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Using an Experimental Approach to Study the Effect of Different Nanomaterials on Thermal, Mechanical, and Optical Properties of Epoxy Coating

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ABSTRACT

Epoxy coatings face performance limitations under harsh environmental conditions, including poor UV resistance and discoloration over time, necessitating the enhancement of their properties through additives and modifications. This study aims to develop a high-performance epoxy coating by improving its structure through the addition of carefully selected nanomaterials. It investigates the contribution of these materials to improving mechanical strength, enhancing operational stability, and increasing optical stability, thereby improving coating quality and suitability for diverse application conditions. In this work, nanoparticles were prepared and incorporated into a polymer matrix, specifically an epoxy matrix, using ultrasonic stimulation combined with solution mixing techniques to achieve high homogeneity and efficient particle dispersion within the material. The results, as observed in the DSc test, showed an increase in the glass transition temperature (Tg) at specific concentrations of some of the materials used. Furthermore, the adhesion strength was significantly enhanced by the addition of the nanomaterials. MMT exhibits superior performance compared to zinc oxide (ZnO) and titanium dioxide (TiO_2) due to its layered structure, which enhances its interaction with the epoxy matrix. It achieved the highest bond strength improvement at a 2% concentration, reaching 3.27 MPa. Furthermore, in UV tests, UV absorbance increased with the presence of various nanoparticles (zinc oxide, MMT, and titanium dioxide), but the highest absorbance was observed with 2% titanium dioxide, reaching 0.5% at 350 nm. This makes it the most protective additive for coatings. Transmittance decreased with increasing filler concentration, indicating improved radiation shielding performance. In impact strength tests, a 71% improvement was observed with 1% zinc oxide. These impact tests demonstrate a significant improvement in impact strength with nanoparticles compared to pure epoxy, confirming the effectiveness of these materials in enhancing the overall performance of coatings.

1. INTRODUCTION

Coating, especially organic coatings, is one of the most widely utilized methods for protecting metals from corrosion. The primary goal of organic coatings is to create a physical barrier against corrosive agents such as chlorides, water, and oxygen. Furthermore, these coatings are inherently impermeable, meaning that once a defect happens, the corrosive material will seep through. In general, organic coatings are an effective method for protecting metal substrates from corrosion since their ease of use, availability, and cost-effectiveness. Therefore, the importance of organic coatings in industry is significant, with approximately $2 billion spent annually on organic coatings in the United States [1-3]. With their mechanical features, good stability, excellent adhesion, excellent corrosion resistance, high efficiency, and high durability, epoxy coatings are among the most attractive and effective kinds of coatings. These coatings prevent corrosion by isolating the substrate from corrosive agents such as oxygen, ionic particles, and moisture. Since the existence of aromatic components in epoxy resins, they are susceptible to degradation and absorption in the presence of ultraviolet light. Therefore, the main reason for limiting the use of epoxy resins in outdoor applications is the discoloration and calcination of epoxy coatings in the presence of UV radiation. Although epoxy resins are an important optical coating material, they do not block UV radiation. Nevertheless, they can be modified to block UV radiation by adding inorganic fillers [4-6]. Among these inorganic fillers, ZnO and TiO_2 nanoparticles are the most widely utilized in coating applications, where they are utilized as reinforcing agents to enhance the mechanical features and thermal stability of polymeric materials. These particles, ZnO, TiO_2, act as UV absorbers and have demonstrated excellent chemical stability under UV radiation and at elevated temperatures. Furthermore, these particles have the additional function of acting as shielding agents, reducing radiation penetration into the epoxy matrix and thus reducing photodegradation rates. They also contribute to enhanced mechanical and thermal features due to their large surface area. MMT is one of the most widely utilized clay fillers for improving optical, mechanical, and thermal features since its layered structure, high aspect ratio, and high stiffness. Nevertheless, its UV-blocking impact is limited in comparison with inorganic fillers because it acts as a physical barrier that slows the penetration of UV rays and moisture. Therefore, its layered structure exhibits a limited barrier impact [7-10]. Many researchers have conducted various studies utilizing various nanofillers and studying their impact on mechanical features and ultraviolet radiation. Zhang et al. [11] explored the impact of Nano-ZnO on the UV resistance of epoxy resin systems and the epoxy composites utilizing experimental methods and thermodynamic simulations. The findings indicated that the addition of Nano-ZnO to epoxy resins reduced the UV activity, while the UV resistance was optimal at a weight percentage of 0.3%. Meanwhile, Shafaamri et al. [12] explored the impact of adding Nano-TiO_2 on the overall performance and corrosion protection capacity of a pure epoxy coating system modified with dimethyl sulfoxide (PDMS) and various weight proportions of TiO_2 to the modified epoxy matrix. The findings demonstrated that a specific amount of Nano-TiO_2 was able to enhance the corrosion protection performance of epoxy-based coating systems, and good curing levels with high T_g magnitudes were achieved for all composite nanocoating systems. Kumar et al. [13] explored the development of the mechanical and thermal features of a TiO_2 nanocomposite matrix at various weight percentages (5, 10, 15%) utilizing a dual-stage ultrasonic mixing technique. The findings demonstrated that the optimum percentage was 10%, which enhanced the mechanical features of the epoxy matrix, including failure energy (hardness), tensile strength, thermal stability, and storage modulus, compared with pure epoxy. He et al. [14] synthesized ceria nanoparticles of various shapes and sizes and explored their impact on the impact strength of epoxy coatings. The findings demonstrated that the impact strength of epoxy resins made from ceria nanorods was four times higher than that of neat EP, another study, Nguyen et al. [15] explored the impact of utilizing various kinds of nanoparticles on the mechanical features of epoxy. The coatings were applied to the surfaces of steel substrates. The findings demonstrated that nanoparticles enhanced the cross-link density, increasing trough Tg of the epoxy coating from 58 to 170℃ when utilizing TiO_2, thus being considered the best in improving the impact resistance of epoxy coatings. Conversely, the addition of epoxy/ZnO_2 achieved the best thermal stability. The availability of Fe_2O_3 particles also enhanced the adhesion strength of the epoxy coatings. In another study, Han et al. [16]. conducted a study on developing an epoxy matrix reinforced with ZnO/CdS nanoparticles that effectively blocks ultraviolet and blue light while maintaining high transparency. The results indicated that adding these nanoparticles to the epoxy matrix at a concentration of 0.3% blocked most ultraviolet radiation and over 80% of blue light, while maintaining transparency in the rest of the visible spectrum, similar to pure epoxy. In another research paper, Li et al. [17] explored that adding Nano-ZnO to epoxy resin at very low amounts provides good optical features, i.e., high UV-blocking efficiency and high transparency to visible light [18-21]. This research aims to determine how nanoparticles affect the properties of epoxy coatings when used in varying weight ratios. This is achieved by studying changes in thermal behavior, UV resistance, and durability. The goal is to better understand the role of these particles in coating development. Over time, epoxy resin has seen widespread use in engineering and construction applications. While many previous studies have investigated the effect of a single nanomaterial on specific properties, most have focused on only one material and at relatively high weight ratios. The study did not address the combined effect of three nanomaterials within the same epoxy matrix. Therefore, the interaction of these materials within the epoxy matrix and their impact on the properties remain unclear. For example, some studies have shown that titanium dioxide (TiO_2) can improve corrosion resistance or mechanical properties at certain weight ratios, while others have studied zinc oxide (ZnO) or MMT separately. Hence, the role and importance of this research in bridging this research gap, which aims to integrate three nanomaterials (ZnO, TiO_2, MMT) within an epoxy matrix and study their interaction on the aforementioned properties, and to develop a clear and important vision through the possibility of enhancing the performance of epoxy coatings through multiple nano-additives.

