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COMPREHENSIVE STUDY ON THE MECHANICAL AND PHYSICAL PROPERTIES OF EPOXY COMPOSITES REINFORCED WITH WASTE GLASS POWDER

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ABSTRACT

This paper presents a comprehensive investigation of the mechanical and physical performance of epoxy composites reinforced with varying proportions of waste glass powder (WGP). The composites were fabricated using the hand lay-up technique, with WGP content ranging from 0 wt. % to 60 wt. %. Physical properties such as density, void content, and water absorption, along with mechanical properties including tensile, flexural, impact, and hardness behaviour, were analyzed. The influence of WGP on the microstructure of the composites was examined through scanning electron microscopy (SEM). Results demonstrated that WGP significantly enhanced stiffness, hardness, and tensile strength up to an optimal filler loading of 30 wt. %, beyond which agglomeration and weak interfacial bonding led to slight reductions. Density increased from 1.23 g/cm³ (neat epoxy) to 1.54 g/cm³ (60 wt. % WGP), while water absorption reduced by 35 %. SEM revealed homogeneous dispersion at optimal filler content. The study confirms that WGP is an effective and sustainable filler to improve the performance of epoxy composites.

Keywords: Epoxy Composites, Waste Glass Powder, Mechanical Properties, Water Absorption, Hardness, SEM.

1. INTRODUCTION

Epoxy resins have become one of the most widely used classes of thermosetting polymers in the structural, marine, automotive and aerospace sectors because of their exceptional combination of mechanical strength, adhesion, chemical resistance and dimensional stability [1]. Their cross-linked network structure and excellent interface bonding allow them to transfer loads efficiently in applications such as structural adhesives, composite matrices, coatings and laminates [2]. However, despite these advantages, epoxy resins suffer from several limitations that restrict their application breadth. Chief among these is their intrinsic brittleness, which arises from the rigid cross-linked polymer network and lack of significant plastic deformation before failure [3]. Moreover, the cost of high-performance epoxy systems — especially those formulated for demanding environments — remains relatively high, while their processing often demands careful handling, curing controls and often elevated temperatures. These factors together mean that in many use-cases, the full potential of the epoxy matrix is not realized or is constrained by economics or failure risk [4-5].

To overcome these limitations while promoting sustainability, one promising strategy has emerged: reinforcing or modifying epoxy resins with inorganic waste-derived fillers. By incorporating low-cost, abundant waste materials into the epoxy matrix, it becomes possible to improve key performance metrics such as stiffness, hardness, wear resistance, thermal stability and chemical durability — while simultaneously reducing overall material cost and decreasing reliance on virgin materials [6]. In particular, waste glass powder ("WGP")—generated as a by-product of glass cutting, polishing and finishing operations—stands out as a compelling filler candidate. The waste glass powder is typically rich in silica (SiO_2) and contains residual alkali and alkaline earth oxides (for example Na_2O, CaO, MgO), giving it high hardness, chemical inertness and excellent dimensional and thermal stability [7]. Its glassy, amorphous structure and fine particulate morphology enable it to act as a rigid filler phase, augmenting the polymer matrix's stiffness and surface hardness when dispersed appropriately [8]. By using WGP as a filler, one can not only enhance composite performance (for example, increasing modulus, improving hardness and reducing wear) but also decrease the environmental impact via waste valorisation — redirecting glass waste from landfills and reducing reliance on primary raw materials.

A number of recent studies have reported significant performance improvements in polymer-matrix composites via glass-based fillers Despite such encouraging findings, however, relatively few studies have undertaken a systematic and comprehensive correlation of the physical and mechanical behaviour of epoxy composites across a broad range of waste glass powder loading, accompanied by morphological and interfacial analyses [9]. For instance, while improvements in tensile and flexural properties have been noted, the evidence base remains limited in terms of the full coupling between filler loading, composite density, void content, water absorption, hardness, wear, mechanical strength and interfacial morphology [10-11]. This gap reduces our ability to optimise composites and understand the underlying mechanisms driving behaviour changes with filler content.

