

CHAPTER II

THEORY

2.1 PHYSICAL AGING

Physical aging has been known for many years as an intrinsic property of glassy materials. It takes place because of the non-equilibrium state of the material when cooled through the glass temperature (T_g) region at such a rate that the molecules can not obtain their equilibrium configuration corresponding to the temperature T at which the cooling is stopped ($T < T_g$). Above T_g , retardation times are short enough to enable material properties, for instance, volume and entropy to follow the changes in temperature, but below T_g the retardation times become too long. To a first approximation, the state existing at T_g is frozen-in and the material properties at temperature $T < T_g$ deviate from those in the equilibrium state at T . The result is a slow structural relaxation process that induces changes in many material properties. This slow approach to equilibrium is called physical aging.

Physical aging shows itself in several ways, e.g., as volume relaxation and changes in viscoelastic properties. Therefore, physical aging reflects the thermal history of polymeric material. The aging and weathering, a term used for the exposure outdoor, behavior of a plastic material will be dependent on many factors. The following factors may cause a change in the properties of a polymer:

- (1) Chemical environments, which may include atmospheric oxygen, acidic fumes and water.
- (2) Heat.
- (3) Ultra-violet light.
- (4) High-energy radiation.

In a commercial plastic material, there are regularly a number of other ingredients that may be affected by the above factors. Moreover, they may interact with each other and with the polymer so that the effects of the above factors may be more, or may be less, violent.

A serious present problem for polymeric technologists is to be able to predict the aging behavior of a polymer over a prolonged period of time, often 20 years or more. Thus, it is desirable that some reliable accelerated weathering test should exist. Unfortunately, accelerated tests that have been used until now attain solely very limited success. One reason is that when more than one deteriorating factor is present, the overall effect may be quite different from the sum of the individual effects of these factors. In an accelerated light aging test, it is more desirable to expose the specimen to the same light distribution as 'average daylight' but at greater intensity. However, it is difficult to obtain light sources that imitate the energy distribution. For this reason, exposure to sources such as daylight, carbon arc lamps and xenon lamps have different results on plastic materials.

2.2 COMPOSITES

Composite materials have a long history of usage. In their widest form, composites are the result of two or more materials that are combined on a macroscopic scale to form a useful material. Distinct materials can be combined on a microscopic scale but the final material is macroscopically homogeneous. Generally, the main phase is known as matrix and the other phase is called the dispersed phase. The functions and requirements of a matrix are to keep the dispersed phase in the structure, distribute or transfer load, protect the dispersed phase either in the structure or before fabrication and control chemical and electrical properties.

There are several advantages of composites, as well as some disadvantages. The advantages include weight reduction, longer life (no corrosion), lower manufacturing costs due to lower part count. In contrast, the disadvantages include difficulty in analysis, cost of raw materials and

fabrication, possible weakness of transverse properties and environmental degradation of matrix.

For classification of composites, there are many types of composites. Depend on the types of matrix, composites can be categorized as polymer matrix composites, metal matrix composites, ceramic matrix composites, carbon-carbon composites, intermetallic composites or hybrid composites (Schwartz, 1997). Polymeric composites have been widely used nowadays and are the most developed class of composite materials in that they have widespread applications, can be made into large, complicated shapes. The most extensively used matrix for advanced composites has been the epoxy resins. Their benefits include adhesion to fibers and resin, no by-products formed during cure, resistance to solvents and chemicals, wide range of curative options. They also have some disadvantages such as change in physical properties because of moisture absorption, high thermal coefficient of expansion, slow curing and may be sensitive to ultraviolet light degradation.

Based on the form of the dispersed phase, composite materials can be classified in to three commonly accepted types, fibrous composites, laminated composites and particulate composites, respectively (Jones, 1975). Fibrous composites consist of continuous or discontinuous fibers in a matrix, while laminated composites consist of layers of various materials and particulate composites are composed of particles dispersed within a matrix.

