# AN INVESTIGATION INTO THE MECHANICAL CHARACTERISTICS OF EPOXY RESIN WHEN SEVERAL HARDENERS ARE PRESENT

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## Abstract:

Diglyceryl ether of bisphenol-A (DGEBA) epoxy resin was synthesised with two hardeners, triethylene tetramine (TETA) and diamino diphenyl methane (DDM), at varying hardener/resin ratios (below, at, and above stoichiometry), and their mechanical properties were evaluated through mechanical testing. The research aims to investigate the mechanical properties, including impact strength, tensile strength, flexural strength, compression strength, and bending strength, of the DGEBA/TETA and DGEBA/DDM systems at various hardener/resin ratios, assessing their influence on the mechanical properties of the epoxy resin system to identify the optimal hardener/resin ratio formulation and the superior epoxy resin system. The examinations were conducted at ambient temperature. The DGEBA/TETA system was tested using four hardener/resin ratios (10, 13, 15, and 20) phr, while the DGEBA/DDM system utilised four hardener/resin ratios (24, 27, 30, and 34) phr. The findings indicated that the specified stoichiometric ratios (15 phr for the DGEBA/TETA system and 30 phr for the DGEBA/DDM system) yielded optimal mechanical properties. The DGEBA/DDM system exhibited superior mechanical qualities compared to the DGEBA/TETA technology.

**Keywords:** Epoxy Resin, Impact Strength, Tensile Strength, Flexural Strength.

## 1.0 Introduction

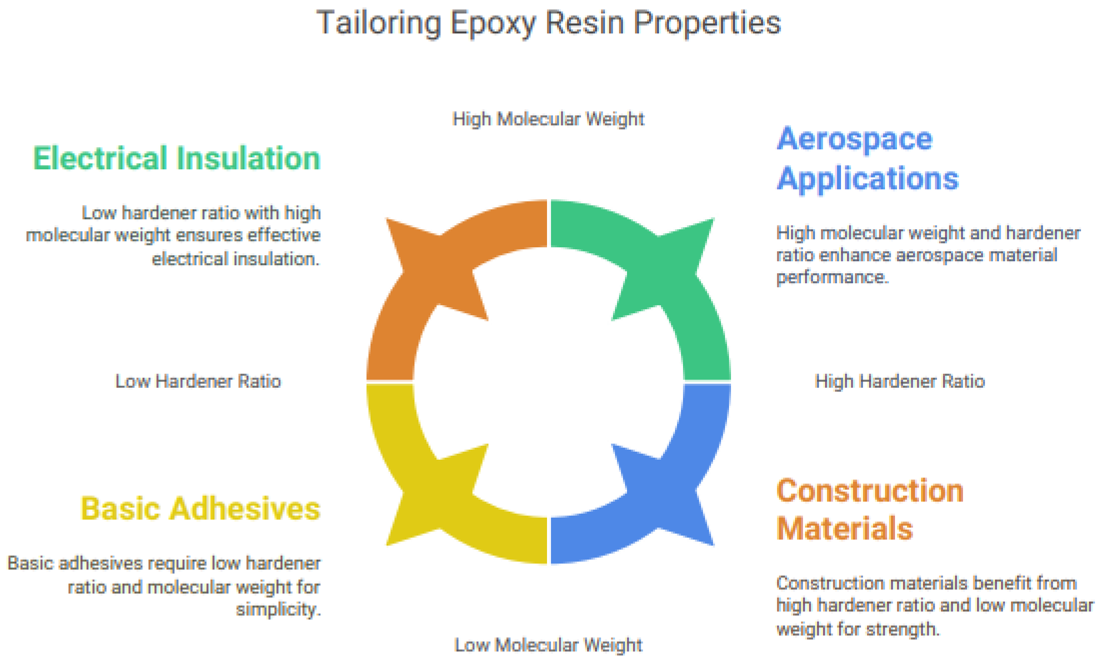
Epoxy resins are among the most versatile and widely used polymers in various industrial and commercial applications, owing to their remarkable adaptability. Their diverse uses span from being integral components in high-performance composite materials for aerospace structures to serving as durable coatings and reliable adhesives for everyday residential use [1-3]. The reason behind such broad applicability lies in the variety of epoxy systems that can be synthesized, with different chemical substances playing a crucial role in initiating the polymerization of epoxy monomers. This enables the tailoring of epoxy resins to meet the specific needs of a wide range of applications.

A key aspect of epoxy resin chemistry is the ability to modify the resin's properties by selecting various hardeners. These hardeners, typically anhydrides or amines (both aromatic and aliphatic), participate in the polymerization process of the epoxy monomers. The choice of hardener, combined with the resin's specific formulation, allows for the creation of epoxy systems with a wide spectrum of chemical and physical properties, from rigidity to flexibility, and from high-temperature resistance to electrical insulation [3-6].

For instance, a commonly used epoxy resin system involves the reaction of the defective epoxy monomer, diglycidyl ether of bisphenol A (DGEBA), with aliphatic amines. This system can exhibit a range of characteristics based on several factors: the molecular weight of the hardener, the processing conditions, and the ratio of hardener to monomer. These factors contribute to the customization of the resin's final properties, such as curing time, thermal stability, and mechanical strength. The adjustment of these ratios often leads to off-stoichiometric compositions, where the ratio of the resin to hardener is altered to modify the properties of the final product.