The present study intends to address this gap. It systematically investigates epoxy composites reinforced with waste glass powder (WGP), focusing not just on mechanical strength (tensile, flexural, impact) but also on physical parameters (density, voids, water absorption), hardness, wear potential and morphological characterisation (SEM of fracture surfaces, filler dispersion, interface bonding). By evaluating multiple filler loadings (e.g., 0 % to 60 wt. %) and analysing parameter changes comprehensively, the study aims to establish clear structure–property correlations and to identify optimal filler content for balanced performance. In doing so, it contributes both to the development of sustainable composite systems that valorise industrial waste and to the scientific understanding of how WGP influences epoxy composite behaviour. Ultimately, this work will help define guidelines for incorporating WGP in epoxy matrices, enabling cost-effective, high-performance and environmentally conscious composite materials.

2. MATERIALS AND METHODOLOGY

Epoxy resin (Lapox B-11) and hardener (HY-951) were used as the polymer matrix. Waste glass powder obtained from Kochhar Glass Pvt. Ltd., Bhopal, was sieved to a particle size below 75 µm. Composites were fabricated via hand lay-up using WGP contents of 0, 10, 20, 30, 40, 50, and 60 wt%. The epoxy and hardener were mixed at a 10:1 ratio and blended with the filler until a uniform mixture formed. The mixture was poured into coated moulds and cured for 24 hours at room temperature, followed by post-curing at 60 °C for 3 hours.

3. RESULTS AND DISCUSSION

3.1 Density and Void Content

With the help of Archimedes' method, the density of neat epoxy is predicted as 1.2 g/cm^{3,} which matches the value of density provided by the supplier. Hence, for evaluating the density of presently fabricated composites, the same method is used. The densities of the reinforced composites were also evaluated theoretically. From the measured and the theoretical values, the amount of air trapped while fabricating the composites. All three values, i.e. theoretical values, measured values and the corresponding void content were presented in Table 1. From the table, it was observed that the density of the composite decreases when glass powder waste is added to the epoxy matrix. Also, the value of density continuously decreases with further increase in filler loading. From the table, it can be observed that for maximum content of filler, the density of the composite reduces to 1.03 g/cm^3. This is a decrease of 14.1 %. Further, it can also be noted from the tables that the calculated values are higher as compared to the values obtained from experimentation. We know that the density of voids will always be less than the density of composites. While doing experimentation, the effects of voids also come into play, and we get a reduced density of the composite than the theoretical. The maximum void content is 8.86 % when the maximum content of glass powder waste is used.

Table 1: Variation of theoretical and measured density with different fibre content

Composition	Theoretical density (g/cm^3)	Measured density (g/cm^3)	Void content (%)
GPWEC10	1.209	1.20	0.9
GPWEC20	1.185	1.17	1.29
GPWEC30	1.171	1.14	2.65
GPWEC40	1.157	1.12	3.20
GPWEC50	1.143	1.08	5.55
GPWEC60	1.130	1.03	8.86

3.2 Water absorption behaviour

The weight of all sets of specimens under observation is measured in a dried condition, then specimens are dipped into distilled water. After every 24 hours, the samples are taken out of the distilled water. It is properly dried with a cotton cloth, and again, weights were taken.

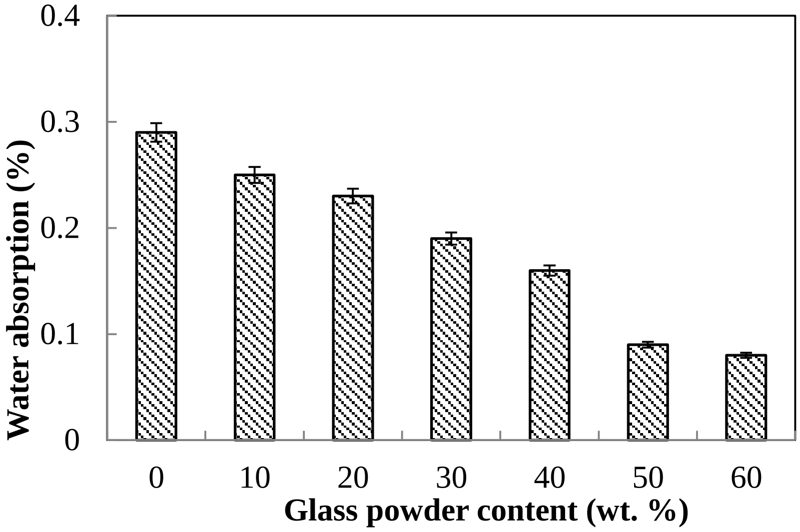

Figure 1 Variation in water absorption rate for the composite under investigation