2. EXPERIMENTAL SECTION

2.1 Preparing work materials

Table 1. Basic and general specifications of neat epoxy

Characteristic	Date
Form	Liquid
Type	Storage coat 400
Color	White
Tensile strength	⩾18 MPa @ 7 days
Compressive strength	⩾80 MPa @ 7 days
Flexural strength	⩾30 MPa @ 7 days
Specific gravity	1.55 ± 0.10
Full cure	After 7 days @ 25℃

Table 2. Basic and general specifications of Zinc oxide nano

Characteristic	Date
Form	Powder
Size and Purity	10-30 nm, 99.8%
Color	White
True density	5.606 g/cm³

Table 3. Basic and general specifications of Titanium Dioxide nano

Characteristic	Date
Form	Powder
Size and Purity	10-30 nm, 99.5%
Color	White
True density	4.23 g/cm³

Table 4. Basic and general specifications of Montmorillonite nano clay

Characteristic	Date
Form	Powder
Size	≤ 20 micron and thickness 1 nm
Color	White to beige
Density	200-500 kg/m³

The materials used in this research are zinc oxide, titanium dioxide, montmorillonite clay, epoxy, and ethanol solvent. The attached Tables 1-5 show the basic and general specifications for each material used.

Table 5. Basic and general specifications of the Ethanol solvent

Characteristic	Date
Purity	99.9%
Color	Transparent liquid
Boiling point	70°C
Density	789 kg/m³

2.2 Neat epoxy specimen preparation

The epoxy and hardener (3:1) were mixed utilizing a mechanical stirrer for 5 min. To ensure homogeneity, it also reduces the bubbles that occur during the preparation process, and in addition, it contributes to faster mixing of the materials together compared to manual mixing. The blend was then placed in an Air removal device for a period of 30 minutes. Next, the cured blend was added to a pre-prepared and cleaned silicone mold. This blend was then left to dry in the mold for 7 dates at normal temperature (laboratory temperature). As shown in Figure 1 the basic stages of preparing epoxy.