An example of this adjustment can be seen in the variations between epoxy systems employing different hardeners. Specifically, the use of triethylene tetramine (TETA) as the hardener with DGEBA results in a different set of mechanical properties compared to the system with 4,4-diaminodiphenylmethane (DDM) as the hardener. By varying the hardener-to-monomer ratio, these systems show significant changes in mechanical performance, such as tensile strength, elongation at break, and impact resistance [14]. This highlights how subtle changes in the formulation can have a profound impact on the material's properties.

To better understand and quantify the performance of these epoxy resin systems, dynamic testing methodologies are employed. These tests, which assess the resin’s response to applied stresses and strains, provide valuable insights into the material’s mechanical properties. The performance of the resin can be characterized by its elasticity, toughness, and resilience, all of which are dependent on the specific configuration of the epoxy resin system [15, 16]. Dynamic testing techniques such as tensile, compression, and flexural tests enable researchers and engineers to evaluate the resin's behavior under real-world conditions and determine the most suitable formulation for a given application.



Low hardener ratio with high molecular weight ensures effective electrical insulation.

High molecular weight and hardener ratio enhance aerospace material performance.

Basic adhesives require low hardener ratio and molecular weight for simplicity.

Construction materials benefit from high hardener ratio and low molecular weight for strength.

Figure: 1 Tailoring Epoxy Resin Properties

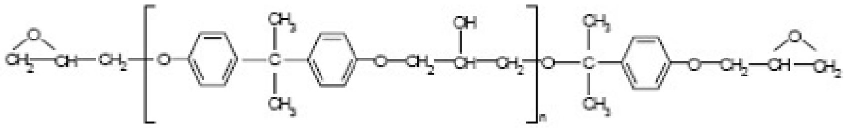
the adaptability of epoxy resins is driven by the wide variety of systems that can be synthesized, each with a unique set of properties determined by factors such as hardener choice, molecular weight, and ratio of components. Through careful formulation and dynamic testing, epoxy resins can be tailored to meet the demands of diverse applications, from aerospace to construction and beyond.

## 2. Review Literature:

**2.1 Epoxy Resins**: Epoxy resins are thermosetting polymers characterised by the presence of one or more active epoxide or oxirane groups at the terminal ends of the molecule, together with several repeating units in the central region. Chemically, they may consist of any compounds containing one or more epoxy groups that can transform into thermosetting materials. Their molecular weights may fluctuate significantly. They exist either as low-viscosity liquids or as solids. The ring-opening reaction allows the active epoxide groups in uncured epoxy to react with various curing agents or hardeners that possess hydroxyl, carboxyl, amine, and amino groups [17, 18].

Epoxy resins possess distinct chemical and physical features in comparison to other materials. Epoxy resins can be formulated to exhibit superior chemical resistance, exceptional adhesion, commendable thermal and electrical resistance, little shrinkage, and favourable mechanical qualities, including high strength and toughness. The advantageous characteristics of epoxy resins lead to their extensive applications in several industries, including packaging, aircraft, and construction. They have discovered significant applications in bonding and adhesives, protective coatings, electrical laminates, textile finishes, fiber-reinforced plastics, flooring and paving, and composite pipes. Since their initial commercial manufacturing in the 1940s by Devoe-Reynolds Company, the use of epoxy resins has steadily increased nearly every year [19, 20]. The primary makers of epoxy resins are Shell Chemical Company, Dow Chemical Company, and Ciba-Geigy Plastics Corporation. They manufacture the majority of the world's epoxy resins. The United States, along with other industrialised nations like Japan and those in Western Europe, are the primary producers and users of epoxy resins.

**Table 2.1 (Showing Chemical Structure of Epoxy Resin Taken For Experiment)**

| COMPOSITION | CHEMICAL STRUCTURE |
|---|---|
| Diglycidyl ether of bisphenol-A (DGEBA) |  |

Since the 1930s, when the formulation of epoxy resins was patented, numerous varieties of epoxy resins have been produced from epoxides. Conventional epoxy resins are primarily synthesized from bisphenol A and epichlorohydrin. The predominant epoxy resins are derived from diglycidyl ethers of bisphenol A (DGEBA). The characteristics and reaction mechanisms with various curing agents have been thoroughly documented [21, 22]. Additional categories of epoxy resins include glycidyl ethers derived from novolac resins, phenoxy epoxy resins, and (cyclo)aliphatic epoxy resins. Glycidyl ethers of novolac resins and phenoxy epoxy resins often exhibit high viscosity and superior high-temperature characteristics, whereas (cyclo)aliphatic epoxy resins display poor viscosity and reduced glass transition temperatures.