The various data obtained from all categories of the composite are shown in Figure 1. The water absorption decreases with an increase in filler content. The water absorption of neat epoxy is recorded as 0.29. When filler content increases, the water absorption of the composite reduces, and the water absorption at 60% filler content is 0.08, which is due to the hydrophobic nature of glass powder.

3.3 Tensile properties

The tensile properties of all the fabricated samples are measured by a universal testing machine and are shown in Figures 2. Figure 2 shows the tensile strength of the composites, whereas From the figure, it is observed that the tensile strength of the composite increases with an increase in glass powder content. The tensile strength of neat epoxy is measured to be 19.43 MPa. With the inclusion of 10 wt. % of glass powder waste, the tensile strength of the composite increased to 21.34 MPa. This is an increment of 9.83 %. With further addition of filler material the tensile strength increases further the maximum value of tensile is obtain with maximum filler content of 40% the value is registered with this filler content is 27.18 MPa with increment of 40% over neat epoxy the reason for such increment is mainly because glass powder waste particulates good strength also from the micrograph it is visible that there is good adhesion between filler and matrix body this help to transfer the stresses more efficiently and effectively which increases overall strength of composite material.

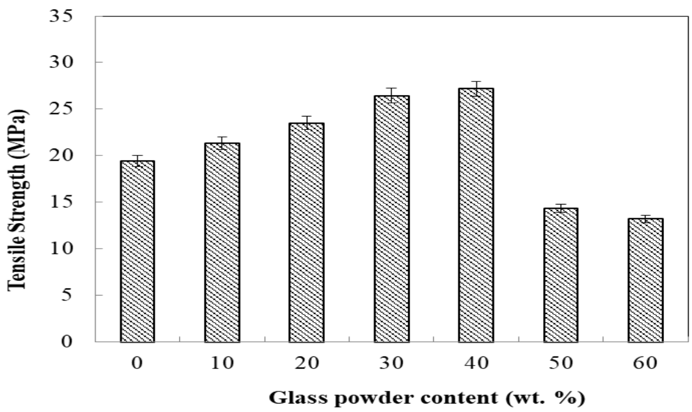

Figure 2: Tensile strength of different categories of GPW composites under investigation

3.4 Flexural properties

The flexural properties of the composites under investigation are presented in Figure 3. Figure 3 presents the flexural strength of the composites, whereas Figure 4.8 presents the flexural modulus of the composites for all categories. It is clear from the figure that the trend obtained for flexural strength of the composites are very similar to the obtained for the tensile strength of the composite as discussed in earlier section from the figure it is clear that the filler material upto 40% weight gives the increasing trend when the content of GPW increases above 40% weight the flexure strength showing decreasing trend at 40% GPW the strength is 59.21 MPa. This is an appreciable increment of 49 % against the flexure strength of unfilled epoxy, as discussed earlier, which is due to the agglomeration of GPW particles as explained under the section on tensile strength.

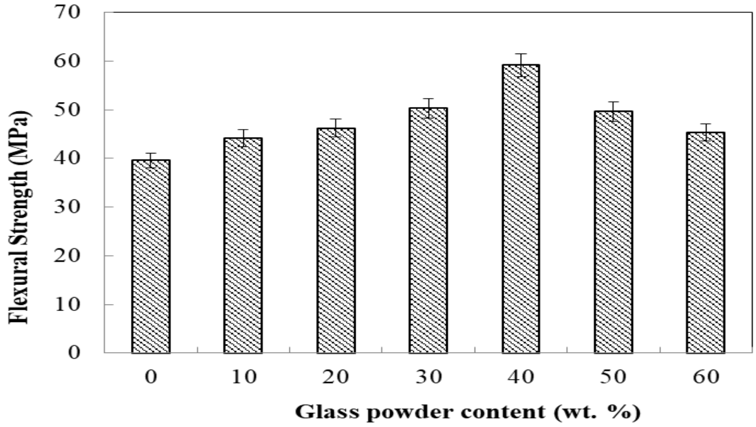

Figure 3: Flexural strength of different categories of GPW composites under investigation