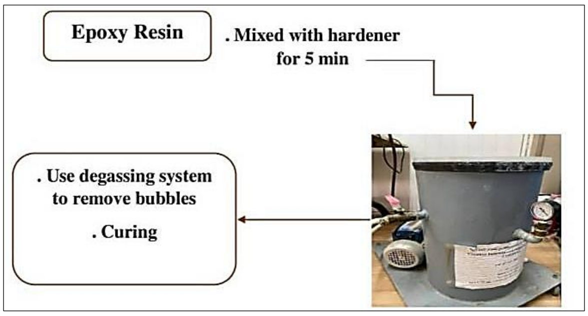

Figure 1. Comprehensive steps for preparing the neat epoxy matrix are used

2.3 Nanoparticles preparation

- Nano Montmorillonite Clay
- Titanium Dioxide
- Zinc Oxide

Initially, the materials were made utilizing various proportions 0.25-2 wt.% of NPs, including Titanium Dioxide, Zinc oxide, and Montmorillonite nano clay see Table 6. The nanoparticle suspension was prepared in ethanol. By using a mechanical mixer for a period of 15 min., the mixture was then subjected to ultrasonic processing for a period of 45 min. to ensure effective particle dispersion (Figure 2).

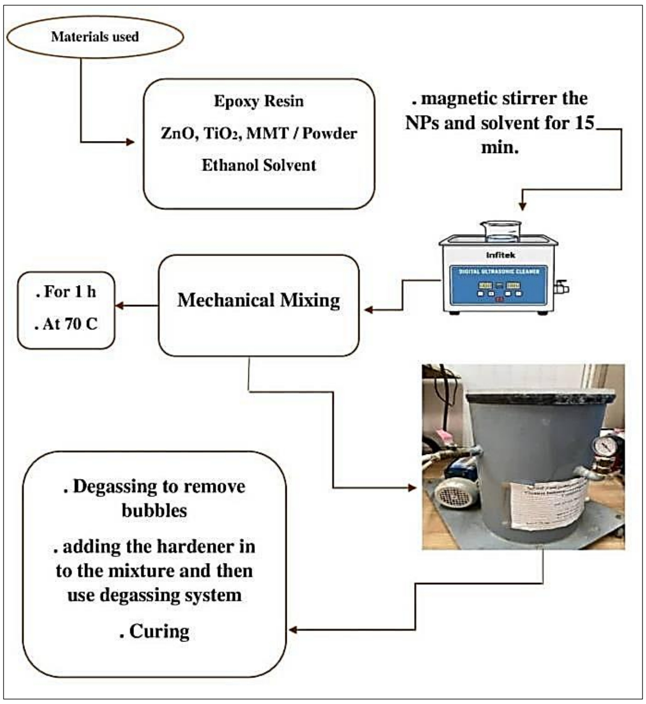

Figure 2. Comprehensive steps for the method of preparing the nanomaterial used

Table 6. The composition of samples

No. of Samples	Samples Abbreviation	Samples Components
S1	EP	Pure Epoxy
S2	0.25 E-Z	Epoxy-Zinc oxide with 0.25%
S3	0.5 E-Z	Epoxy-Zinc oxide with 0.5%
S4	1E-Z	Epoxy-Zinc oxide with 1%
S5	1.5 E-Z	Epoxy-Zinc oxide with 1.5%
S6	2 E-Z	Epoxy-Zinc oxide with 2%
S7	0.25 E-T	Epoxy-Titanium Dioxide with 0.25%
S8	0.5 E-T	Epoxy-Titanium Dioxide with 0.5%
S9	1 E-T	Epoxy-Titanium Dioxide with 1%
S10	1.5 E-T	Epoxy-Titanium Dioxide with 1.5%
S11	2 E-T	Epoxy-Titanium Dioxide with 2%
S12	0.25 E-T	Epoxy-Montmorillonite nano clay with 0.25%
S13	0.5 E-T	Epoxy-Montmorillonite nano clay with 0.5%
S14	1 E-T	Epoxy-Montmorillonite nano clay with 1%
S15	1.5 E-T	Epoxy-Montmorillonite nano clay with 1.5%
S16	2 E-T	Epoxy-Montmorillonite nano clay with 2%

2.4 Nanocomposite preparation

Add the previously prepared blend to the epoxy resin, and then blend was mechanically. For a period 1 h and without stopping, and at 70°C with a speed of 400 rpm to remove the ethanol solvent by evaporation. Mechanical mixing is an important method aimed at mixing different materials to ensure the homogeneous distribution of components, and also to increase the interaction between nanoparticles and the epoxy matrix, and to reduce the clumping and bubbles that occur during preparation. During this process, the mass of the mixture was monitored for a period of 10 min to ensure that the solvent is completely removed before it was placed in an Air removal device at a temperature of 70°C. Consequently, the mixture was reweighed several times consecutively over ten minutes until its mass was stabilized. The blend was then cooled to room temperature (25°C) for half an hour, and the hardener was added, with mechanical stirring for five minutes to ensure homogeneity. The blend was then put into an Air removal device for 30 minutes to remove trapped air and finally poured into silicone molds for 7 days to cure, as shown in Figure 2 and Table 6. After the processing stage is complete and the samples are removed from the mold, they are ready for testing. Three samples were taken from each percentage for tests to ensure the accuracy of the results.

3. TESTS

3.1 Differential Scanning Calorimeter Test (DSC)

The test was conducted based on ASTM D 3418-03 specification and utilizing the SH1MADZ-4 DSc-60 device made in Jaban, it is considered an important technique for measuring the temperature of specimens, providing valuable data on the features of materials and the thermal behavior of pure epoxy specimens, as well as various nanocomposites, including (EP with ZnO, EP with TiO_2, and EP with MMT). Specimen banned and a heating rate of 10°C/min with a heating range of 25 to 300°C.

