of current polymer-layered silicate nanocomposites in this field. This brief article describes the theory behind barrier improvement in polymers by flake reinforcement, describes ways of evaluating the anticorrosive properties of flake filled polymers reported in recent studies, and reviews some existing applications of flake filled polymers for corrosion protection in the field of chemical processing.

Introduction

Over the years, polymer coatings and linings have been developed for corrosion protection and barrier applications. However, neat polymer coatings and linings are still permeable to corroding agents. In order to enhance the barrier and anticorrosive properties of polymer coatings and linings, inorganic flakes are used as fillers. The addition of flake fillers into polymer coatings and linings offers a more economical method and durable protection against corrosion. When these impermeable flake fillers are aligned parallel to the surface of a polymer coating or lining as shown in **Figure 1**, they decrease the area available for permeation, effectively increase the diffusion pathways of corroding agents, and enhance the corrosion stability of the polymer coating or lining. Among the list of impermeable flake fillers available for reinforcement in polymer coatings and linings, glass and mica flakes have a long history of successful application in the field of corrosion protection. Glass flake linings have been replacing glass fiber reinforced polymers (GFRP) for anticorrosion applications in process plants (Butt, 1982). Polymers reinforced with aligned glass or mica flakes have effectively combated corrosion in the chemical process industry as coatings and linings for new process equipment or reconditioning of used chemical vessels, absorbers, scrubbers, pipes, ducts, and stacks.

Flake filled polymer coatings and linings belong to a class of composite materials wherein the type of filler is two-dimensional in shape, e.g., flakes, platelets, ribbons, etc. Other types of reinforcement used in polymers are one-dimensional (e.g., fibers, whiskers) and three-dimensional (e.g., spheres, beads) in shape. Aside from glass and mica, other examples of two-dimensional reinforcement materials are layered silicates including clay minerals such as smectite, montmorillonite, and saponite; aluminium diboride, and silicon carbide platelets (Maine and Shepherd, 1974). Although one-dimensional fibers give greater stiffness and strength than flakes and platelets, the latter are usually considered for planar structures due to their capability of reinforcing in two dimensions (Vu-Khanh and Fisa, 1986).

Recently, a number of review articles (Pavlidou and Papaspyrides, 2008; Yeh and Chang, 2008; Zaarei *et al.*, 2008) and research papers (Chen *et al.*, 2003; Bagherzadeh and Mahdavi, 2007; Abacha *et al.*, 2009; Nematollahi *et al.*, 2010) have reported the corrosion performance of polymeric coatings filled with nanosize flake particles. In comparison to traditional fillers like glass and mica flakes, the addition

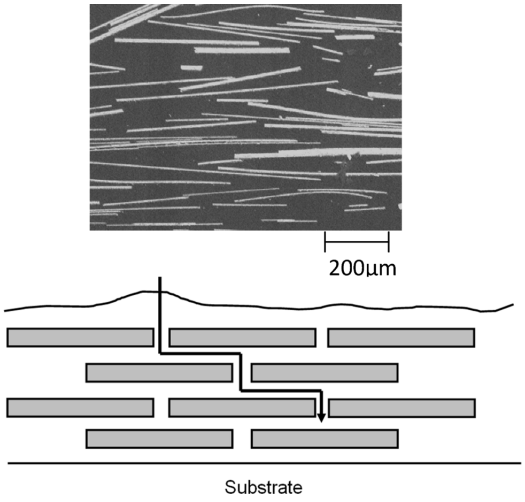

Fig. 1 Aligned glass flakes in amine-cured epoxy; flakes decrease the available area and increase the path length of diffusing corrosive species

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of nanosize flake particles into polymeric coatings offers a more economical improvement in barrier and anticorrosion properties compared with pristine polymers. Due to high specific area, high strength, high aspect ratio, and unique nanoscale dispersion of layered silicates into the matrix, polymer nanocomposites exhibit advanced gas barrier, thermal stability, and improved mechanical properties at very low volume fraction loading of layered silicates. Though the nanosize flakes are randomly dispersed and aligned in the polymer coating, most reports still mainly attribute the decreased permeability and enhanced corrosion resistivity of nanocomposite coatings to increased tortuosity. However, experience from the corrosion protection performance of traditional polymer coatings and linings reinforced with microsize glass and mica flakes suggests that increased tortuosity is only achieved by parallel alignment of flakes with the coating or lining surface. Thus, aside from tortuosity, other mechanisms for decreased diffusivity in coatings reinforced with nanosize flakes should be considered. One possible mechanism is the reduction in molecular mobility of the polymer matrix after clay incorporation (Pavlidou and Papaspyrides, 2008), which is intimately connected to coating permeability.

