Examining the Mechanical and Thermal Properties of an Epoxy Composite that Contains Blast Furnace Slag

Ajay Kumar Verma, Ayush Kumar, Sakshi Singh, Prince Kumar Das, Siddharth Kumar, Subham Jha, & Adarsh Kumar Saw

Department of Mechanical Engineering
K.K.Polytechnic, Dhanbad

Abstract

Slag from blast furnaces is a significant industrial waste produced in large amounts when iron is extracted from its ores. One of the main environmental remediation techniques used today to manage threats to human health and the environment is the elimination, reduction, or recycling of garbage. The purpose of this paper is to examine the thermal and physical properties of epoxy composites that are loaded with blast furnace slag, an industrial waste. In addition to being utilised in metal matrix applications, concrete mixtures, and soil stabilisation, ongoing research is being conducted to find additional uses for it. In keeping with the theme of coherence, the purpose of this research is to investigate the potential of BF slag in the production of composites that may enhance specific mechanical properties and serve as an affordable alternative to other composites. It has been discovered that the composite produced by this process has better thermal conductivity.

Keywords: Epoxy, Polymer Composites, Thermal conductivity, and Blast Furnace Slag

I. INTRODUCTION

Composite Materials:-

Materials that are composite, also known as composites, are composed of two or more structural units or constituents with substantially different physical and chemical properties that, when combined, give the final material unique properties not found in the individual structural units. The reinforcing structures and matrices make up the structural units, whether they are synthetic or natural. The reinforcements are arranged in a systematic manner within the binder or matrix. The fact that the reinforcements are typically discontinuous helps to distribute load among them. In order to create structures with superior qualities, the reinforcement provides unique mechanical and physical properties. This gives designers and engineers a significant advantage over traditional monolithic materials and allows for great design freedom.Building structures, bridges, boat hull structures, shower stalls, bathtubs, storage tanks, race cars (carbon fibre bodies), etc. are examples of common applications.

Types of Composite Materials

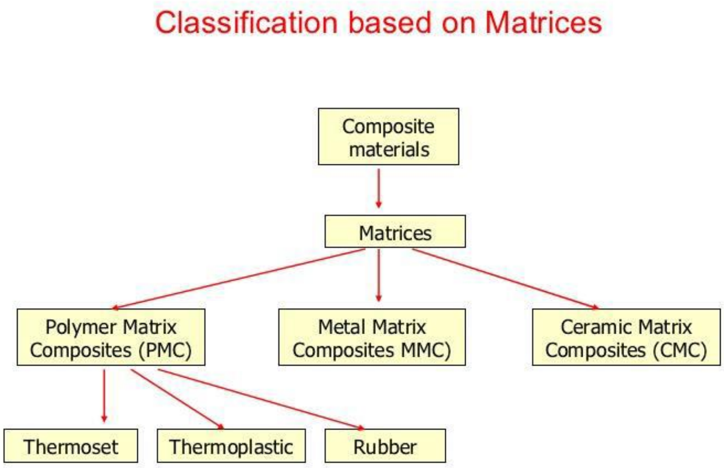

Fig 1: Classification of composites

Composites are broadly classified accordingly:

- **Metal Matrix Composites (MMC):-** These composites have metal as the matrix component, while the other component may be an organic compound, metal, or ceramic. Because of their high specific strength, wide working temperature range, enhanced electrical and thermal conductivity, higher specific modulus, reduced thermal expansion coefficient, and other characteristics, these composites outperform monolithic metals. These characteristics support the use of this range of composites in a number of applications, including radio frequency quadruples (RFQs), tank armour, and carbide drills. Given its high degree of specific heat and thermal conduction, carbon fibre in a silicon carbide matrix is used in the rotors of modern high-performance sports automobiles, such those built by Porsche[1].
- **Ceramic Matrix Composites (CMC):-**These composite materials feature ceramic fibre reinforcement within a ceramic matrix, producing ceramic fibre reinforced ceramics (CFRCs) with exceptional resistance to cracking and fracture toughness. Ceramic matrix composites are generally found to exhibit a corresponding gain in strength and stiffness. Glass, glass ceramics (lithium aluminosilicate), carbides (SiC), nitrides (SiN4, BN), oxides (Al2O3, Zr2O3, Cr2O3, Y2O3, CaO, ThO2), and borides (ZrB2, TiB2) are the most common types of ceramic matrices. Particles, flakes, whiskers, and fibres are examples of the high temperature inorganic materials that are typically used as reinforcements, including ceramics. Carbon, silica, alumina, and silicon carbide are the most often utilisedfibres. With a temperature resistance of up to 30,000C, carbon-carbon composites are the most important type of ceramic matrix composites. Carbon-reinforced fibres are arranged in a matrix made of carbon to form these. Applications for extreme temperatures gas turbine components, such as stator vanes and combustion chambers, are rare.
- **Polymer Matrix Composites (PMC):**These composites, sometimes referred to as fiber-reinforced polymers, are made up of glass, carbon, and aramid fibres for reinforcement and a polymer-based resin for the matrix