Figure 3. The device for the impact test

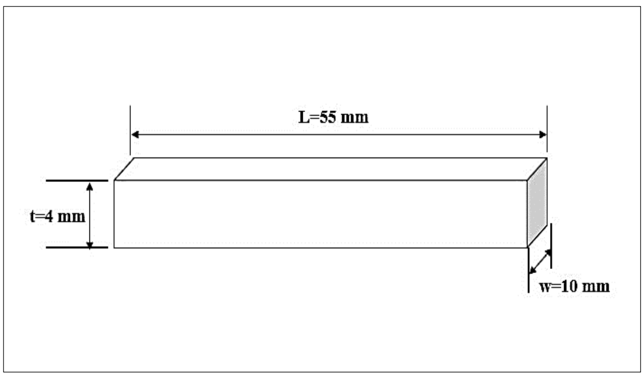

Figure 4. Diagram of the impact test specimen with the dimensions

3.2 Impact test

It is one of the most important tests that contribute to determining the ability of plastic materials to withstand stress. The WD 400 is a German-made machine located in Hamburg at the Department of Polymer Engineering and Petrochemical Industries (DOPEPI) - College of Materials Engineering - University of Babylon (Figure 3). The Charpy test method is utilized based on ISO 179-1 [22] (Figure 4). The test mechanism is carried out by testing three specimens of each percentage. To impact the specimen, a pendulum is dropped freely from a predetermined height, thus hitting the specimen, causing fracture [23]. The impact strength (acU) is then determined by calculating the energy required for fracture utilizing the following formula [24].

$$\mathrm{acU} = \frac{W_B}{bh} \times 10^3 \tag{1}$$

where,
acU: Impact strength (J/mm²).
b: Thickness of specimen (mm).
h: Width of specimen (mm).
W_B: Energy at break (J).

3.3 Pull-off adhesion strength test

To evaluate the adhesives and the quality of the coating, various methods are utilized, one of which is the pull-off test based on the ASTM D 4541 specification [25]. This device is located at the Department of Polymer Engineering and Petrochemical Industries (DOPEPI)-College of Materials Engineering-University of Babylon (Figure 5). The pull-off strength (adhesion strength) of the coating is then determined by dividing the force required to remove the coating from the substrate surface by the contact area after the dolly and adhesive or coating are removed from the substrate, measured by drawing perpendicular to the surface. Before the adhesion test, a series of essential preparatory steps were performed to ensure the accuracy of the results. The surfaces of the selected steel substrates were sanded with 40, 60, and 80 grit sandpaper to smooth the steel surface. The surfaces were then thoroughly wiped with acetone to remove dust, dirt, and other contaminants. Following this, they were dried in an 80°C oven to eliminate any remaining moisture on the steel substrate surface. Once the surfaces were confirmed to be completely clean and dry, they were ready for the next steps of the test. High-quality Araldite 2011A adhesive was used to secure steel screws to the epoxy-coated or nanoparticle-reinforced steel substrate. The screw diameter was 16 mm. The test was performed using a tension device (WDW-5E electronic universal testing equipment), and a sufficient vertical pulling force was produced to remove the coating layer from the steel substrate's surface. The adhesion strength was then determined utilizing the formula [26].

$$Adhesion\ strength = \frac{f}{Aa} \tag{2}$$

where,
f = pull force (KN).
Aa = Adhesion area (mm^2): contact area between coating layer and dolly surface.

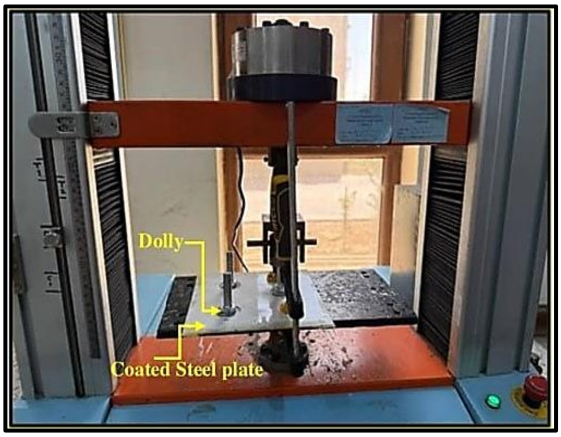

Figure 5. Pull-off adhesion strength testing device

3.4 Ultraviolet-visible spectrophotometer test

A CECIL 2700 interphase spectrometer was utilized to measure the optical features of (EP with ZnO, EP with TiO_2, and EP with MMT) nanocomposites. Also, the absorption of light in the UV/visible range of nanocomposites was measured. The UV range consists of two light sources: a deuterium lamp and a tungsten lamp, with wavelengths ranging from 190 to 390 nm and 390 to 1100 nm, respectively. The Lambert-Beer law is utilized to calculate the absorbance spectroscopy [27].

$$I = I_0 e^{-\alpha X} \tag{3}$$

According to the following formula, transmittance (T) is defined as the proportion of the intensity of light coming out of the specimen (I) to the intensity of light entering it I_0:

$$I = I_0 \tag{4}$$

According to the following formula, permeability could be related to absorptivity.