The aim of this review is to describe diffusion theory in flake filled polymers for barrier and corrosion protection applications. This review also reports ways of evaluating the anticorrosive properties of flake filled polymers applied by recent studies. Existing applications of flake filled polymers for corrosion protection in the chemical process industry are also presented and reviewed.

1. Barrier Improvement by Flake Reinforcement

In the chemical process industry, a lot of metal surfaces from process equipment and concrete surfaces from chemical plant structures are always in need of protection from corrosion. Polymer coatings and linings usually offer an economical way of accomplishing this important task. Past researches have studied different degradation mechanisms of polymer materials commonly used in chemical processing, in particular thermosetting polymer resins and its glass fiber reinforced composites, during exposure to acids and alkalis at elevated temperature (Hojo *et al.*, 1998; Hojo and Tsuda, 2002; Negishi *et al.*, 2002; Tsuda, 2007). Results from past researches like these have enabled some authors to compile polymer-chemical systems that are compatible at specified service conditions (Schweitzer, 2007). Nevertheless, there is no perfect polymer coating or lining, as all materials are permeable to chemicals to some extent. Moreover, material defects like pinholes and cracks, either occurring during installation or evolved during service, will cause polymer coatings and linings to fail.

A primary method for enhancing the anticorrosion properties of polymer coatings and linings is to use pigments and fillers for reinforcement. Reinforced pigments and fillers could enhance the anticorrosion properties of polymers by electrochemical, chemical, and physical mechanisms. In a study by Rammelt and Reinhard (1994) on characterizing active pigments in the damage of alkyd primer coatings on steel, one could classify pigments or fillers either as active or inert. Active pigments, such as zinc chromate, can prevent corrosion of protected substrates by the build-up of permanently passive conditions at the protected surface (electrochemical protection) and/or by build-up of solid compounds which plug the coating damages (chemical protection). Aside from electrochemical/chemical protection from corrosion, active pigments like zinc oxide on exposure to acids can also delay the corrosion of protected substrates by being chemically reactive, as suggested by Moggridge *et al.* (2003). Immobile reactive pigments are distributed throughout the coating, which will react to the diffusing species. This will increase the lag time for penetration of polymer coating or lining, since the diffusing species must consume all of the reactive pigments before it can cross and reach the substrate. Meanwhile, inert pigments such as chopped glass fibers, glass flakes, and silica beads prevent corrosion by lengthening the pathways of diffusion through the coating (barrier protection). The barrier action of inert pigments is best illustrated by aligned flakes, as shown in **Figure 2**. While the concentration profile of a diffusing substance in a neat polymer coating or lining of thickness l follows the Fickian model, the concentration profile in a flake filled coating or lining of the same thickness shows delayed penetration of diffusing substance. Since inert flakes provide corrosion protection by a physical barrier mechanism, this section of the review briefly describes the theory of effective diffusion in flake filled polymers.

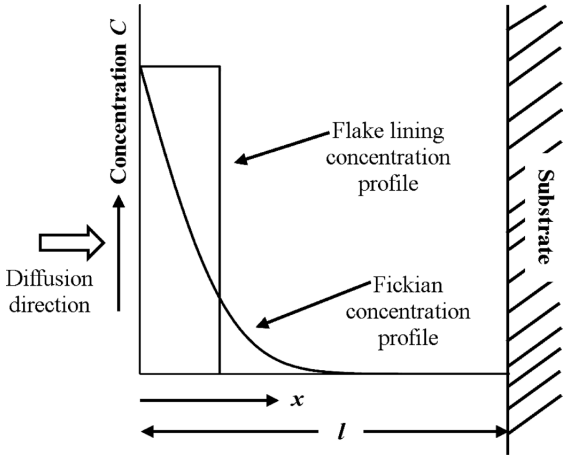

Fig. 2 Concentration profile of diffusing substance in a flake lining compared to a pure lining following Fickian diffusion

Compared to the other available shapes of inorganic filler, flakes of high aspect ratio provide the greatest improvement in barrier properties by an increase in diffusion path length and a reduction in diffusion area. **Figure 3** shows theoretically the dramatic effect of adding impermeable and aligned flakes to a permeable medium compared to the other shapes (Moggridge *et al.*, 2003; DeRocher *et al.*, 2005). In this figure, the barrier improvement is expressed in terms of normalized diffusivity (D/D_0), where D and D_0 are the

diffusivities of flake filled and unfilled permeable medium, respectively. Diffusivity of a composite with spheres or cylinders is only a linear function of volume fraction loading ϕ. Thus, for a volume fraction loading ϕ of 0.1, impermeable spheres could theoretically reduce the diffusivity of the unfilled coating by 14% and impermeable aligned cylinders by 18%. However, for impermeable aligned flakes with an aspect ratio α of 30, the corresponding reduction in the diffusivity of unfilled coating is 91%, which is significantly different to the modest improvement provided by spheres and cylinders.