Polymers have poor mechanical properties for structural use because of their covalently bound macromolecular repeating structural unit[2]. In contrast to metals and ceramics, their strength and stiffness are relatively modest.These composites, sometimes referred to as fiber-reinforced polymers, are made up of glass, carbon, and aramid fibres for reinforcement and a polymer-based resin for the matrix. Polymers have poor mechanical properties for structural use because of their covalently bound macromolecular repeating structural unit. Therefore, this flaw is mitigated by reinforcement of additional component materials, such as organic or ceramic components. Low pressure and temperature requirements, together with simpler production equipment, determine whether the polymer is a thermoset (processing temperature of 200°C) or a thermoplastic (processing temperature of 300°C to 400°C) and are relevant to the use of these composites in real-world applications.

Three further types of Polymer Matrix Composites can be distinguished based on the type of reinforcement material employed[3].

BLAST FURNACE SLAG:

Slag from blast furnaces is a kind of solid industrial waste produced by the melting of iron ore or pellets, coke and flux (limestone or dolomite) in a blast furnace. Following the completion of the metallurgical smelting process, the flux's lime reacts chemically with the ore's silicates and aluminates as well as coke ash to produce a non-metallic product. A slag's chemical makeup might vary significantly based on the burden chemistry of the raw materials used in the manufacturing process.In the blast furnace, silicate and aluminate impurities from the ore and coke are mixed with a flux to lower the slag's viscosity. When pig iron is produced, the flux primarily consists of a combination of limestone and forsterite, or occasionally dolomite[4]. Slag is poured for separation in the blast furnace and floats on top of the iron. Slag melts that cool slowly produce an unreactive crystalline substance called Ca-Al-Mg silicates. The slag melt must be quickly cooled or quenched below 800 °C to avoid merwinite and melilitecrystallisation and to achieve a satisfactory slag reactivity.A granulation technique, in which molten slag is exposed to pressurised jet streams of water or air, can be used to cool and fracture the slag. Alternatively, a revolving drum is used to propel the liquid slag into the air during the pelletisation process after it has been partially chilled with water. The resulting fragments are ground to the same fineness as Portland cement in order to achieve an appropriate reactivity
The range below represents the chemical composition of BF slag under Indian circumstances[5].

Calcium Oxide (CaO): 31%- 39%
Silicon Dioxide (SiO_2): 29%-37%
Aluminium Oxide (Al_2O_3): 14%-21%
Magnesium Oxide (MgO): 7%-10%
Ferrous oxide (FeO): 0.1%-1.8%
Manganese Oxide (MnO): 0.01%-1.1%
Sulphur: 1%-1.8%
Basicity (CaO/ SiO_2): 0.90%-1.2%

II. MATERIALS & METHODS

Matrix Material:

The matrix material employed in this work is epoxy LY 556 resin, which is chemically related to the epoxide family and was purchased from Ciba-Geigy India Ltd. Bisphenol-A-Diglycidyl-Ether is its colloquial name. As advised, a 10:1 weight ratio is used to combine the matching hardener (HY 951) with the low temperature curing epoxy resin (Araldite LY 556). The main reasons epoxy is used are because it is the most widely used polymer, and it is insulating due to its low density (1.1 gm/cc) and poor heat conductivity (approximately 0.363 W/m-K).

Filler Material (Blast Furnace Slag):

Using optimal methods, the production of iron and steel results in about 300 kg of slag per thm. Major methods yield 500–600 kg of slag/thm, whilst poor practices yield 700–800 kg. They are primarily granulated slag, air-cooled slag, pellitized or expanded slag, the smaller gradation air-cooled slag, or the air-cooled rip rap BF slag, depending on the cooling procedures used. Grinded granulated BF slag has a density of 2.85–2.95 g/cm3. At normal temperature, BF slag appears to have a thermal conductivity of 1.08 W/m K[6].