In fiber-reinforced composites, the dispersed phase is high-strength, high stiffness, long fibers in a surrounding matrix, a resinous binder for polymeric composites. The fibers used may be in the form of either single fibers with diameter of about 7 to 15 μm , or multiple fibers twisted together in the form of a yarn or tow. Fibers are embedded in or bonded to a matrix with individual interfaces between them. In this form, both fibers and matrix maintain their physical and chemical properties. Nevertheless, they will produce a combination of properties that can not be received with either of

the constituents acting alone. Generally, the main fibers in commercial use are various types of glass fiber and carbon fiber, as well as aramid fiber and boron fiber.

2.3 EPOXY RESINS

Generally, the term *epoxy* refers to a chemical group comprising of an oxygen atom bonded with two carbon atoms, called epoxide group, already united in some other way. The simplest epoxy is a three-membered ring, to which the -epoxy or 1,2-epoxy is applied. Ethylene oxide is an example of this type. The structure of ethylene oxide is shown in Figure 2.1.

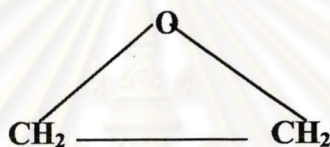


Figure 2.1: Ethylene oxide

There is no universal agreement on the nomenclature of the three-membered epoxy ring. There is division even on the term epoxy itself. They have also been known by other names, for example, epoxides, ethoxylines, oxiranes, glycidyl polyethers and diepoxide polymers.

Cured epoxy resins form the prime matrix for high performance glass, aramid and carbon fiber composites, while the unsaturated polyester resins are primarily used in industrial applications. This is because epoxy resins combine good mechanical properties with 'easy' processing that meets the generalized requirements of a matrix polymer. They are low viscosity for fiber impregnation, high reactivity on curing, chemical control of cure without volatile formation, low shrinkage, and good mechanical and thermomechanical properties.

2.3.1 Types of epoxy resins

Epoxy resins have been divided by the raw material from which they were derived. Three major types of commercial epoxy resins are cycloaliphatic epoxy resins, epoxidized oils and glycidated resins. Their structures are shown in Figure 2.2.

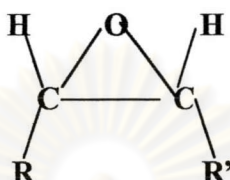


Figure 2.2: General structure of an epoxy resin.

2.3.1.1 Cycloaliphatic epoxy resins

Cycloaliphatic epoxy resins have low viscosity. They are composed of two components, cycloolefins epoxidized with peracetic acid and diglycidyl esters of cyclic dicarboxylic acids. Curing agents which can best react with these resins are the anhydride and the phenolic types of curing agents. Cycloaliphatic epoxy resins have high UV resistance and high arc-track resistance. Therefore, they have been widely used to form parts of transformers, insulators, wire, cable, generators and motors.

2.3.1.2 Epoxidized oils

Epoxidized oils (triglycerides) and other epoxidized esters naturally happen from fatty acids. They are effective plasticizers and stabilizers for polyvinyl chloride and copolymers when they are cured. Epoxidized soybean oil is the most widely used epoxidized oil.

2.3.1.3 Glycidated epoxy resins

Epoxy resins types used in most commercial applications are glycidated epoxy resins. Examples of this type of epoxy resin are bisphenol A, novolac epoxy resins and bisphenol F.

Most epoxy resins are made from bisphenol A. Historically, the first commercial epoxy resin was a reaction product of epichlorohydrin and bisphenol A, the reaction giving the diglycidyl ether of bisphenol A, salt and water. The chemical structure of bisphenol A is illustrated in Figure 2.3.

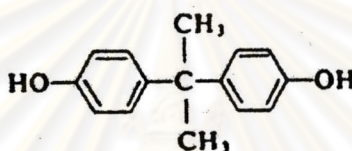


Figure 2.3: The chemical structure of bisphenol A.

The novolac resins produce more tightly crosslinked-cured systems than other types of epoxy resins. As a result, their elevated temperature performance are improved and their chemical resistance are likely to be greater than that of the epoxy resins from bisphenol A. The structure of novolac resins are shown in Figure 2.4. Novolac resins can be utilized in adhesives, storage tanks, corrosion-resistant coatings, structural and electrical laminates and filament-wound pumps.