The theoretical barrier improvement of aligned impermeable flakes shown in Figure 3 is mathematically expressed as Eq. (1) (Cussler *et al.*, 1988; Eitzmann *et al.*, 1996; Falla *et al.*, 1996; Ly and Cheng, 1997; Moggridge *et al.*, 2003; Lape *et al.*, 2004; Yang *et al.*, 2004; DeRocher *et al.*, 2005; White and Cussler, 2006; Chen and Papathanasiou, 2007).

$$\frac{D}{D_0} = \frac{1}{1+\alpha^2\phi^2/(1-\phi)} \tag{1}$$

Here, the flake aspect ratio α is defined as half the width of the flake divided by its thickness. The derivation of Eq. (1) is based on the assumption that the flakes are two-dimensional rectangles arranged in a staggered array, all oriented perpendicular to the diffusion direction. The flakes in Eq. (1) are also assumed to be of high aspect ratio and present in many layers, thereby neglecting the reduction in overall diffusion caused by regular slits and necking. The complete form of Eq. (1) is found in many published papers (Wakeham and Mason, 1979; Aris, 1986; Falla *et al.*, 1996; Moggridge *et al.*, 2003; Chen and Papathanasiou, 2007). The complete form of Eq. (1) suggests that the barrier characteristics of a permeable continuum containing flakes are attributed to: 1) diffusion resistance of the matrix without the flakes; 2) diffusion resistance caused by "wiggling," a term coined for the increased diffusion path length and decreased diffusion area at the presence of a flake; 3) diffusion resistance due to the uniform slit or space between two adjacent flakes; and 4) diffusion resistance due to necking, when diffusing molecules are forced to funnel down into the slits as they approach and leave the first and last layers of flakes, respectively.

Aside from the drastic change in diffusivity compared to spheres and cylinders at low volume fraction loading, Eq. (1) also offers other interesting features of flake filled matrices. First, the improvement in barrier properties expressed as (D/D_0) is independent of D_0. It does not matter if the impermeable flakes are reinforced in thermosetting or thermoplastic resin; the improvement in barrier characteristics (D/D_0) is only dependent on the shape and volume fraction of flakes. Also, the improvement in barrier properties (D/D_0) depends on the aspect ratio and volume fraction loading and not on the size of impermeable flakes. It does not matter if the glass flakes of a polymer microcomposite are of size 300×5 μm or the clay platelets of a polymer nanocomposite are 60×1 nm, so long as the flakes have equal aspect ratios, equal volume fraction loadings, equal spacing, and all oriented perpendicular to the diffusion direction, their effect on diffusion will be the same (Eitzmann *et al.*, 1996; Falla *et al.*, 1996; Moggridge *et al.*, 2003; Yang *et al.*, 2004; DeRocher *et al.*, 2005).

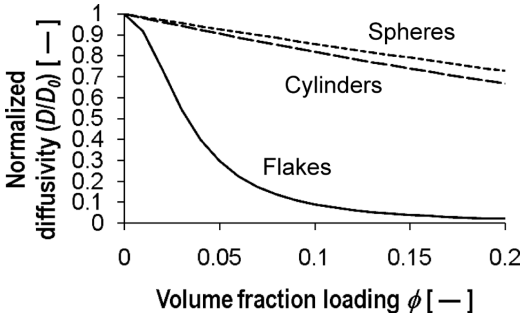

Fig. 3 Diffusivity changes caused by impermeable fillers at different shapes; the changes caused by aligned impermeable flakes at aspect ratio 30 are much lower compared to spheres and cylinders (Moggridge *et al.*, 2003; DeRocher *et al.*, 2005)

Other analytical models aside from Eq. (1) are suggested in literature to offer realistic estimates of barrier improvement in films reinforced with aligned impermeable flakes. Before Eq. (1), Nielsen's formula was mostly used (Yang *et al.*, 2004; DeRocher *et al.*, 2005; White and Cussler, 2006; Chen and Papathanasiou, 2007) with the assumption that the flakes are arranged in a quadratic array instead of staggered. Lape's models (Lape *et al.*, 2004; Chen and Papathanasiou, 2007) take into account the random arrangement in space of mono- and polydisperse flakes. Cussler *et al.* (1988) proposed a modified version of Eq. (1) using a geometric constant to consider the shape, size, and positional order of flakes (Brydges *et al.* 1975; Fredrickson and Bicerano, 1999; Moggridge *et al.*, 2003; DeRocher *et al.*, 2005). Numerical simulations and modelling were also performed to verify and compare the results derived from these analytical models (Swannack *et al.*, 2005; Goodyer and Bunge, 2009; Minelli *et al.*, 2009).