Composite Fabrication:

When necessary, a 10:1 weight ratio is used to combine the low temperature curing epoxy resin (LY 556) and matching hardener (HY951) provided by Ciba Geigy India Ltd. The composites are prepared by reinforcing blast furnace slag (avg. density of 2.85-2.95 gm/cc) with an average size of 100 µm with epoxy resin (density 1.1 gm/cc). The silicone releasing agent is uniformly thinly coated with wax before the dough, which is epoxy filled with blast furnace slag, is carefully poured into the molds, giving it exceptional releasing properties. The composites are cast using a well-established manual lay-up procedure to produce specimens with a disc shape. Six distinct compositions of blast furnace slag—1.4, 3.35, 5.23, 7.85, 9.4, and 11.3 vol.%—are combined to create composites. After the castings have cured for around 24 hours at room temperature, the molds are cut open and samples are released so that qualities can be studied[7].

Operating principle of UnithermTM 2022:

The temperature of the two polished surfaces is regulated by the sample being held under a consistent compressive load. Heat moves in one direction: from above axial temperature gradient in the stack is produced by the surface passing through the sample and down to the lower surface[11]. Along with the output from the heat flow transducer, the temperature difference across the sample—that is, the difference in temperature between the top and lower surfaces—is detected after the thermal equilibrium is attained. The thermal conductivity was calculated using these numbers as well as the sample thickness as input variables. Temperature sensors on both sides of the sample are used to measure the temperature drop through the sample[12].

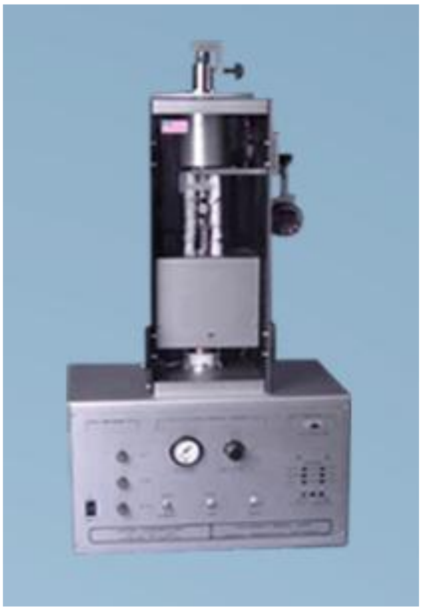

Fig 2.1**:** Determination of Thermal Conductivity Using Unitherm™ Model 2022

The rate at which heat moves through a material for a specific temperature differential is known as its thermal conductivity. The equation for one-dimensional heat transfer via conduction is as follows: equation 3.1

$$Q = \frac{KA(T1-T2)}{x}$$

where A is the cross sectional area (m2), T1-T2 is the change in temperature across the body (K), x is the sample thickness (m), Q is the heat flux (W), and K is the body's thermal conductivity (W/m-K).

A sample's thermal resistance can be expressed as follows:

$K=x/R$

By measuring the Q value, the heat flux transducer in the Unithermtm 2022 determines the temperature differential between the upper and bottom plates. Equation can be used to determine the effective thermal conductivity of composite samples given the sample thickness and known cross sectional area as input values[11].

Numerical Analysis: Concept of Finite Element Method (FEM) and ANSYS:

Turner et al. [12] first presented the Finite Element Method (FEM) in 1956. It is a potent computer method for approximating solutions in a range of engineering problems with complicated domains that are subject to general boundary constraints. In many engineering domains, FEM has emerged as a crucial stage in the modeling of a physical phenomenon. There are an endless number of solutions inside the domain as a result of the field variables' point-to-point variations[8].

The foundation of FEM is the division of the domain into a finite number of subdomains (the sample in a finite number of elements), for which the weighted or variational residual methods are used to produce the systematic approximation solution. By breaking the domain up into elements and expressing the unknown field variable as presumptive approximation functions inside each element, FEM simplifies the problem to a finite set of unknowns. Interpolation functions are another name for these functions. These functions specify the field variable values at discrete locations known as nodes. Adjacent elements are connected by nodes. This approach is useful because it can distinguish between irregular domains with finite elements. and useful analytical tool for resolving beginning, boundary, and eigen value issues that come up in a variety of engineering specialties[10].

Basic Steps in FEM:

The very first step is to convert the governing differential equation into an integral form. The two techniques to achieve this are:
(i) Variational Technique
(ii) Weighted Residual Technique.

Advantages of the finite element method over other numerical methods are as follows:

- This method can be applied to the analysis of any kind of boundary condition or irregularly shaped domain. clearly illustrates the advantages.
- It is simple to analyze domains that contain several materials.
- Major improvements in accuracy can be achieved by choosing higher degree polynomials or properly refining the mesh.