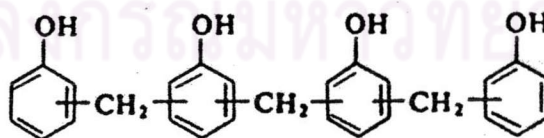


Figure 2.4: The chemical structure of novolac resins.

Bisphenol F epoxy resins generally have the properties falling between bisphenol A and novolac resins. They are used in high-solids-high-build systems such as tank and pipe lining, industrial floors, road and bridge deck toppings. Figure 2.5 illustrates the chemical structure of bisphenol F.

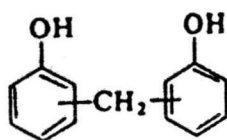


Figure 2.5: The chemical structure of bisphenol F.

The epoxy resins obtained from bisphenol A are easy to process and control. Hence, they are widely used and is also the epoxy resin selected for the present study.

2.3.2 Preparation of epoxy resins

Nowadays, about 95% of the epoxy resins used extensively in commercial industries are diglycidyl ether of bisphenol A. They are synthesized by the reaction of bisphenol A (2,2-bis (4-hydroxyphenyl)-propane) and epichlorohydrin.

Bisphenol A can be prepared from the reaction of two molecules of phenol and one molecule of acetone at a temperature range of 50-60°C with hydrochloric acid as a catalyst. The reaction is shown in Figure 2.6.

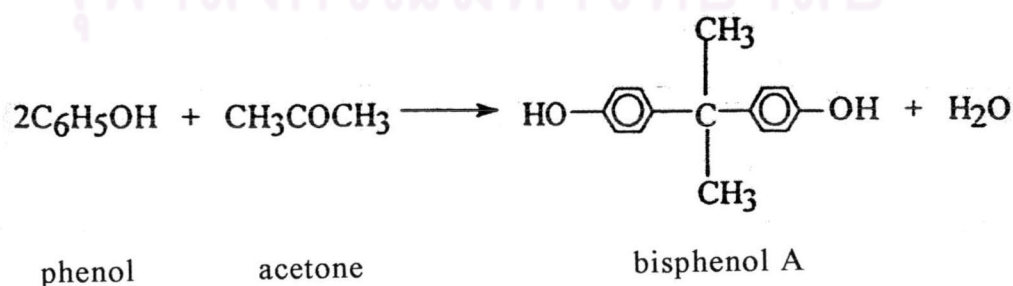


Figure 2.6: Formation of bisphenol A.

Epichlorohydrin is acquired by the chlorination of propylene under high temperature. Allyl chloride is the main product from the reaction. Then, the hypochlorous acid is added to the allyl chloride at 30°C to yield glycerol dichlorohydrin. Finally, dehydrochlorination occurs and produces epichlorohydrin. The formation of epichlorohydrin is displayed in Figure 2.7.

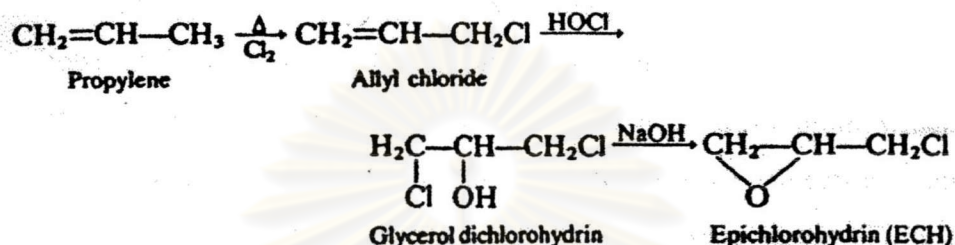


Figure 2.7: Formation of epichlorohydrin.

Bisphenol A epoxy resins used in the present study is diglycidyl ether of bisphenol A (DGEBA). The formation of DGEBA from bisphenol A and epichlorohydrin is shown in Figure 2.8. From the reaction, DGEBA is obtained by reacting epichlorohydrin with bisphenol A in the presence of sodium hydroxide. The reaction takes place in two steps; they are the formation of a chlorohydrin intermediate and the dehydrohalogenation of the intermediate to the diglycidyl ether, respectively. Each molecule of the diglycidyl ether will react with that of the bisphenol A at the epoxide group, forming eventually the higher molecular weight DGEBA at last.