The discussion on reviewed models thus far are about coatings reinforced with impermeable flakes that are all oriented perpendicular to the diffusion direction (or parallel to the planar structure where the coating is applied). Such perfect alignment is difficult to achieve in the actual application of flake filled polymer coatings. Misaligned flakes cause the coating to be less tortuous and more prone to permeation, reducing the effectiveness of flakes in improving the barrier performance. The effect of flake orientation in barrier improvement is explored in several studies (Eitzmann *et al.*, 1996; White and Cussler, 2006) Flake alignment in coatings is influenced by solvent evaporation or application of shear. Likewise, flake settling and Brownian motion can destroy the uniform distribution of aligned flakes that is desired for maximum barrier performance. Large flakes are more susceptible to flake settling, while small flakes usually suffer misalignment by Brownian motion (Yang *et al.*, 2004).

Lastly, the resulting interphase after mixing two immiscible materials like inorganic flakes and organic polymer also affects the barrier improvement. Weak interphases are preferred diffusion pathways that result in lowered barrier

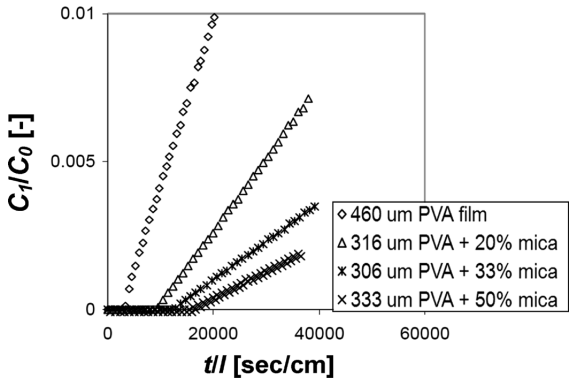

Fig. 4 Permeability of 0.15 M HCl solution in mica reinforced PVA films at different wt% (Yang *et al.*, 2004)

properties, as recently observed in epoxy composites filled with glass flakes without silane treatment (Pajarito *et al.*, 2012).

2. Anticorrosive Properties of Flake Filled Polymers

2.1 Results from diffusion measurements

Researchers have employed several ways to describe and evaluate the anticorrosive properties of flake filled polymers. Since conventional flake polymer composites provide corrosion protection by means of a barrier mechanism as explained previously, one way of assessing their anticorrosive properties is by studying their performance on reducing permeation and diffusion. **Figure 4** shows typical permeability data, in a case of mica flakes reinforced in polyvinyl alcohol films at different weight percentages during exposure to $C_0 = 0.15$ M HCl solution (Yang *et al.*, 2004). Measured data such as in Figure 4 shows the temporal variation of normalized acid concentration C_1/C_0 in the receiving compartment of a diaphragm cell, a sample setup schematically shown in **Figure 5** (DeRocher *et al.*, 2005). As shown, adding impermeable flakes to polymer films increases the lag time and decreases the permeation rate of acid as compared to pure polymer film. The permeability of the flake filled polymer is then determined from the permeation rate or slope of the graph, while the diffusivity is obtained from the measured lag time (Cussler, 1988; Ward *et al.*, 1991; DeRocher *et al.*, 2005). The experimental setup shown in Figure 5 is convenient for determining the permeability and diffusivity of thin polymer films.

Weight changes of flake filled polymers are also monitored during absorption and immersion to investigate the anticorrosive properties of flake filled polymers. Nematollahi *et al.* (2010) performed water absorption tests of DGEBA epoxy coatings reinforced with nanoglass flake and montmorillonite organoclay at 70°C, as shown in **Figure 6**. The water absorption test was carried out under the specifications of ASTM D570. The slope of the graphs in their study is observed to be decreasing as the amount of filler is increased, indicating reduced diffusion by flake reinforcement. Also, the epoxy composites were able to reach equilibrium,

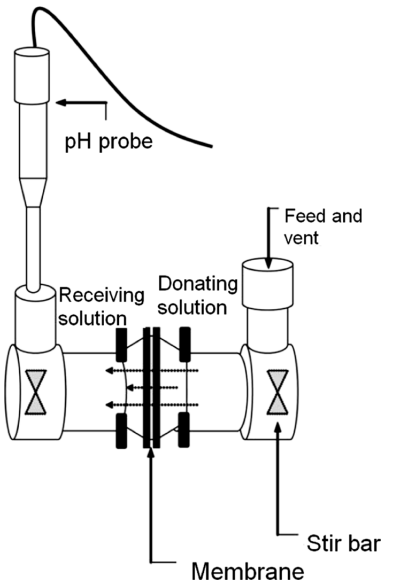

Fig. 5 Diaphragm cell for permeation studies in thin flake filled polymers (DeRocher *et al.*, 2005)