Assumptions:

The following qualities are considered to be present throughout the entire procedure in the ideal scenario of thermal analysis:

1. The composite is regarded as homogeneous on a macroscopic level.

2. The matrix and filler material is considered to be entirely homogeneous and isotropic.

3. It is considered that there is very little or no thermal contact resistance between the filler material and the matrix.

4. The composite lamina is free of voids or material flaws.

5. A 3D physical model forms the basis of the problem under consideration.

6. The filler particles are evenly dispersed throughout the polymer matrix in a square-periodic arrangement.

7. The thermal model in use only allows for one-dimensional heat conduction.

III. RESULTS AND DISCUSSION

Numerical Analysis

The temperatures at the nodes of the surface ABCD are specified as T1 (=1000C) in the numerical analysis of the problem, and for an ambient temperature of 27°C, the convective heat transfer coefficient is considered to be 2.5 W/m2-K. Figure 3.1 depicts the boundary conditions and the direction of the heat flow (heat flow from face ABCD to EFGH). It is assumed that all the other surfaces are adiabatic. With the aid of the finite-element program package

ANSYS, the unknown temperatures at the nodes in the interior region and on the adiabatic boundaries are determined[9].

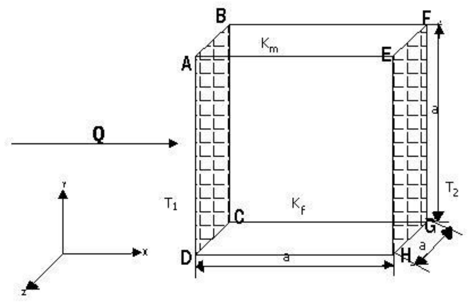

Fig.3.1 Boundary conditions

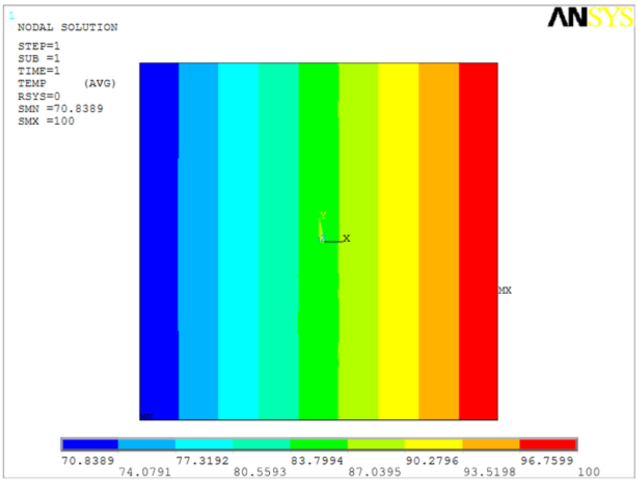

Fig 3.2: Temperature profile for BF slag filled epoxy composite of 1.4 % filler concentration

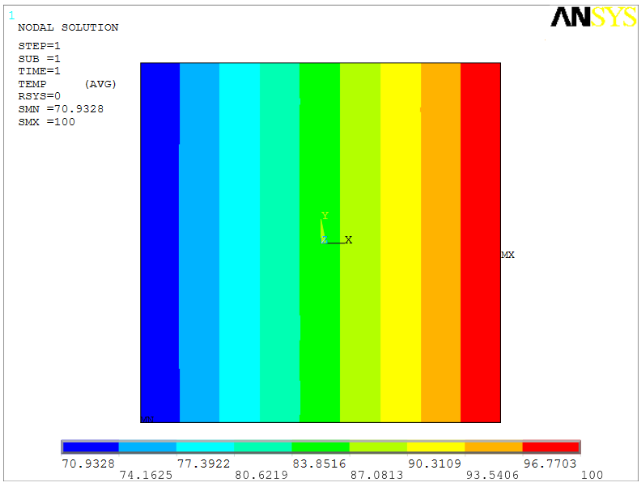

Fig3.3: Temperature profile for BF slag filled epoxy composite of 3.35 % filler concentration

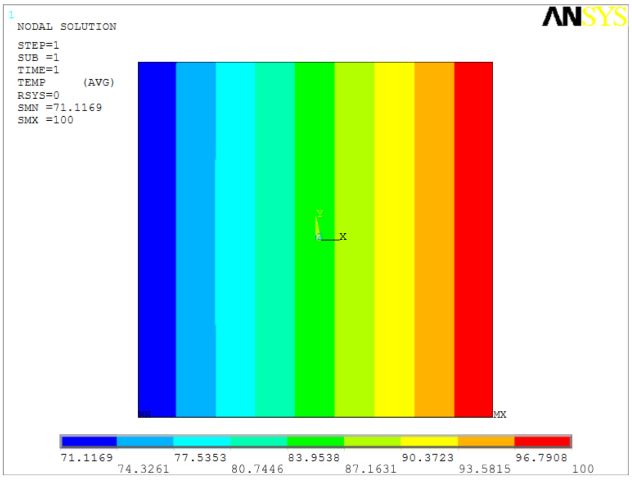

Fig 3.4: Temperature profile for BF slag filled epoxy composite of 5.25 % filler concentration