$$A = log\left(\frac{I_o}{I}\right) = log\left(\frac{1}{T}\right) \tag{5}$$

The absorption coefficient (α) could be determined by replacing Eq. (4) with Eq. (3) and utilizing the following formula.

$$\alpha = \frac{-\log(T)}{X} \tag{6}$$

The sum of the intensity of absorbed and transmitted light at the bound light is known as the incident light intensity(I_o).

$$I = I_T + I_A + I_R \tag{7}$$

$$\frac{I_T}{I_O} + \frac{I_A}{I_O} + \frac{I_R}{I_O} = T + A + R = 1 \tag{8}$$

Absorption is determined by utilizing the following formula.

$$A = 1 - T - R \tag{9}$$

where,

A: absorbance.
I_0: intensity of incident light at a given wavelength.
I: intensity of the transmitted.
X: specimen of thickness through which light passes.
T: transmittance.
R: reflection.

4. RESULT AND DISCUSSION

4.1 Impact strength

Figure 6 demonstrates the relationship between impact strength and additive proportions (0.25-2) wt.% of Zinc oxide, Titanium Dioxide, and Montmorillonite nano clay in neat EP. In this study, impact strength was considered the key performance indicator to determine the effectiveness of nanoparticle kinds and amounts on the features of epoxy resin. Pure epoxy resin was utilized as the reference material, with a fracture energy of approximately 3.47 J/m². The findings demonstrate that the most significant development in impact strength happened with the addition of Nano-ZnO, with the impact energy increasing significantly with increasing ZnO amount, reaching its maximum magnitude at a 1% ZnO amount (approximately 5.957 J/m²), Therefore, it is considered superior to pure epoxy. This is attributed to the high capacity of ZnO to absorb impact energy and prevent crack propagation, since its homogeneous and well-distributed composition within the epoxy matrix. These nanoparticles generate effective point obstacles, thus limiting the progression and deviation of the cleft path, strengthening the polymer structure, and it's a large surface area. When TiO_2 was added to the epoxy matrix, a moderate development in impact strength was observed compared with pure epoxy, with impact strength magnitudes ranging from 5.08 to 5.32 J/m² at various amounts (0.25, 0.5, 1, 1.5, and 2) wt.%. Nevertheless, TiO_2 is less effective than ZnO, as the agglomeration of the nanoparticles results in a reduction in impact strength and a loss of energy dissipation.

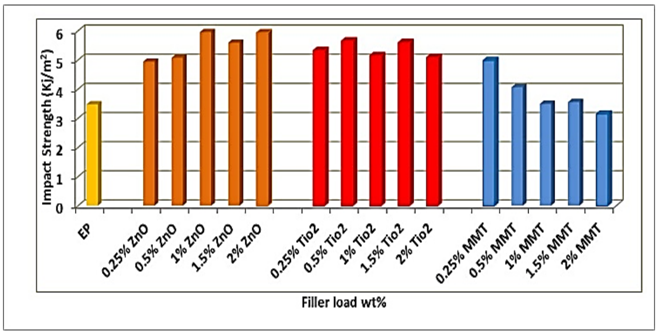

Figure 6. Effect of the weight ratio of added nanomaterials on the impact strength of neat EP

In contrast, MMT has the least positive impact, with the highest impact strength magnitude at 0.25% MMT, reaching 4.981 J/m². This magnitude then reduces significantly at higher amounts, reaching 3.146 J/m² at 2% MMT, a magnitude lower than that of pure epoxy because the resulting agglomeration and loss of good dispersion negatively affect the material's impact resistance, for the same reasons mentioned previously. Based on the impact strength diagram results, we conclude that zinc oxide (ZnO) nanoparticles exhibit the greatest improvement in impact strength compared to other nanoparticles used, such as TiO_2 and MMT, at various addition ratios. This indicates that incorporating ZnO into epoxy coatings enhances their resistance to mechanical failure and significantly improves the durability of the protective layer. In other words, it helps protect the layer from sudden and premature cracking by increasing the paint's ability to absorb energy and also limiting the widening of cracks. Making it a preferred choice for improving the performance of engineering coatings. These findings are compatible with Al Saadi et al. [28].

4.2 Pull off adhesion strength

Figure 7 demonstrates the effect of the proportions of added nanomaterials (ZnO, TiO_2, MMT) on the pull-off adhesion strength of a neat epoxy matrix at specific weight percentages of 0.25-2%. The findings indicate that the pull-out adhesion strength of the epoxy matrix is enhanced by adding nanofillers of ZnO, TiO_2, and MMT at varying weight proportions. However, this improvement in adhesion strength when adding nanoparticles was not uniform at all concentrations, as the results showed higher or lower values than pure epoxy, indicating that the effect of these nanofillers depends largely on the type of particles and their concentration within the matrix, with the pure epoxy magnitude reaching 2.0 MPa. The adhesion strength magnitude was recorded when MMT was added at 2% by weight, reaching 3.27 MPa, followed by ZnO 2.55 MPa and TiO_2 2.05 MPa, which is related to the kind and distribution of nanofillers in the epoxy matrix and their impact on adhesion. For the same reason mentioned above. These modifications are attributed to the fillers' ability to enhance the mechanical bonding of the matrix to the substrate surface by roughening the microstructure of the epoxy matrix and enhancing the wettability of the resin on the steel surface, creating an effective mechanical interlocking between the epoxy matrix and the steel substrate surface.