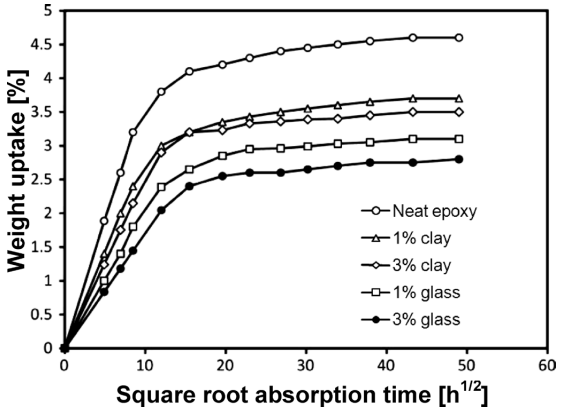

Fig. 6 Water absorption curves of DGEBA epoxy coatings reinforced with nanoglass flake and organoclay at 70°C (Nematollahi *et al.*, 2010)

suggesting Fickian diffusion behaviour and enabling the calculation of diffusivity from the initial slope of the graphs.

Abacha *et al.* (2009) studied water and sulfuric acid absorption curves of epoxy composites reinforced with montmorillonite organoclay at different temperatures. The weight changes of samples continue to increase with immersion time without reaching equilibrium. Though the clay platelets are expected to lower the liquid absorption of epoxy composites, they are hydrophilic enough to absorb water, and thus increase the weight uptake of epoxy composites. These results are rarely observed in glass and mica flake filled polymer composites since the fillers are inert and incapable of absorbing the diffusing environment.

Figure 7 illustrates another method of describing and evaluating the anticorrosive properties of flake filled polymers. The figure shows the detection of sulfur ions as they diffuse and penetrate the epoxy composites reinforced with montmorillonite organoclay during full immersion in 10

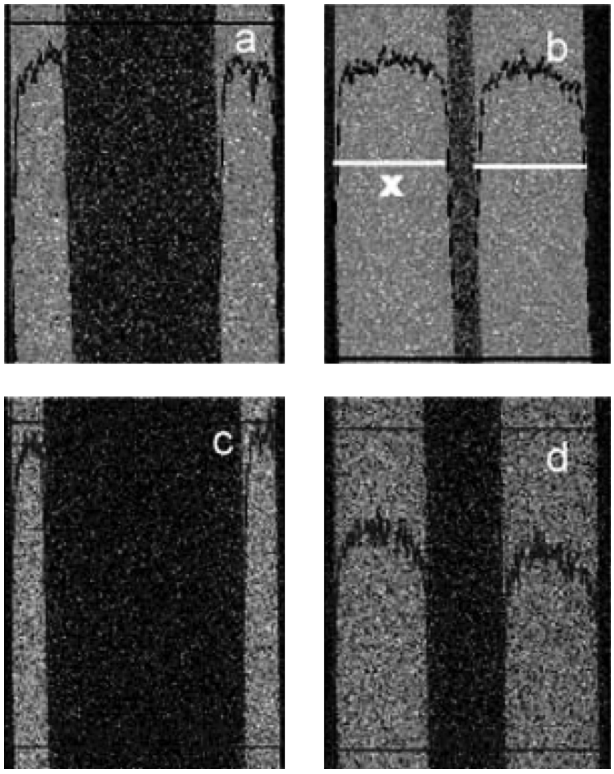

Fig. 7 Detection of sulfur element during diffusion of 10 wt% sulfuric acid solution in epoxy composites reinforced with montmorillonite organoclay by EDS: a) after 8 h in epoxy; b) after 50 h in epoxy; c) after 8 h in 0.5 phr composite; d) after 50 h in 0.5 phr composite (Abacha *et al.*, 2007)

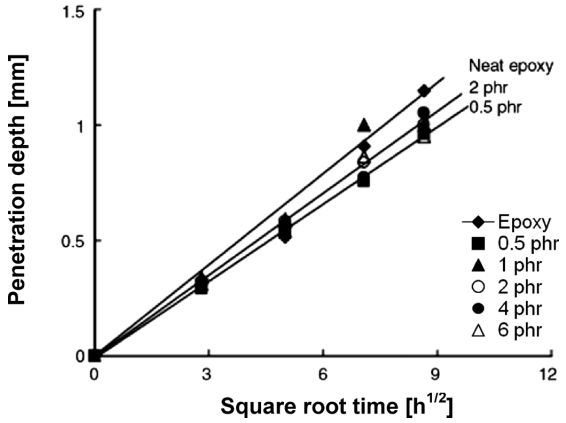

Fig. 8 Sulfur penetration depth as a function of square root immersion time in epoxy composites reinforced with montmorillonite organoclay (Abacha *et al.*, 2007)