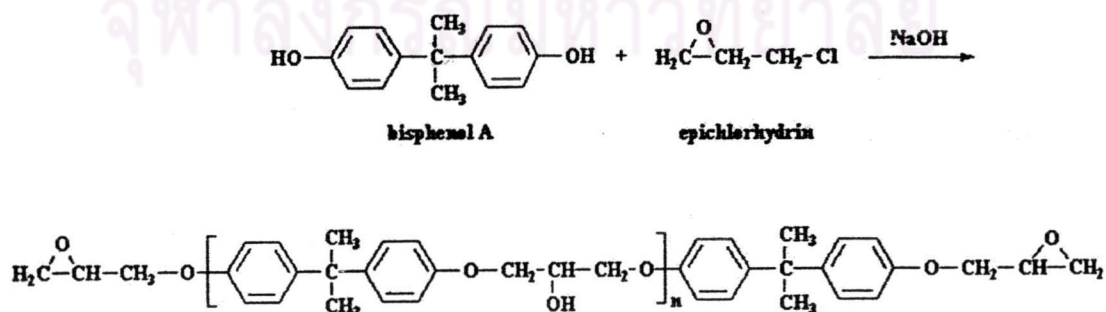


Figure 2.8: Formation of diglycidyl ether of bisphenol A (DGEBA).

2.3.3 Basic characteristics of epoxy resins

Many good properties of epoxy resins have led them to fast growth and their use in a wide range of industries. The epoxy resins possess a preferably unique combination of properties as following:

2.3.3.1 Low viscosity. The liquid epoxy resins and their curing agents can produce low viscosity, easy to process (or modify) systems.

2.3.3.2 Easy cure. Epoxy resins cure rapidly and easily at practically any temperature from 5 to 150°C, depending on the selection of curing agents.

2.3.3.3 Low shrinkage. Their low shrinkage during cure are one of the most advantageous properties of the epoxy resins. Furthermore, epoxy resins react with very little rearrangement and without volatile by-products being evolved.

2.3.3.4 High adhesive strengths. Owing to the chemical makeup, mainly the presence of the polar hydroxyl and ether groups, the epoxy resins are excellent adhesives. They can be cured with low shrinkage, thus the various surface contacts set up between the liquid epoxy resins formulation and the adherents are not disturbed during cure. Adhesive strengths without the need for both open time and high pressure are perhaps the best available in the contemporary plastic technology.

2.3.3.5 High mechanical properties. The strength of appropriately formulated epoxy resins usually surpasses that of other types of casting epoxy resins. This is due to their low shrinkage and comparatively unstressed structure after curing.

2.3.3.6 High electrical properties. Cured epoxy systems exhibit good electrical properties over a range of temperatures and frequencies. They are excellent electrical insulators.

2.3.3.7 Good chemical resistance. The chemical resistance of the cured epoxy resin relies considerably on the curing agent used. Generally, most epoxy resins possess extremely high resistance to caustics and good to excellent resistance to acids.

2.3.3.8 Versatility. The epoxy resins are likely the most versatile of the modern plastics. The basic properties may be modified in many ways such as by blending of resin types, by selection of appropriate curing agents, and by application of modifiers and fillers.

2.3.4 Applications for epoxy resins

Due to their versatility, the epoxy resins are applied in several industrial applications. There are many indicators of the range of applications. For example, epoxy resins are used as adhesives for aircraft honeycomb structures, for the paintbrush bristles and for concrete topping compounds. They also utilized as body solders and caulking compounds for the repair of plastic and metal boats, automobiles, etc. For caulking and sealant compounds, epoxy resins are also applied in building and highway construction applications and in applications where high chemical resistance is required. As potting and encapsulation compounds and impregnating resins for electric and electronic equipment, epoxy resin provides an interesting extension to the use of plastics materials as insulators. Moreover, epoxy-based solution coatings are used as maintenance and product finishes, marine finishes, masonry finishes, aircraft finishes and so on. They are also applied for concrete-floor paints and floor vanishes.

2.4 CURING AGENTS

The most valuable property of the epoxy resins is their ability to reform easily from the liquid state to tough, hard thermoset solids. The conversion is achieved by an addition of a chemically active curing agent or hardener.