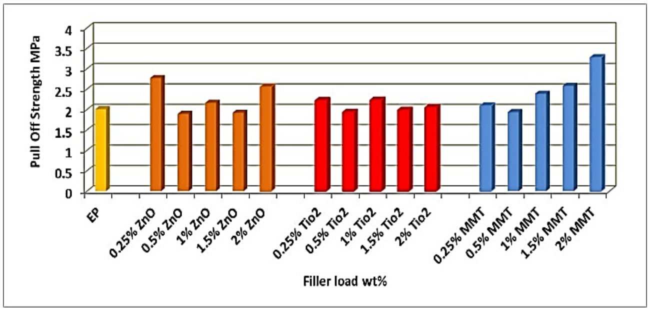

Figure 7. Effect of the weight ratio of added nanomaterials on the pull-off adhesion of neat EP

Furthermore, the addition of nanofillers enhanced the barrier performance of epoxy coatings by reducing their permeability and increasing the complexity of the penetration path of moisture and corrosive materials towards the steel surface. This impact enhances the long-term protection of the steel substrate, especially in harsh environments. The layered structure of MMT also contributed to the formation of an effective physical barrier, reducing corrosion rates and extending the coating life. It forms hydrogen bonds and mechanically interacts with the epoxy chains, leading to enhanced stress distribution and strong coating adhesion, while ZnO and TiO_2 particles have fewer active surfaces, resulting in weaker adhesion. These findings are compatible with Saeed et al. [29].

Figure 8. Image of adhesive failure demonstrated on the steel substrate

All pull-off adhesion test specimens demonstrate cohesive and adhesive failure, as demonstrated in Figure 8, due to the cohesion force of the epoxy and ZnO, TiO_2, and MMT nanocomposites being greater than the adhesive force between the steel and adhesive.

4.3 UV-Visible

4.3.1 Absorption

Figure 9 demonstrates the effect of the zinc oxide addition ratios on the absorption spectrum of epoxy coatings compared to neat EP (S0). Absorbance demonstrates a significant increase in all specimens in the UV range (300-400 nm), while it gradually increases with increasing ZnO amount, based on the Beer-Lambert law. The maximum absorbance is obtained for S5 (2%), with an absorbance magnitude of approximately 4.7 at a wavelength of 350 nm, compared with the reference specimen, which is pure epoxy S0 (0%), with an absorbance magnitude of 3.7 at this wavelength. This increase happens because Nano-ZnO is very effective at absorbing in the UV range since its large energy gap (band gap ≈ 3.3 eV), providing greater UV protection and reducing degradation of the epoxy network due to light exposure. These findings are entirely consistent with the findings of researchers Moussa et al. [30].

Figure 10 demonstrates the influence of the Titanium Dioxide addition ratios on the absorbance spectrum of epoxy coatings compared to neat EP (S0). Absorption spectroscopy results showed that the addition of TiO_2 nanoparticles to the pure epoxy matrix resulted in a gradual increase in absorbance with increasing nanoparticle concentration compared to pure epoxy. In the 300-400 nm range, which represents the UV region affecting the stability of coatings, the absorbance increased from 3.7 (S0) for pure epoxy to 5.0 at 2 wt.% (S5), indicating TiO_2 's high ability to absorb UV radiation due to electron transitions across the wide energy gap (~3.2 eV). At 1050 nm, the absorbance increased represents 2 wt.% compared to pure epoxy, reflecting the particles' contribution to enhancing internal scattering and reducing light transmittance through the epoxy matrix. This consistent increase in absorbance with increasing TiO_2 concentration indicates that the nanoparticles act as effective barriers within the coating layer, absorbing and scattering UV and visible light, thereby limiting the access of high-energy photons to the epoxy chains. As a result, photo-degradation rates are reduced, the operational life of the coating is increased, and its mechanical properties are maintained under radiation exposure conditions. These findings are entirely consistent with the findings of Bouzidi et al. [31].

Figure 11 demonstrates the influence of the montmorillonite addition ratios on the absorbance spectrum of epoxy coatings compared to neat EP (S0). The findings demonstrate that as the nanoparticle amount increases, the absorbance increases. The absorbance magnitude for S0, which represents pure epoxy without additives, reached 3.7 at a wavelength of 350 nm. After that, the absorbance magnitude increases to 4.4 (the specimen containing 2% MMT, S5). This development is attributed to the effective scattering and absorption of UV radiation by the Nano-MMT, due to its high surface area and homogeneous dispersion within the epoxy matrix. However, it does not show strong absorption in ultraviolet rays, because it is not a semiconductor and does not have a suitable energy gap that enables it to absorb the UV spectrum efficiently. These findings are entirely consistent with the findings of researchers Batool et al. [32].