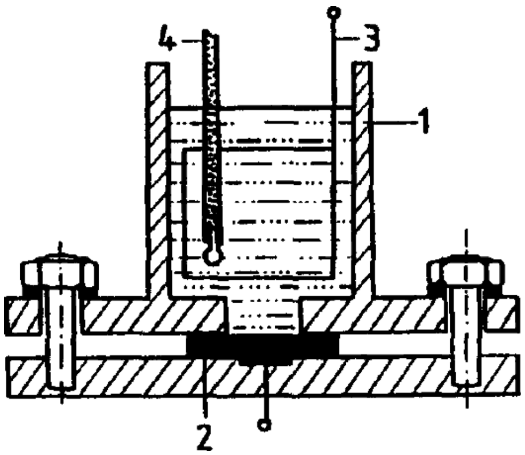

Fig. 9 Sample electrochemical cell configuration for corrosion studies on substrates coated with flake filled polymer; 1. electrolyte container; 2. coated metal as working electrode; 3. Pt gauze as counter electrode; 4. reference electrode (Rammelt and Reinhard, 1994)

wt% sulfuric acid solution (Abacha *et al.*, 2007). The images are taken by coupled scanning electron microscopy-electron dispersive spectroscopy (SEM-EDS). The method is usually applied in acidic immersions containing detectable elements such as sulfur and chlorine. The penetration of sulfur in the flake composite material is visually slower compared to pure epoxy resin. Using the generated concentration line profile, the penetration depth of diffusing element can be monitored during immersion. **Figure 8** shows the penetration depth of sulfur element in epoxy composites reinforced with montmorillonite organoclay as a function of the square root immersion time (Abacha *et al.*, 2007). The penetration depth of sulfur element in pure epoxy and its flake composites is linear with the square root immersion time. The slope of the line describes the rate of sulfur element penetration in the material. Reinforcing epoxy with organoclay flakes decreases the rate of penetration in the material.

2.2 Results from electrochemical evaluation

While the previous reviewed papers evaluate the anticorrosive properties of flake filled polymers by their performance in reducing diffusion and permeation of moisture and acids, most research studies assess the corrosion protection of flake filled polymers by electrochemical methods. It is an established fact that the corrosion of coated metals is an electrochemical process, and using electrochemical methods to evaluate the corrosion performance will provide a better understanding on how a flake filled polymer coating protects a metal substrate (Rammelt and Reinhard, 1994). Electrochemical study of corrosion in flake filled polymers requires an electrochemical cell, a sample configuration shown in **Figure 9** (Rammelt and Reinhard, 1994). The electrochemical reaction being studied occurs at the working electrode, which is the substrate coated with reinforced polymer. The coated substrate is usually exposed to a corrosive environment (salt spray, condensation chamber, atmospheric exposure, etc.) before testing. Several techniques are commonly used to evaluate the corrosion activity in substrates covered with flake filled polymers.

The half-cell potential method involves measuring the variation of open circuit potential and estimating the likelihood of corrosion activity in the specimen at the time of measurement. Sathiyanarayanan *et al.* (2008) studied the variation in open circuit potential of glass flake and polyaniline glass flake composite containing epoxy paint in 3%

NaCl solution. The epoxy paint filled with polyaniline and glass flake has higher corrosion protection ability than the epoxy paint filled with untreated glass flake, as shown by the shift to positive open circuit potential values with time. The paint filled with plain glass flakes, on the other hand, has open circuit potential values shifting to the active direction. Though both types of flakes are capable of anticorrosion by barrier protection, the polyaniline glass flake filler is also capable of electrochemical protection by passivation of iron substrate.

Figure 10 shows Tafel plots of bare, epoxy-coated, and flake-filled epoxy coated specimens in 5 wt% NaCl solution (Yeh and Chang, 2008) obtained by the potentiodynamic polarization resistance method. The curved lines show the total current contributed from anodic and cathodic currents. The open circuit potential at the equilibrium state of the system is first measured and is recorded as the corrosion potential E_{corr}. The polarization resistance R_p is then measured by sweeping the applied potential below and above the recorded corrosion potential at a certain scan rate. The corresponding current change is recorded as shown, and the polarization resistance is obtained from the slope of the potential-current plot. The corrosion current I_{corr} is determined by superimposing the straight line along the linear portion of the anodic or cathodic curve and extrapolating it through E_{corr}. The corrosion rate R_{corr} is then calculated from I_{corr} (Yeh *et al.*, 2006). Improved anticorrosive properties of specimens are characterized by higher values of E_{corr} and R_p and lower values of I_{corr} and R_{corr}, as observed in Figure 10, due to flake reinforcement.