**2.2 Curing Agents (Hardeners):** Curing agents are crucial in the curing procedure for epoxy resin as they influence curing kinetics, reaction rate, gel time, degree of cure, viscosity, curing cycle, and the ultimate attributes of the cured goods. The three primary categories of curative agents are delineated as follows:

**2.2.1** The initial category of curative agents comprises active hydrogen molecules and their derivatives. Substances containing amine, amide, hydroxyl, acid, or acid anhydride groups are classified within this category. They typically undergo polyaddition with epoxy resin, yielding an amine, ether, or ester. Aliphatic and aromatic polyamines, polyamides, and their derivatives are frequently utilized as amine-based curing agents. Aliphatic amines exhibit high reactivity and possess a brief lifespan. Their applications are constrained due to their typical volatility, toxicity, or irritability to the eyes and skin, resulting in health issues. Aromatic amines exhibit lower reactivity, reduced toxicity to humans, and require elevated curing temperatures and extended curing durations compared to aliphatic amines. Hydroxyl and anhydride curing agents typically exhibit lower reactivity compared to amines, necessitating elevated curing temperatures and extended curing durations. They possess extended lifespans. Polyphenols are the most often utilized hydroxyl-type curing agents. Polybasic acids and acid anhydrides serve as prevalent curing agents of their respective types in the coatings industry.

**2.2.2** The subsequent category of curing agents include anionic and cationic initiators. They serve to catalyze the homo-polymerization of epoxy resins. Molecules capable of supplying an anion, such as tertiary amines, secondary amines, and metal alkoxides, serve as excellent anionic initiators for epoxy resins. Molecules capable of supplying a cation, such the halides of tin, zinc, iron, and the fluoroborates of these metals, serve as excellent cationic initiators.

**Table 2.2 (Showing Hardeners Taken For Experiment)**

| COMPOUNDS | CHEMICAL STRUCTURE |
|---|---|
| Diamino Diphenyl Methane (DDM) |  |
| Triethylene Tetramine (TETA) | $NH_2 \left[ CH_2 - CH_2 - NH \right]_2 CH_2 - CH_2 - NH_2$ |

The third category of curing agents is referred to as reactive cross-linkers. They often possess greater equivalent weights and crosslink with the secondary hydroxyl groups of the epoxy resins or by self-condensation. Examples of such curing agents include melamine, phenol, and urea-formaldehyde resins. Of the three categories of curing agents, those containing active hydrogen are the most commonly utilized and have achieved significant commercial success. Most anionic and cationic initiators remain economically unutilized due to their extended curing processes and suboptimal characteristics of the cured products. Cross-linkers are mostly utilized as surface coatings and are often cured at elevated temperatures to generate films with superior physical and chemical qualities.

**Table 2.3 (Showing Various Properties of Epoxy & Hardeners)**

| Properties | Test Method | Values For (LY-556)/ EPOXY RESIN | For Hardener (HY-951)/TETA | For Hardener (DDA) |
|---|---|---|---|---|
| Epoxy Group Content | SMS 2062 | 5150-5490 M Mol/Kg | - | - |
| Molecular Weight | - | 182-194 gram | 146.24 gm. | 198 gm. |
| Viscosity | ASTM D445 | 9-14 Pa | 450 Mpa | 455 Mpa |
| Color | Appearance | White | Clear Light White/Yellow | Clear Light Brown |
| Density (At $25^0$ C) | SMS1374 | 1.16 Kg/$M^3$ | 0.90 Kg/$M^3$ | 0.92 Kg/$M^3$ |
| Flash Point | ASTM D93 | >150 $^0$C | 129 $^0$C | 230 $^0$C |

## 2.3 Selection of Curing Agents

The choice of curative chemicals is a crucial factor. Various chemical reagents can interact with epoxy resins. Curing agents influence the viscosity and reactivity of the formulation, as well as the types of chemical bonds created and the functionality of the resulting cross-link junctions. The structure of the hardener influences its thermal stability [22, 23].

## 2.4 The Stoichiometry

The stoichiometric connection between curing agents and resins significantly influences the physical and mechanical properties of epoxy resin [24]. The many forms of curative agents necessitate consideration of the stoichiometric balance among the reactive species. To assess the characteristics of the epoxy resin, the ratios of curing agents to resins must be computed and optimized. In cured systems involving primary and secondary amines, the hardener is typically utilized in a nearly stoichiometric ratio. The tertiary amine generated in the reaction exerts a catalytic influence on the interactions between epoxy and the concurrently created secondary alcohols; hence, a quantity somewhat below the theoretical maximum should be utilized [19].

Example of a Stoichiometric Calculation:
**Resin:** DGEBA
**Amine Curing Agent**: Triethylene Tetramine (TETA)
**Chemical Formula:** $H_2N(CH_2)_2NH(CH_2)_2NH(CH_2)_2NH_2$
Molecular weight of amine:
6 carbons = 6x12 = 72 (g/mol)
4 Nitrogen's =4x14 = 56 (g/mol)
18 hydrogens = 18x1 = 18 (g/mol)
Molecular weight = 146 (g/mol)
There are 6 amine hydrogen functionally reactive with an epoxy group. Therefore,

$$\frac{146(grams/mol)}{6(equivalents/mol)} = 24.3 grams/equivalent$$

Consequently, 24.3 grams of TETA are utilized for each equivalent of epoxy. If the DGEBA had a weight that was comparable of 190 (380 g/mol/2 eq./mol), then 24.3 grams of TETA are utilized with 190 grams of DGEBA, resulting in approximately 13 grams of TETA per hundred grams of DGEBA (24.3/190 = 13 g).