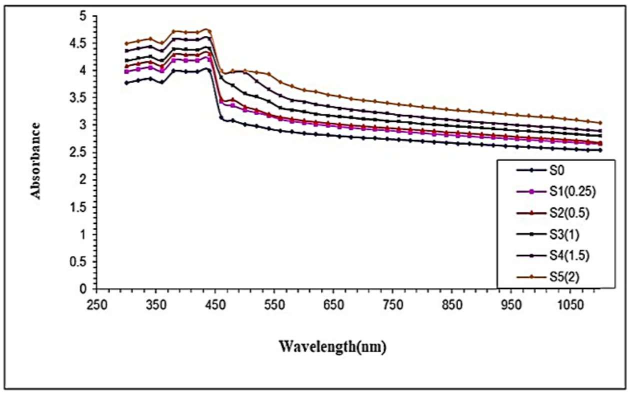

Figure 9. Optical features (absorbance) of neat epoxy and epoxy-ZnO nanocomposites

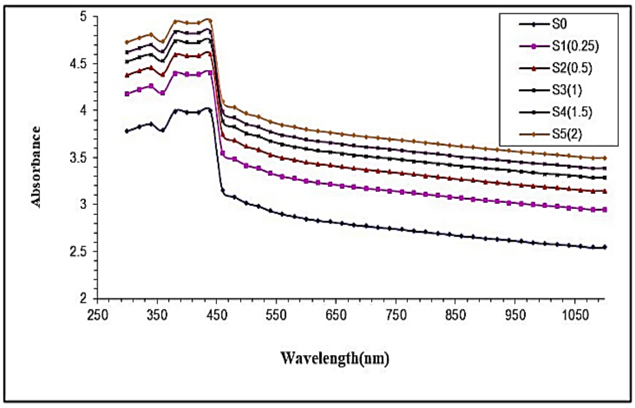

Figure 10. Optical features (absorbance) of neat epoxy and epoxy-TiO_2 nanocomposites

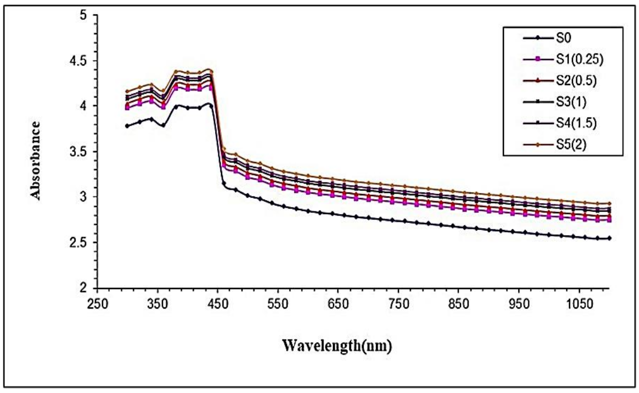

Figure 11. Optical features (absorbance) of neat epoxy and epoxy-MMT nanocomposites

4.3.2 Transmittance

Figure 12 demonstrates the influence of the zinc oxide addition ratios on the transmittance spectrum of epoxy coatings compared to neat EP (S0). The findings demonstrate that the transmittance reductions with increasing ZnO amount; in the UV range from 300 to 400 nm, a reduction is observed from approximately 0.12 for the reference specimen, epoxy without additives (S0), to approximately 0.07 for ZnO (S5) at an amount of 2%. This reduction arises from the high UV-blocking impact of ZnO, since its effective absorption in this spectral region hinders the passage of radiation to the inner layer of the coating and protects the polymer matrix from photodegradation. It is also evident in the longer wavelength region (600-1050 nm) that the transmittance gradually reduces with increasing filler loading, where the transmittance at 1050 nm was 0.21 in S0 and 0.18 in S5, respectively, indicating the overall reduction in transparency with increasing nanoparticle proportion. These findings are in complete agreement with previously reported work by Moussa et al [30].

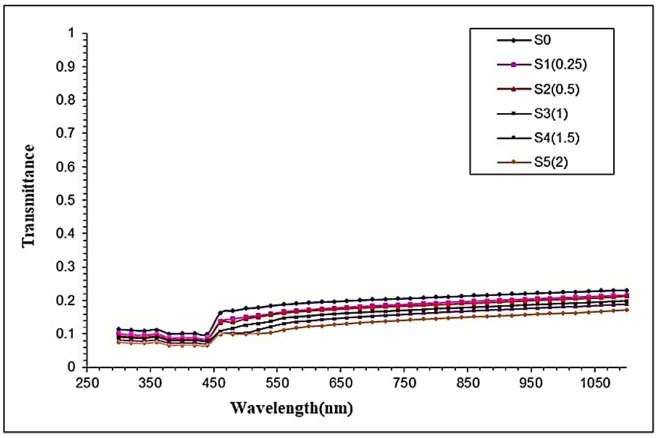

Figure 12. Optical features (transmittance) of neat epoxy and epoxy-ZnO nanocomposites