In the electrochemical impedance spectroscopy method, a pertubating voltage is applied to the system and the corresponding current is measured in a wide range of frequencies. The impedance Z is then determined experimentally as a function of frequency. Typical examples of Nyquist and Bode impedance plots obtained using this method are shown in **Figure 11** (Gonzalez-Guzman *et al.*, 2010). The measured impedance spectra is then described by an equivalent circuit, which consists of electrical equivalent such as capacitances, resistances, and distributed elements. The combination of these elements in the equivalent circuit should have the same impedance as the measured system (Rammelt and Reinhard, 1994). Based from the plots in Figure 11, two time constants are operating and the spectra could be analysed in terms of an equivalent circuit for a defective coating. The equivalent circuit for a defective coating is made up of the resistance of the test electrolyte, the capacitance of the intact coating layer, the pore resistance due to penetration of electrolyte, the polarization resistance of the substrate, and the double layer capacitance at the substrate/electrolyte interphase (Gonzalez-Guzman *et al.*, 2010; Shreepathi *et al.*, 2011).

3. Flake Filled Polymers in the Chemical Process Industry

The current use of flake filled polymers in the chemical process industry has always been in the form of coatings and linings for the corrosion protection of metal and concrete structures. They provide exterior coatings for structural steel, walls, and ceilings and act as linings for tanks, chemical vessels, absorbers, scrubbers, ducts, and stacks; they also serve as linings for floors and for concrete secondary containment of chemical spills and leakage. Flake reinforcement is most effective in reducing the permeation of polymer

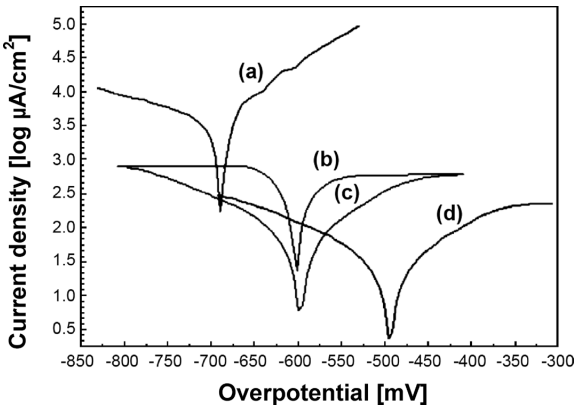

Fig. 10 Tafel plots for (a) bare, (b) epoxy-coated, (c) 1 wt% clay–epoxy coated, and (d) 5 wt% clay–epoxy coated cold rolled steel samples in 5 wt% NaCl solution (Yeh and Chang, 2008)

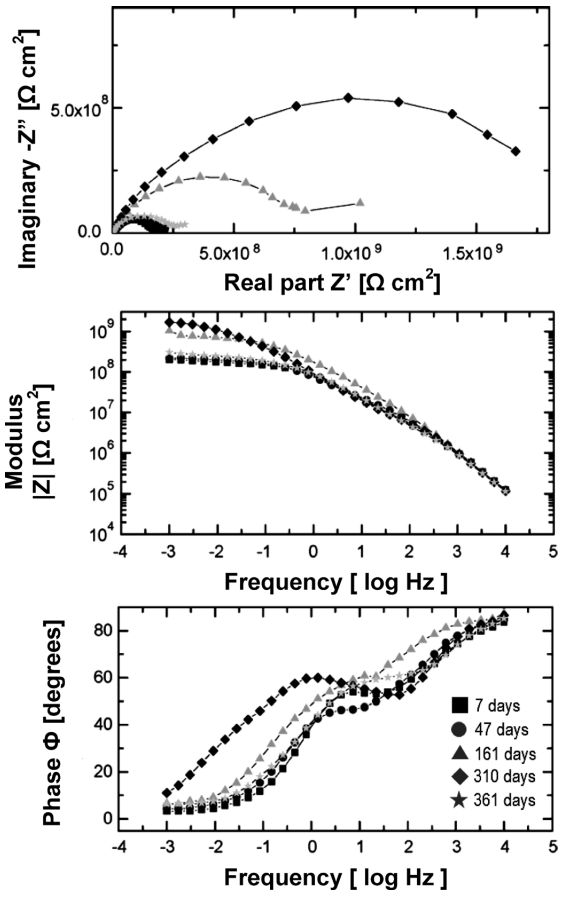

Fig. 11 Impedance spectra of a carbon steel coated with epoxy–polyamine film containing glass flakes in 3 wt% NaCl solution (Gonzalez-Guzman *et al.*, 2010)

Table 1 Permeability of various polyester and vinyl ester linings (Slama, 1996)