Curing may occur at room temperature with heat produced by exothermic reaction, or it may require external heat to cure. Therefore, the properties of epoxy resins resulted from the cure tend to vary depending on the type of the curing agent. Nowadays, curing agents are categorized into four general types: aliphatic amines, aromatic amines, anhydrides and amides, respectively. Selection of the curing agents depends on many factors. In consideration of the convenient processing, aliphatic amine is preferable in concrete structure applications because curing can take place at ambient temperature. Examples of aliphatic amines are diethylenetriamine (DETA), triethylenetetramine (TETA). A modified amine curing agents is selected for the present study.

2.4.1 Modified amine curing agents

A number of modifications have been developed to improve the performance of commercial amines as curing agents. Adducts have been produced from alkyl mono- and diepoxies, from ethylene and propylene oxide, from acrylonitrile, and from aldehydes. Ethylene and propylene oxide adducts are applied in this study.

Ethylene or propylene oxide adducts of amines are achieved by reaction with amine in the presence of water. Base upon the ratio of the reactants and the reaction conditions, the end product will comprise predominantly of the mono- or bishydroxyalkyl derivatives. With bis(hydroxyethyl)diethylenetriamine, for instance, a polysecondary amine is formed. Polysecondary amines react similarly to primary amines and provide satisfactory cure by crosslinking with diepoxy resins when the number of active hydrogens exceeds two.

2.5 CARBON FIBER

Carbon fibers are fine filament composed largely of carbon with structures and properties varying from those of amorphous carbon to those of well-developed crystalline graphite. They are characterized by their flexibility, electrical conductivity, and in their high performance varieties. Their Young's moduli range from 5 million p.s.i., which is half of that of glass fiber, to 120 million p.s.i., which is four times of that of steel. The ratio of stiffness to density is very high for most carbon fiber because the density of carbon is low. For this reason, they are the most widely used and are notably effective as reinforcing elements in advanced composite materials.

2.5.1 Carbon fiber types

The structure and properties of a certain carbon fiber depend on the raw material used, generally a polymer fiber. With current manufacturing technology, just three precursors have been used for commercial products: rayon, acrylic or PAN (polyacrylonitrile) fibers, and fibers spun from pitch. These products are discussed separately in the next subsection.

The manufacturing of carbon fiber operations involve the heat treatment of a carbon-containing raw material. Carbon fibers are produced by appropriately orientating and aligning the molecular chains of a polymer fiber and then carbonizing them.

2.5.1.1 Rayon-based carbon fibers

The first high-stiffness carbon fibers were produced from rayon. However, rayon-based Carbon fiber did not compete with the PAN-based carbon fiber that became commercially available by the late sixties. The production process for rayon-based carbon fiber has three steps: preparation and heat treating, carbonization, and optional high temperature heat treatment. The products are usually used in the form of cloth for aerospace

application. Several major rayon manufacturers had discontinued production of rayon-based Carbon fiber because its manufacturing process is quite expensive.

Many applications for rayon-based carbon fibers depend on their stability at very high temperatures and the high carbon content of over 99%. In these issues, they are not easily replaceable by the standard PAN-based fibers that have a lower carbon content. Mesophase pitch-based fibers can be manufactured with properties very similar to those of rayon-based fibers and may be expected to be a substitute in many applications.

2.5.1.2 PAN-based carbon fibers

Historically, PAN was the original precursor for high strength carbon fibers and is still the most important carbon fiber. In this field, production of PAN-based carbon fibers involves three steps namely low temperature heat treatment, carbonization, and optional high temperature heat treatment. The principal difference from the rayon-base fiber process is that the orientation is performed during the first step of heat treatment under tension, and it is essentially maintained through carbonization. Figure 2.9 illustrates the manufacturing process of carbon fiber from acrylic fiber.