## 3.0 HYPOTHETICAL METHODOLOGY

The epoxy resin along with the hardener were combined in various hardener/resin ratios. The chosen ratio was contingent upon the stoichiometry of the epoxy resin system. The epoxy resin (LY-556) (DGEBA) and the volatile amine hardening agent Diaminodiphenylmethane (DDM) were formulated in four hardener/resin ratios:

1. **24 PHR (Under stoichiometry).**
2. **27 PHR (Stoichiometry).**
3. **30 PHR (Above stoichiometry)**
4. **34 PHR (Above stoichiometry).**

The ratios have been established based on the equivalent weights of DGEBA and DDM utilized in sample preparation to examine the impact of varying the hardener/resin ratio on mechanical qualities by conducting mechanical tests on the DDM/DGEBA resin specimens. Two test samples from each formulation were analyzed, and the average values were documented. The hardener Diamino diphenyl methane (DDM) is solid at room temperature and must be heated to react with the DGEBA epoxy resin. The formulations are created by combining DGEBA with DDM in the correct ratio and thereafter heating the mixture on a hot plate to the DDM melting temperature (90°C) for roughly 10 minutes. The slurry was put into the mold and cured at 90°C for 1.5 hours, followed by post-curing at 150°C for 1 hour.

The DGEBA epoxy resin was combined with the hardener HY 951 TETA in four distinct hardener/resin ratios:

1. **10 PHR (Under stoichiometry).**
2. **13 PHR (stoichiometry).**
3. **15 PHR (Above stoichiometry).**
4. **20 PHR (Above stoichiometry).**

The ratios were derived from the equivalent weight of the DGEBA epoxy resin and the hardener TETA. specimens were made in the aforementioned four ratios and thereafter subjected to mechanical properties testing. Two test samples from each formulation were analyzed, and the mean values were documented.

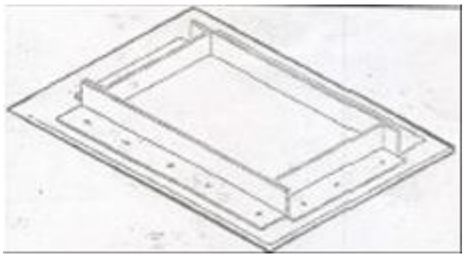


Fig 3.1 Mould Used for Casting

The DGEBA epoxy resin and the TETA hardener were combined at room temperature using a disposable stirrer to prevent the formation of air bubbles. The mixing was conducted for around 20 minutes to guarantee the homogeneity of the mixture and to ensure that the two components were well blended, resulting in a sample with uniform concentrations throughout. The mixture was subsequently poured into the mold (shown in Fig. 3.1) and allowed to rest for 24 hours at the surrounding temperature, followed by post-curing at 100°C for 1 hour.

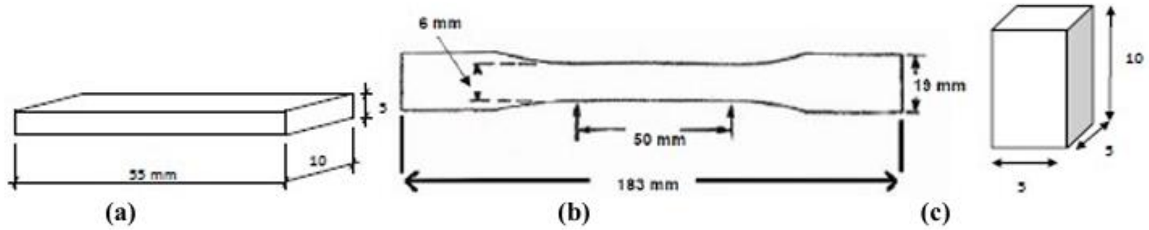


Figure 3.2 Showing Various Work Piece for Different Tests (a. For Charpy Test, b. For Tensile Test, c. For Compressive Test)

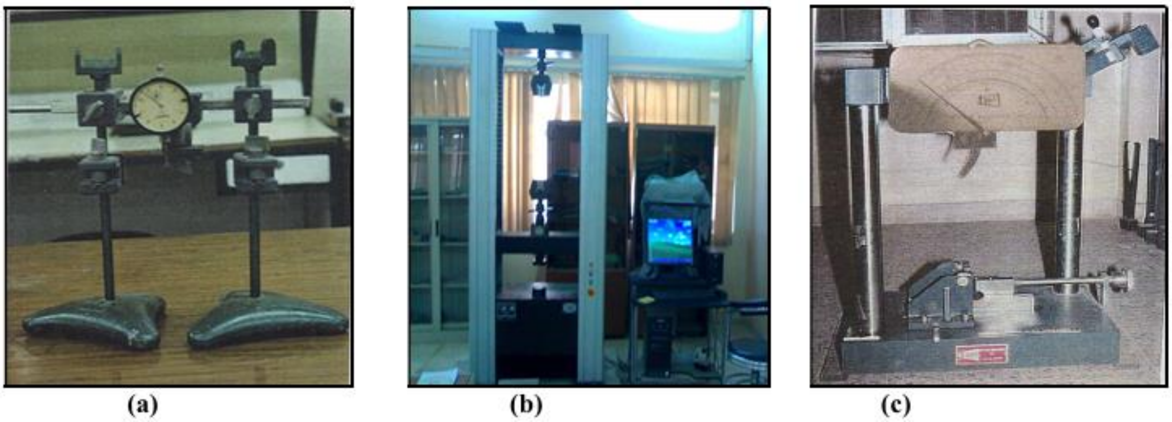


Figure 3.3 Showing Various Instruments for Different Tests (a. 3 Point Bending Machine for Bending Test, b. Universal Testing Machine for Tensile & Compressive Tests, c. Impact Testing Machine For Charpy Test)

Subsequent to curing the object, multiple sample sections of differing dimensions were made according to the testing specifications (as illustrated in Fig. 3.2). Subsequent to the preparation of the sample pieces, several tests were conducted (as illustrated in Fig. 3.3).