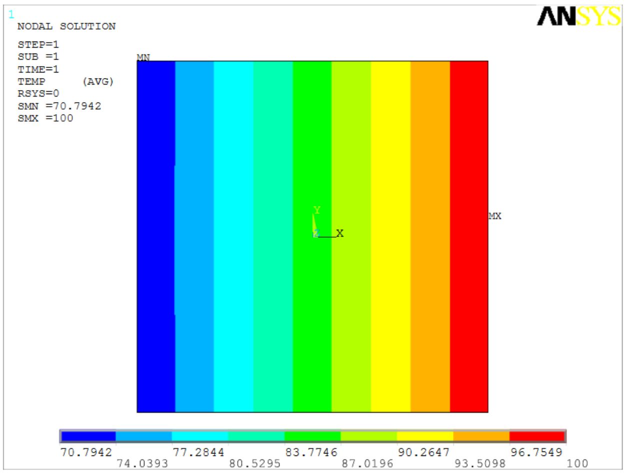

Fig 3.5: Temperature profile for BF slag filled epoxy composite of 7.85 % filler concentration

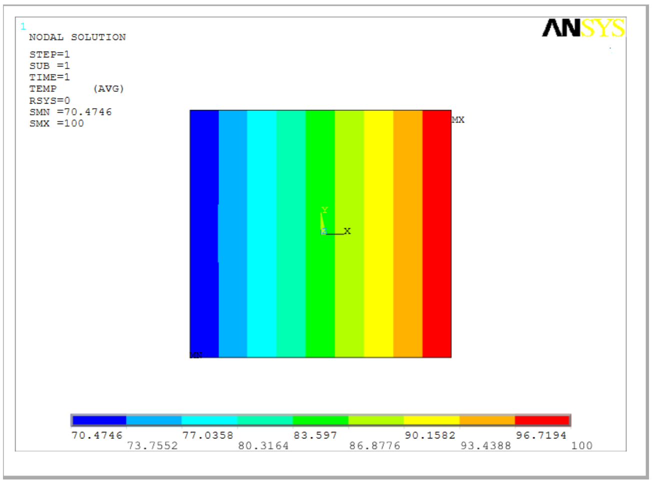

Fig 3.6: Temperature profile for BF slag filled epoxy composite of 9.4 % filler concentration

Table 1: Thermal conductivity for composites obtained from FEM and Experiment

Sample No	**BF Slag Content Vol %**	**EffectiveThermalConductivity**		
		FEM Simulated value (sphereincube)	**Experimental Measured Value**	**Analytical Model Value**
1	0	0.363	0.365	0.363
2	1.4	0.37	0.379	0.465
3	3.35	0.38	0.387	0.496
4	5.23	0.40	0.413	0.515
5	7.85	0.41	0.423	0.536
6	9.4	0.42	0.426	0.547
7	11.3	0.43	0.434	0.560

Table2:Percentage errors associated with the FEM simulated values with respect to the measured values (for blast furnace slag filled epoxy composites)

Composite Sample	BF slag Content (Vol.%)	Percentage errors associated with FEM results w.r.t. The experimental value (%)
1	1.3	2.10
2	3.34	1.54
3	5.22	2.90
4	7.84	2.83
5	9.3	1.16
6	11.2	0.68

Fig.3.7 Comparision of effective K of Sphere-in–cube & Cube-in–cube arrangement

IV.CONCLUSION

Blast Furnace Slag-filled epoxy composites can be successfully made by hand-lay-up process.

1. BF-Slag can be employed as a filler material in the epoxy matrix despite being an industrial waste.
2. For a wide range of BF-Slag filler concentrations, the effective heat conductivity (keff) of these particulate-filled polymer composites may be profitably determined using the Finite Element Method (FEM).
3. Effective thermal conductivity (keff) values determined using Finite Element Method (FEM) for a range of composite models closely approximate experimental values throughout a broad filler concentration range (1.4 vol% to 11.3 vol%).
4. The epoxy resin's thermal conductivity is enhanced by the use of blast furnace slag particles. The thermal conductivity of neat epoxy resin increases by approximately 19.28% with the addition of 11.3 vol.% filler content, and the error percentages fall within a minimal range of 3%.

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