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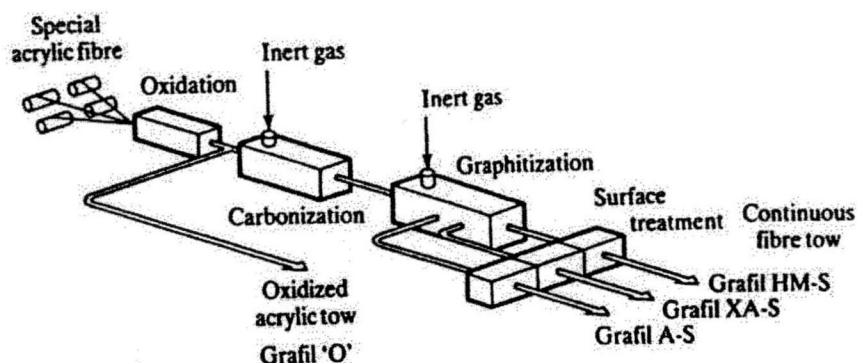


Figure 2.9: Carbon fiber manufacturing process from polyacrylonitrile

Until 1972, Pan-based carbon fibers were used almost exclusively in epoxy preregs where structures for the aerospace industry were fabricated. The higher cost was remedied by its advantages of weight savings and performance improvements. By 1976, fiber price reduction and important advances in composite fabrication technology had made carbon fiber composites cost competitive with many metal parts in aircraft construction. During the same period, a second major market for PAN-based carbon fibers was developed in the sporting goods industry. Applications in textiles and computer machinery, automotives and general transportation also grew rapidly.

2.5.1.3 Mesophase pitch-based fibers

Pitch, a widely available by-product of the coal gasification and petrochemical industries, has long been considered an attractive, low cost precursor for the production of carbon fibers. However, all such fiber yields composites with comparatively low strengths. At present, the high modulus of pitch is offset by a reduction in strength. Moreover, pitch-based carbon fibers have very poor compressive strengths. Hence their use under tensile applications is limited. Pitch-based fibers are commonly favored when stiffness is the desired material property and secondary to strength.

2.5.2 Applications of carbon fiber

Large weight savings are possible when carbon fiber composites are used to replace more conventional materials, so they are frequently applied in areas where weight reductions are valuable. For instance, they are used in a variety of aerospace components. Carbon fibers and their composites exhibit many useful characteristics apart from their basic mechanical properties and weight saving potential. For example, their electrical conductivity is coupled with excellent mechanical properties in thermoplastic molding compounds for structures in electronic equipment. Their corrosion resistance is useful for making pipes, reactors or containers for chemical plants or in marine environment. Example of sports equipments that contain carbon fiber reinforcement include skis and ski poles, golf clubs, tennis racquets, fishing rods, and racing cycles. Additionally, the fatigue resistance and low inertia of the Carbon fibers rendered them to be employed in high speed rotating and reciprocating components in machine tools, business machines and computer memory devices.

2.6 ARAMID FIBER

Aramids are high performance polymeric material known for their lightness in weight, good thermal stability and excellent toughness. The name 'aramid' is a United States Federal Trade Commission denomination for a manmade polymer that has the common structure of aromatic rings alternating with amide linkages (*aromatic polyamide* fibers). In the United States, aramid is available in either a straight-chain structure, known as the Kevlar family, or a bent-chain structure, known as Nomex, depending on whether the aromatic rings are para- or meta-distributed, respectively. Both are manufactured by Dupont. In the Netherlands, Akzo produces 'Twaron', which has a para-substituted structure.

Aramid fiber has outstanding heat resistance. It is used extensively in electrical insulation, protective apparel applications, and in honeycomb cores for composite sandwich structures. Nowadays, it is widely used in reinforced plastics, tires, belts and hoses, cables, brakes, gaskets, and coated fabrics.

2.6.1 Methods of preparation

The usual methods for the preparation of aliphatic polyamides are unfitted to the preparation of high molecular weight, totally aromatic polyamides. Nevertheless, two general synthetic methods are currently available for the preparation of medium to high molecular weight polymer. They are a low temperature polycondensation and a direct polycondensation in solution using phosphites, particularly in the presence of metal salts.

For the low temperature polycondensation approach, the principal low temperature methods are interfacial polycondensation and solution polycondensation. The most important polymerisation process for aromatic polymers is the low temperature polycondensation of diacid chlorides and diamines in amide solvents. This type of polymerisation is often more conveniently carried out than the interfacial polycondensation. It also has the advantage of providing a solution of the polymer amenable to direct fabrication of fibers. Both Nomex and Kevlar are produced from the low temperature polycondensation method with different diamine source.