## **4.0 HYPOTHETICAL RESULTS AND DISCUSSIONS**:

### **4.1 The impact Test: Effects of Hardener/ Resin Ratio**

The strength of the impact can be determined using the aforementioned equation for the epoxy resin DGEBA with TETA and DDM as hardeners, employing various hardener/resin ratios (under stoichiometry, stoichiometry, and above stoichiometry). Figure 4.1 illustrates the fluctuation in impact strength of the DGEBA/TETA and DGEBA/DDM systems. The DGEBA/TETA system was examined for four distinct hardener/resin ratios: 10, 13, 15, and 20 phr.

The epoxy-rich formulation at 10 phr exhibits the lowest impact strength, attributable to the abundance of epoxy rings and the formation of a rigid, tightly-knit macromolecular structure, where the sole anticipated mobile group is the dimethylene ether linkage of bisphenol-A. These properties result from the total depletion of all reactive sites on the hardener molecule, leading to a rigid and brittle structure [28].

The stoichiometric ratio of 13 phr exhibits greater impact strength compared to the sub-stoichiometric ratio of 10 phr, indicating that the stoichiometric formulation is more resilient than the epoxy-rich formulation, suggesting enhanced flexibility.

The amino-rich formulations of 15 and 20 phr, along with the stoichiometric formulation of 13 phr, exhibit superior impact strength compared to the epoxy-rich formulation of 10 phr. This enhancement is attributed to the substantial presence of amino hydrogen groups, which facilitate the opening of more epoxy rings through the amino addition reaction, thereby increasing the material's toughness. The amino-rich formulation at 15 phr exhibits the highest impact strength among all hardener/resin ratio formulations, indicating its superior capacity to absorb energy prior to fracture. The applied force is dissipated through the molecular structure, leading to cracking when the material can no longer endure the load, resulting in the rupture of its molecular chains. The amino-rich formulation at 20 phr exhibits lower impact strength compared to the amino-rich formulation at 15 phr; this phenomenon is attributed to the existence of unreacted sites on the harder material molecule, resulting in material breakage [27].

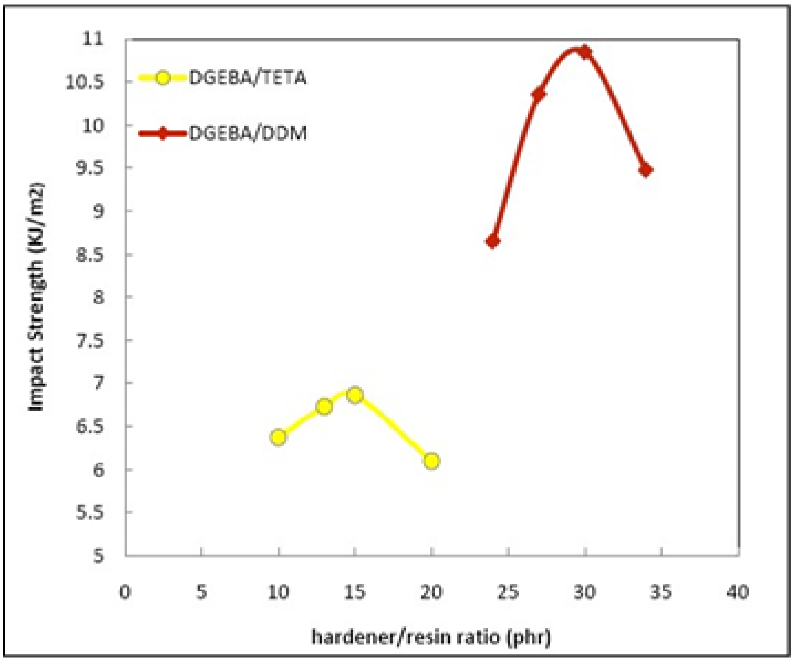


Figure: 4.1

The DGEBA/DDM system was examined using four distinct hardener/resin ratios: 24, 27, 30, and 34 phr. The amino-rich formulation at 30 PHR exhibits the greatest impact strength, attributable to the predominance of the amino addition process, which facilitates cross-linking between the resin and the hardener, resulting in a flexible and stable material [25]. The epoxy-rich formulation of 24 phr exhibits the lowest impact strength, indicating a high concentration of epoxy groups that results in a brittle and fracture-prone material. The DGEBA/DDM system exhibits superior impact strength compared to the DGEBA/TETA system. This can be attributed to the relative instability of aliphatic amines, such as TETA, in contrast to the stability of aromatic amines, like DDM, due to the presence of benzene, which possesses low potential energy, thereby enhancing the stability of the epoxy resin system [29]. The TETA molecule contains two primary amine groups situated on primary carbon atoms at the termini of an aliphatic polyamine chain. The TETA molecule has two secondary amine groups concurrently. The secondary amine groups also participate in the process, forming a network structure of epoxy resin. The DDM molecule contains two amine groups situated on primary carbon atoms at the termini of an aliphatic polyamine chain. The primary amine groups exhibit greater reactivity than the secondary amine groups, resulting in the DGEBA/DDM system demonstrating superior impact resistance compared to the DGEBA/TETA system [18].