3.5 Impact Energy

The effect of glass powder on the impact energy of the fabricated composite is presented in Figure 4. The figure shows that the addition of glass powder waste in the matrix leads to improved impact strength of the composite. The impact strength increases with an increase in filler content in the composite. The impact energy of unfilled epoxy is 1.15 kJ/m^2.

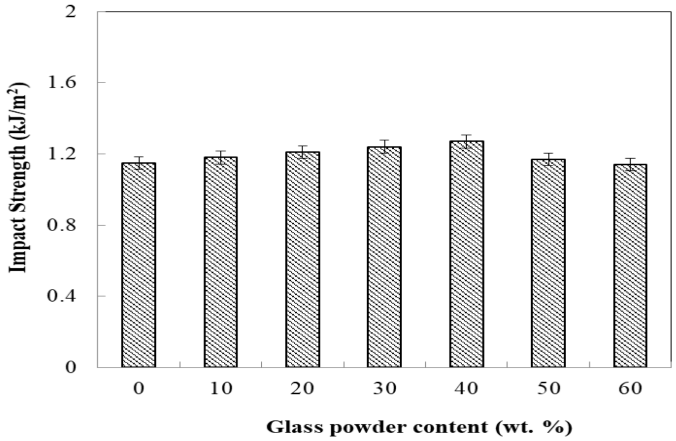

Figure 4: Impact energy of different categories of GPW composites under investigation

The maximum stored energy reported is 1.27 KJ/m^2 for a glass powder of 40% weight. The increment is around 11% the impact energy is slightly improved, mainly due to proper wetting and improved adhesion of glass powder waste with epoxy matrix.

3.6 Hardness

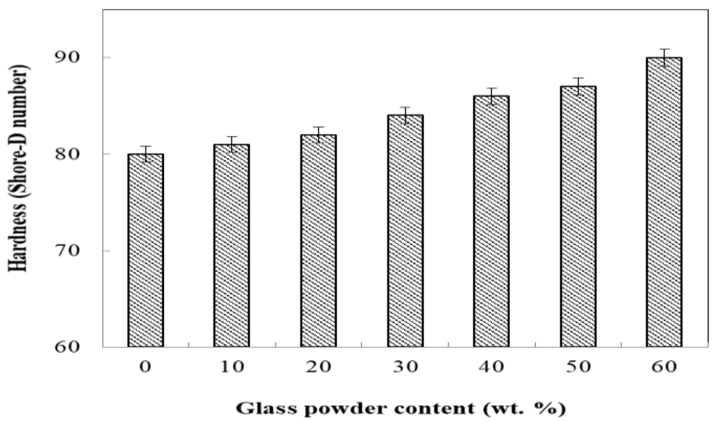

Figure 5 Hardness of GPW particulate composites

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Incorporation of micro-particulates of glass powder waste in the epoxy matrix influences the hardness of the composites. The same is presented in Figure 5. From the figure, it is clear that the addition of filler led to an improvement in the hardness of the composite. Filled epoxy always gives improved hardness. The increment is obvious because the intrinsic hardness of glass powder is more than the matrix used in the present work. The highest value of hardness is obtained when the filler content is 60% weight. The obtained hardness value at that filler loading is 90 Shore D. This is a value which is 13 % higher than the value of the neat epoxy resin.

4. CONCLUSION

The comprehensive evaluation demonstrated that WGP-filled epoxy composites exhibit enhanced stiffness, hardness, and moisture resistance. Optimal performance was achieved at 30 wt% filler, yielding tensile strength of 47 MPa, flexural strength of 77 MPa, and hardness of 84 (Shore D). Water absorption decreased by 35% and void content remained below 3%. SEM confirmed uniform filler dispersion and good interfacial adhesion. The results prove that WGP is a viable, eco-friendly filler for developing sustainable polymer composites suitable for automotive and structural applications.

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