Direct polycondensation of aromatic dicarboxylic acids and aromatic diamines in amide solvents using aryl phosphites in the presence of pyridine has later been demonstrated. Addition metal salts, e.g., LiCl, to the amide solvents has made it practicable to keep the polymer in solution formed during the reaction and thereby allow for the build-up of moderately high molecular weight polymer.

2.6.2 Applications of aramid fiber

Aramid composites were primary adopted in applications where weight savings had high value. Examples of which include components of commercial and general aviation aircraft, helicopters, space vehicles, and missiles. Aramid also is used in sail, kayaks and power boats where light weight, stiffness and damage tolerance are of value. The same quality has led to aramid's application in composites for sports equipment. Moreover, aramid fibers are utilized as elastomer reinforcement for tires, drive belts and conveyor belts. In elastomers, aramid gives high strength, stiffness, light weight, corrosion resistance and thermal resistance. Composite applications continue to grow with the development of the matrix systems that capitalize on aramid's unique properties.

2.7 TIME-TEMPERATURE SUPERPOSITION

2.7.1 Time-Temperature equivalence

One of the most important viscoelastic behaviors of polymeric materials is that modulus-time curve when temperature is set at constant and modulus-temperature curve when time is set at constant have an identical shape. This can be assumed that there are the relationship between time and temperature and the relaxation or retardation times involved vary with temperature in the same manner. In order to have enough data to characterize the viscoelastic behavior of an amorphous polymer, it is required to collect data on stress relaxation over ten to fifteen decades of time, approximately. In practice, this is extremely tedious and may not be possible. It has been suggested earlier by various investigators that for amorphous polymer, mechanical relaxation data obtained at various temperatures whether creep, stress relaxation, or dynamic experiments can be superimposed by a proper shift of time scale. This general phenomenon is known as time-temperature superposition.

Time-temperature superposition is an empirical method for combining data taken at several different temperatures into one curve for the polymer sample. By applying the appropriate shift factor, a_T , a so-called master curve proper to some arbitrary reference temperature is obtained from either mechanical or dielectric relaxation data. Application is made of the fact that a deformation for a short period of time at one temperature is equivalent to a longer period at a lower temperature. Therefore, it becomes possible to build up a master curve of relaxation modulus against time at a single arbitrary temperature by suitable processing of data gained at a variety of temperatures. A typical master curve is shown in Figure 2.10.

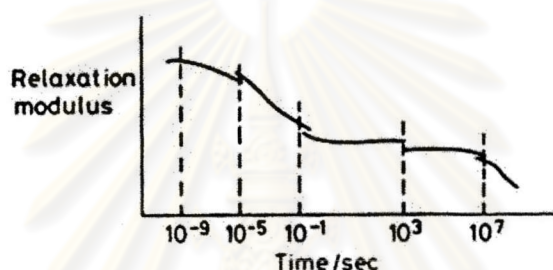


Figure 2.10: Stress relaxation master curve at a given temperature.

In order to draw the master curve exemplified, each section would have been completed in the time ranging from 10^{-1} to 10^4 s, but at different temperature. Then, combining the sections will produce the overall master curve. In order to convert data obtained at a given experimental temperature, T , to the reference temperature, T_0 , a shift factor, a_T is used and is defined in Equation 2.1.

$$a_T = \frac{t_T}{t_{T_0}} \quad (2.1)$$

where t_T is the relaxation time at temperature T , and t_{T_0} is the relaxation time at the reference temperature, T_0 .