### 4.2 Impact of hardener/resin ratio on extreme tensile strength

Ultimate tensile strength (UTS) quantifies the stress exerted on a specimen until it fractures. Figure 4.2 illustrates the correlation between ultimate tensile strength (UTS) and hardener content (PHR) for DGEBA/TETA and DGEBA/DDM subsystems.

In the DGEBA/TETA system, the ultimate tensile strength rose with larger hardener concentration, with the amino-rich formulation at 15 PHR demonstrating the greatest stress at break. The increased degree of cross-linking enhances the material's strength and rigidity, resulting in ductile behavior, unlike the epoxy-rich formulation at 10 PHR, which fractures in a brittle manner due to the presence of ether groups and homopolymerization. Consequently, the 10 PHR formulation requires less strength to fracture compared to the amino-rich formulations at 15 and 20 phr.

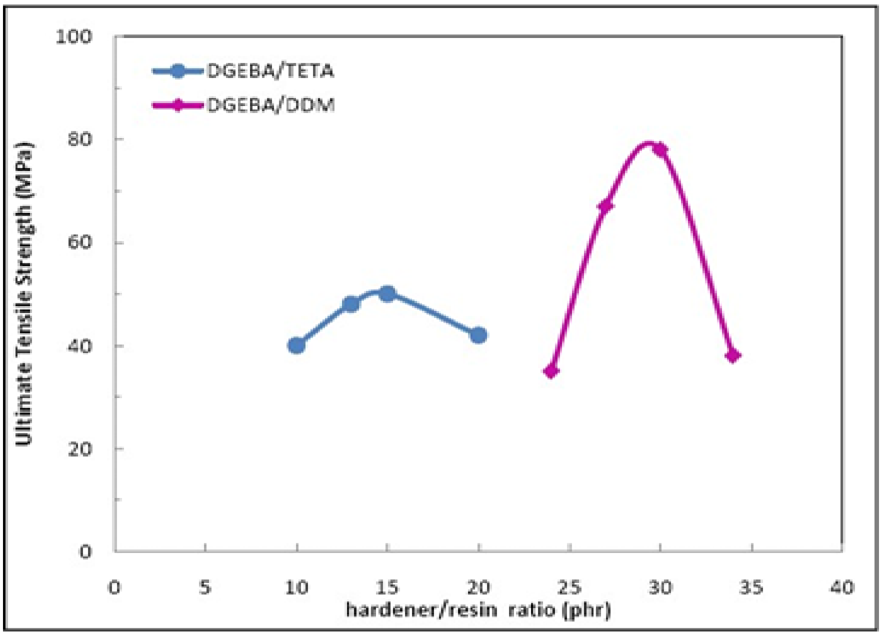


Figure: 4.2

The stoichiometric formulation 13 PHR exhibits superior resistance to tensile loads compared to the epoxy-rich formulation; however, the amino-rich formulation 15 PHR remains the most effective, characterized predominantly by carbon-amine nitrogen linkages, alongside a significant presence of ether groups and homopolymerization byproducts [25]. The stoichiometric formulation of 20 PHR exhibits reduced resistance to tensile loads due to the presence of a significant quantity of unreacted hardener molecules, which compromises the material's stability.

In the DGEBA/DDM system, the material exhibits significant resistance to tensile forces until specimen failure, as the hardener/resin ratio increases. The aforementioned stoichiometric formulations exhibit elevated ultimate tensile strength, particularly the 30 phr formulation, attributable to the amino addition reaction that creates a three-dimensional structure that relaxes upon chain rupture. Conversely, the 34 phr formulation demonstrates inferior ultimate tensile strength compared to the 30 phr formulation, owing to the presence of unreacted hardener

molecules. Figure 4.2 illustrates the stoichiometric network in which the material's chains interact under applied load. The stress formulation of 27 phr requires greater strength to fracture compared to the under-stoichiometric formulation of 24 phr, indicating inadequate cross-linking between the DGEBA resin and the hardener DDM.
The tensile strength of the DGEBA/DDM system surpasses that of the DGEBA/TETA system, as the aromatic structure of the DDM hardener, characterized by the presence of benzene, imparts greater stability and rigidity to the material, whereas the linear structure of the aliphatic TETA hardener results in reduced stability and increased brittleness.

### 4.3 Impact of hardener/resin ratio on The Compression Test

As the load continuously increases, the specimen's thickness diminishes (cross-section) due to the Poisson effect. This results in the isotropic distribution of lateral expansion around the specimen [31].