Lining type			Permeability [g/Pa-s-m]	Thickness [mm]	Permeance [g/Pa-s-m^2]	Max wet service [°C]
Resin	Filler/Reinforcement	Application				
Novolac vinyl ester	3 mm Flake glass	Trowel and roll 2 coats	1.6×10^{-13}	1.8	9.2×10^{-11}	93+
Bisphenol A polyester	3 mm Flake glass	Trowel and roll 2 coats	3.2×10^{-15}	1.8	1.8×10^{-10}	93+
Novolac vinyl ester	0.4 mm Flake glass	Spray 3 coats	1.4×10^{-12}	1.4	1.1×10^{-09}	66
Bisphenol A polyester	Silica filler fiberglass cloth	Trowel/roll and trowel topcoat	4.0×10^{-12}	3.8	1.2×10^{-09}	71
Bisphenol A polyester	Silica filler fiberglass mat	Trowel basecoat mat/ resin coats	6.0×10^{-12}	3.2	2.0×10^{-09}	71
Bisphenol A polyester	Mica flake	Spray 2 coats	2.0×10^{-12}	0.9	2.6×10^{-09}	54
Bisphenol A polyester	Fiberglass mat	Roller-applied fiberglass mat	1.0×10^{-11}	1.5	7.4×10^{-09}	49
Isophthalic polyester	Mica flake	Spray 2 coats	4.0×10^{-12}	0.46	9.5×10^{-09}	49

Table 2 Proposed coatings for concrete secondary containments (Nau and Fultz, 1990)

Facility	Type and concentration of liquid	Description of coating	Published resistance for a specific service			Maximum temperature of coating in general service	
			Concentration [%]	Exposure	Temperature [°C]	Wet [°C]	Dry [°C]
Acid storage tank	98% H_2SO_4	3.2 mm Glass cloth–vinyl ester	80–98%	Immersion	71	71	121
Caustic storage tank	50% NaOH	1 mm Flake-filled vinyl ester	50%	Immersion	54	54	93
Combination acid/caustic storage tanks	98% H_2SO_4 50% NaOH	1.5 mm Epoxy novolac	98% H_2SO_4 50% NaOH	Spillage	54	54	64
Sodium hypochlorite tank	15% NaOCl	1 mm Flake-filled vinyl ester	17%	Spillage	38	54	93
Neutralization basin	2–20% H_2SO_4 or NaOH	1 mm Flake-filled vinyl ester epoxy novolac or 3.2 mm glass cloth–vinyl ester	2–20% H_2SO_4 50% NaOH	Spillage Immersion	54 54	54	93
Demineralizer tank	2–20% H_2SO_4 or NaOH	1 mm Flake-filled vinyl ester	2–20% H_2SO_4 50% NaOH	Spillage Immersion	54 54	54	93
Steam turbine lube oil area	Lubricating oil	1 mm Flake-filled vinyl ester	Crude Mineral Gasoline	Immersion Immersion Immersion	38 38 38	54	93
Boiler chemical feed area	5–10% Phosphate 2–5% Cyclohexylamine 1–5% Isoascorbic acid	1 mm Flake filled vinyl ester	None	None	54	93	
Diesel fuel storage tank	Diesel fuel	Two-coat epoxy	Diesel	Immersion	38		

coatings and linings. **Table 1** shows the permeability and permeance of various reinforced polyester and vinyl ester linings (Slama, 1996). The listed properties were determined by ASTM 96, Test Methods for Water Vapor Transmission of Materials. Trowel-applied glass flake filled systems provide the highest permeation resistance due to inclusion of large glass flakes. Smaller glass or mica flakes are used in spray-applied systems. Since most of these linings will be subjected to immersion at elevated temperatures, determination of the maximum wet service temperature is established with Atlas cell test specified in ASTM C 868, Test Method for Chemical Resistance of Protective Linings (Slama, 1996). A wealth of information on examples and application of flakeglass linings in the chemical process industry is available in Mallinson (1988). The Japanese also have the JIS K 6940-1998 standard for glass flake vinyl ester lining films in the corrosion protection of interior surface of steel tanks, towers, and vessels.

Table 2 shows examples of proposed coated secondary containment concrete structures (Nau and Fultz, 1990) using flake filled polymers in power plants. Secondary chemical containment structures are used for catching and containing leaks and spills from primary storage vessels and transport systems. Flake filled polymer linings are

recommended for intermittent, short-term chemical containment.

Conclusion

This article reviews the theory behind flake reinforcement in polymers for corrosion protection. The aligned flakes form a lamellar barrier structure which reduces the area available for diffusion and increases the diffusing pathways of corroding agents within the polymer coating or lining. Diffusion models are suggested in the literature to describe the reduced transport in flake filled permeable media. A number of experimental methods has been applied in recent studies to measure the corrosion protection capability of flake filled polymers. The experimental techniques for assessing the anticorrosive properties of flake filled polymers include permeation, liquid absorption and immersion tests, and electrochemical methods. At present, flake filled polymer coatings and linings protect metal and concrete surfaces in equipment and structures in the chemical process industry.

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