2.7.2 The WLF equations

In spite of the marked dependence on molecular structure of the relation between a_T and absolute temperature, nearly general empirical relations have been derived by expressing the temperature for each material in terms of its T_g or some closely equivalent reference temperature. Among the most successful of these relations is the Williams-Landel-Ferry (WLF) equation (Williams 1955):

$$\log a_T = \frac{-C_1(T - T_r)}{C_2 + (T - T_r)} \quad \text{-----} \quad (2.2)$$

Here T_r is a reference temperature; C_1 and C_2 are the constants related to holes or free volume within the polymers. According to the more widely used empirical WLF equation, all linear, amorphous polymers have similar viscoelastic properties at T_g and at specified temperatures above T_g , such as $T_g + 50^\circ\text{C}$. When the T_g is the reference temperature, C_1 is 17.44 and C_2 is 51.6.

$$\log a_T = \frac{-17.44(T - T_r)}{51.6 + (T - T_r)} \quad \text{-----} \quad (2.3)$$

This equation has been assumed to be valid at temperatures between T_g and $T_g + 100^\circ\text{C}$. Equations 2.2 and 2.3 have been used to predict the long time behavior of materials from short time measurements.

2.8 FRACTURE OF POLYMER

A systematic study of the mechanical behaviors including fracture was firstly developed for metals, and the concepts were later applied to polymers. The rapid growth in the use of polymers has led to an increase in the number of failures observed in polymers. Some could be tracked to poor design, others were due to deficiencies in the polymer themselves. The

presence of pre-existing crack-like flaws such as cavities or impurities in the polymer or defects on the surface could lead to the beginning of fracture.

A crack within a polymer can be deformed in more than one way. However, the crack deformation can basically be categorized into three modes as shown in Figure 2.11. Cracks that are loaded in the opening or tensile mode are referred to as Mode I. Shear within the plane of the material gives the Mode II or sliding mode. Out-of-plane shear gives Mode III or the tearing mode. Of the three modes, Mode I is the normal mode that most frequently occurs.

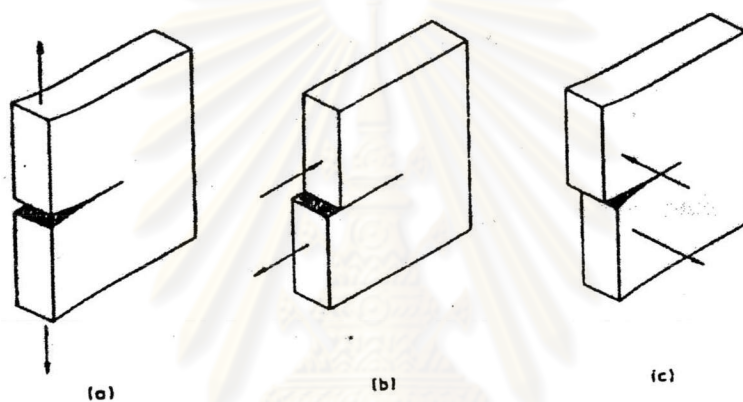


Figure 2.11: The three modes of crack extension. (a) Mode I, opening or tensile mode; (b) Mode II, in-plane shear or sliding mode; and (c) Mode III, antiplane shear or tearing mode.

2.8.1 Fracture toughness

To cause failure of a material, the forces applied have to be enough to overcome the bonding forces between atoms or molecules. The definition of fracture toughness or stress concentration factor is the ratio of the maximum stress that happens at the tip or the point of sharpest curvature to the average stress away from the flaw. It is based upon stress at failure that will occur when the stress intensity factor reaches a critical value, K_C , due to the failure at a defect of critical length a_c .

The stress intensity factor or fracture toughness for Mode I can be estimated as shown in Equation 2.4.

$$K_{IC}^2 = \sigma_c^2 a_c Y^2 \quad \text{-----} \quad (2.4)$$

where K_{IC} is the fracture toughness and σ_c is the stress at failure . Y is a constant depending on geometry, it is equal to π for a large plate with a central flaw or a polynomial in flaw size for more complex shape of material. A material with low fracture toughness is likely to fail in brittle manner while those with high fracture toughness will fail in a more ductile one.

2.8.2 Fracture energy

The strain-energy release rate is synonymous with the fracture energy. The fracture toughness and the fracture energy for Mode I are interrelated through the Young's modulus, E , that depend on the strain rate as indicated in Equation 2.4.

$$G_{IC}^2 = \frac{K_{IC}^2}{E} \quad \text{-----} \quad (2.4)$$

where G_{IC} is the fracture energy for Mode I. Both K_{IC} and G_{IC} can be applied to define the toughness of materials.

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