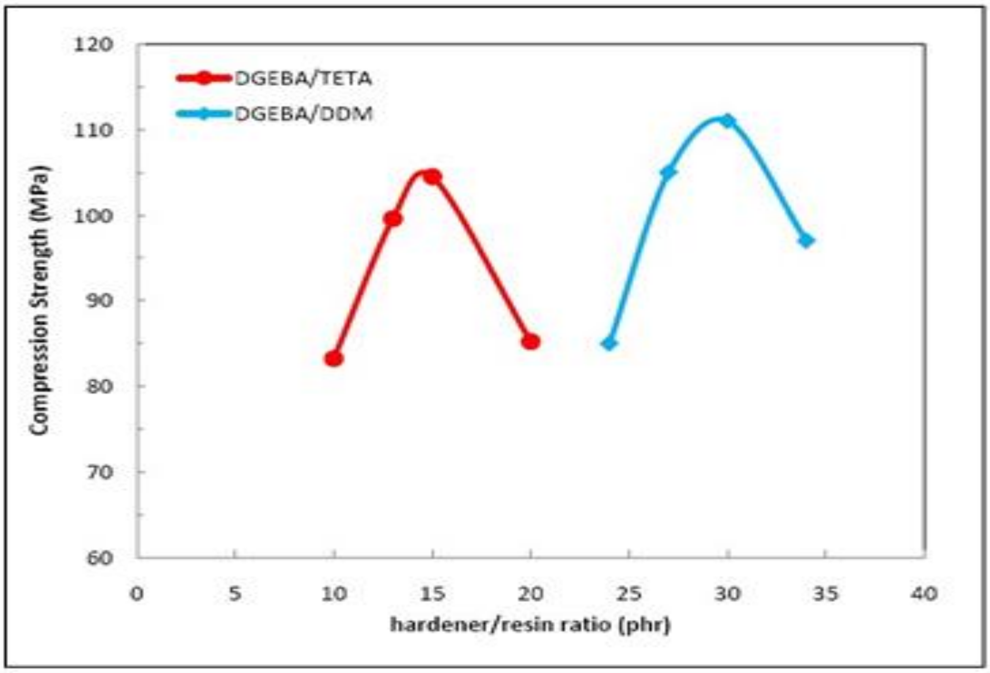


Figure: 4.3

Figure 4.3 illustrates the compressive strength of both the DGEBA/TETA and DGEBA/DDM systems at varying hardener/resin ratios. In the DGEBA/TETA combination, the compressive strength of the amino-rich formulation 15 exceeds that of the epoxy-rich formulation 10 phr. Two distinct mechanisms operate concurrently at various locations, contributing to this type of material failure, which results from compressive and shear stresses. The stoichiometric formulation of 13 PHR necessitates greater compressive strength than the epoxy-rich formulation of 10 PHR, attributable to the development of a three-dimensional network and robust chains, which render the material hard and resilient. The stoichiometric formulation of 20 PHR exhibits reduced resistance to compressive loads, indicating material brittleness, potentially attributable to unreacted hardener molecules [31]. In the DGEBA/DDM system, the compressive strength of the amino-rich formulations at 30 and 34 PHR surpasses that of the epoxy-rich formulation at 24 PHR, as the surplus epoxy groups result in ether group formation and copolymerization, which weakens the material and renders it more compressible.

### 4.4 Impact of hardener/resin proportion on the Flexural Test

Flexural strength tests are conducted on the proposed sample to determine the specimens' capacity to withstand deformation under load. The three-point test is intended for materials that fracture under minimal deflection [31]. This test assessed the flexural strength of both DGEBA/TETA and DGEBA/DDM systems, with specimens exhibiting varying hardener/resin ratios (sub-stoichiometric, stoichiometric, and super-stoichiometric).

Figure 4.4 illustrates the flexural strength of the DGEBA/TETA system and the DGEBA/DDM system. The DGEBA/TETA system has the highest flexural strength at a hardener/resin ratio of 15 phr, indicating a greater degree of cross-linking that confers significant toughness to the material, enabling it to withstand breaking forces. The epoxy-rich formulation of 10 phr exhibited the lowest flexural strength values, attributable to the excessive epoxy groups that induce material brittleness via reactions with hydroxyl groups or by homopolymerization. The stoichiometric formulation of 13 PHR appears to exhibit greater flexural strength than the epoxy-rich formulations of 10 PHR due to the increased number of epoxy rings that have been cleaved by the amino addition reaction. enhances the material's stability and flexibility. The optimal flexural strength was achieved at stoichiometric formulations exceeding 15, characterized by an abundance of amino acids. formulations; this may result from the amino addition event in which the DGEBA monomer evolves into more robust and more inflexible solid due to the reaction with surplus hardener TETA compared to alternative formulations, although the amino The rich formulation at 20 PHR demonstrates inferior flexural strength compared to the 15 PHR formulation, potentially attributable to unreacted hardener molecules, which render the material less flexible and more brittle.

The DGEBA/DDM system with an epoxy-rich formulation of 24 PHR exhibits the lowest flexural strength, bending and fracturing under minimal load, which signifies the material's brittleness and the inadequate bonding between the hardener and the resin [18]. Consequently, the material chains do not flex effectively in response to the applied load. The stoichiometric formulation exhibits superior resistance to flexural loads, necessitating greater strength for bending and eventual failure of the specimen. This signifies the robust connections between the hardener DDM and the DGEBA resin, suggesting it may endure greater loads, which would be distributed across the material's chains until the specimen ultimately fractures. The amino-rich formulation at 30 PHR demonstrates the most favorable outcome, indicating a significant degree of cross-linking among all formulations. The carbon-amine nitrogen linkage imparts greater rigidity and toughness to the material compared to others, allowing the chains to flex and endure forces that could cause breakage through bending.

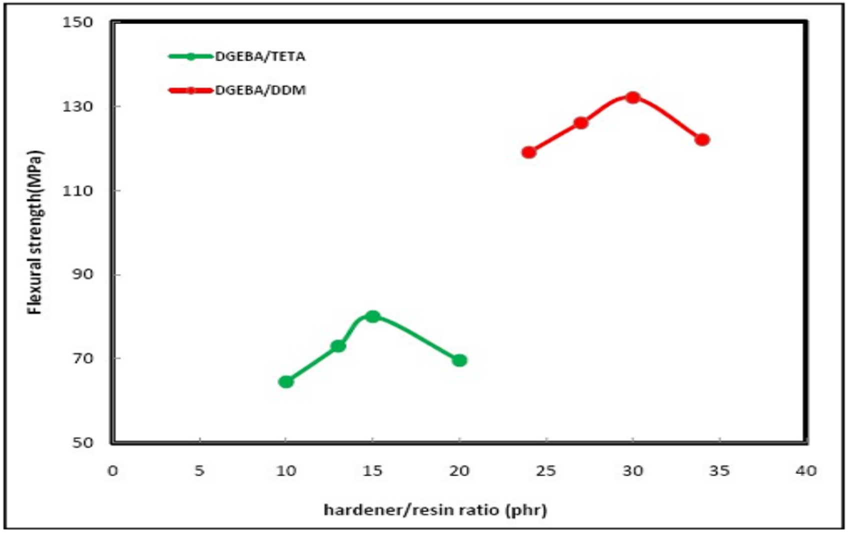
The 34 PHR formulation exhibits decreased flexural strength compared to the 27 PHR formulation, as a significant quantity of hardener molecules remains unreacted, resulting in material fracture. A comparison of the flexural strengths of the DGEBA/TETA system and the DGEBA/DDM system reveals that the formulations of the DGEBA/DDM system exhibit superior values compared to those of the aliphatic DGEBA/TETA system. The aromatic amine curing agent DDM renders the DGEBA monomer more resilient than the aliphatic amine curing agent TETA. [27].

### 4.5 Effect of hardener/resin ratio on the Bending Test

The values of Young's modulus (E) were ascertained by a three-point bending test. The specimen typically maintains its original shape with the removal of the applied stress, indicating that no failure occurs during this test, which is conducted solely in the elastic condition. Figure 4.5 illustrates the Young's modulus values for the DGEBA/TETA system and the DGEBA/DDM system across various hardener/resin ratios. In the DGEBA/TETA system, the Young's modulus elevated with an increase in TETA hardener content. The amino-rich formulations 15 has a greater elastic modulus value, attributable to the material's stiffness, which signifies its ductility and necessitates a substantial force for bending.

The epoxy-rich formulation at 10 PHR exhibits a lower Young's modulus compared to the stoichiometric formulation at 13 PHR. This can be attributed to its reduced stiffness, which results in diminished stress and strain, thereby leading to decreased rigidity and elasticity when subjected to bending under low loads. The amino-rich formulation at 20 PHR has a lower Young's modulus compared to the amino-rich formulation at 15 PHR, indicating the material's brittleness attributed to unreacted harder substance molecules.

In the DGEBA/DDM system, the amino-rich formulations at 30 and 34 PHR, along with the stoichiometric formulation at 27 PHR, exhibit superior Young's modulus compared to the epoxy-rich formulation at 24 phr. This enhancement is attributable to the increased degree of cross-linking, which confers improved ductility and rigidity to the material.



The DGEBA/DDM system exhibits superior Young's modulus values compared to the DGEBA/TETA system, as the aromatic structure of DDM enhances ductility, flexibility, and stability of the epoxy resin system. the increased flexibility of the material. The aliphatic structure of TETA and its simplistic formulation contribute to the reduced stability and flexibility of the epoxy resin system, resulting in diminished elasticity [31].

## 5.0 Conclusion

The creation of p-dioxane rings is, therefore, of limited significance for non-stoichiometric processes [28], although it may account for the consumption of around 1/16 of all epoxy rings. This study examined the mechanical properties of the DGEBA/TETA and DGEBA/DDM systems at various hardener/resin ratios, as well as the thermal kinetics and rheological properties of the DGEBA/TETA system across multiple hardener/resin ratios. The aforementioned stoichiometric ratio (15 PHR) of the DGEBA/TETA system exhibits superior mechanical capabilities compared to other hardener/resin ratio formulations. The specified stoichiometric ratio (30 PHR) of DGEBA/DDM exhibits superior mechanical capabilities compared to other hardener/resin ratio formulations. The DGEBA/DDM system has superior mechanical qualities compared to the DGEBA/TETA system. This work may be expanded by utilizing the same epoxy resin systems (DGEBA/TETA and DGEBA/DDM), reinforcing them with fibers at varying percentages, and examining their impact on the mechanical characteristics.

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