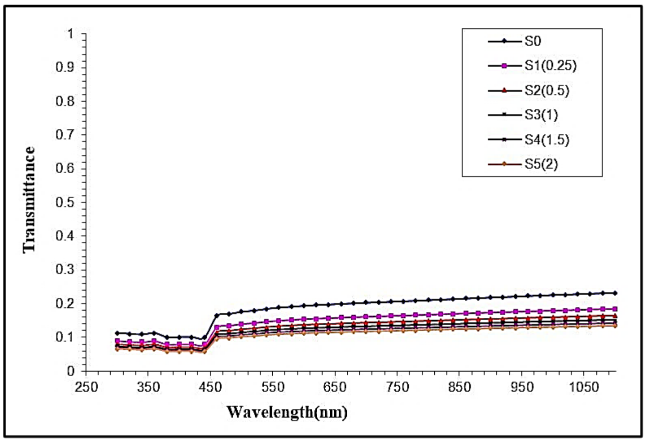

Figure 13. Optical features (transmittance) of neat epoxy and epoxy-TiO_2 nanocomposites

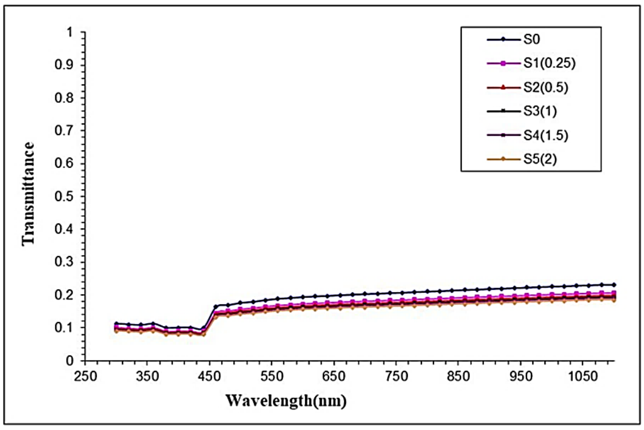

Figure 14. Optical features (transmittance) of neat epoxy and epoxy-MMT nanocomposites

Figure 13 demonstrates the influence of the Titanium Dioxide addition ratios on the transmittance spectrum of epoxy coatings compared to neat EP (S0). The results indicated that transmittance decreased with increasing TiO_2 concentration. The pure epoxy (S0), the reference sample, had the highest transmittance values across the range 250-1100 nm, reaching ≈ approximately 0.12 at 350 nm and gradually increasing to ≈ approximately 0.21 at 1050 nm. However, with the addition of TiO_2 nanoparticles, the transmittance decreased significantly and gradually with increasing weight concentration, decreasing from 0.12 for pure epoxy to 0.08 for 2% at 350 nm, while at 1050 nm, the S5 sample, representing a 2% concentration, reached 0.13. This systematic decrease in transmittance with increasing TiO_2 concentration is consistent with the observed increase in UV and visible light absorption, confirming that the nanoparticles reduce light transmittance to the coating via two main mechanisms: direct UV absorption due to the wide energy gap of TiO_2, and internal light scattering resulting from the distribution of nanoparticles within the epoxy matrix. Therefore, we conclude that TiO_2-reinforced epoxy coatings exhibit effective UV protection, reducing UV transmittance to the inner layers and enhancing the coating's resistance to photodegradation. These findings are in complete agreement with previously reported work by Bouzidi et al. [31].

Figure 14 demonstrates the influence of the montmorillonite addition ratios on the transmittance spectrum of epoxy coatings compared to neat EP (S0). It is found that with increasing filler amount, transmittance reduced sharply, particularly in the ultraviolet (UV) range from 250 - 450 nm. At 350 nm, the transmittance of the reference specimen (S0), representing pure epoxy, is approximately 0.12, while the transmittance of the specimen (S5), enhanced with 2.0 wt.% nano-MMT, is reduced to 0.10. This reduction may be because these nanoparticles can absorb and scatter UV light, making the coating more efficient at blocking harmful radiation. These variations also appear at longer wavelengths, but they are small in the visible spectral range (450–1050 nm). These findings are in good agreement with the absorbance of data and confirm the research objective of enhancing the epoxy coatings' UV resistance. The low light transmittance and high light absorbance reduce harmful light penetration into the substrate, improving its mechanical features (hardness, adhesion). These findings are in complete agreement with previously reported work by Batool et al. [32].

4.3.3 Reflection

Figure 15 demonstrates the influence of the zinc oxide addition ratios on the reflection spectrum of epoxy coatings compared to neat EP (S0). The findings demonstrate that the reflectivity reductions increase with the amount of ZnO and are approximately 6.9 for the reference specimen S0, which represents pure epoxy without additives (0 wt.%), at a wavelength of 1050 nm, and approximately 6.4 at 1050 nm for specimen S5 (2 wt.%). This reduction is because Nano-ZnO adheres to a higher fraction of the incident light, especially in the UV region, which limits the reflected light and enhances the coating's features as an effective optical barrier. All specimens demonstrate a reduction in reflectivity at 450 nm, followed by an increase. This reduction is exacerbated with increasing ZnO amount; The reflectivity of S5 at 2% amount is ~5.2, while it reaches 5.9 at 0% amount (S0). This behavior reflects higher absorption and lower reflectance since light interference with the homogeneously distributed nanoparticles in the epoxy matrix, which causes the radiation to be absorbed rather than reflected. Since lower reflectance and higher absorption will result in a coating with higher UV resistance, the coating will exhibit higher UV resistance.

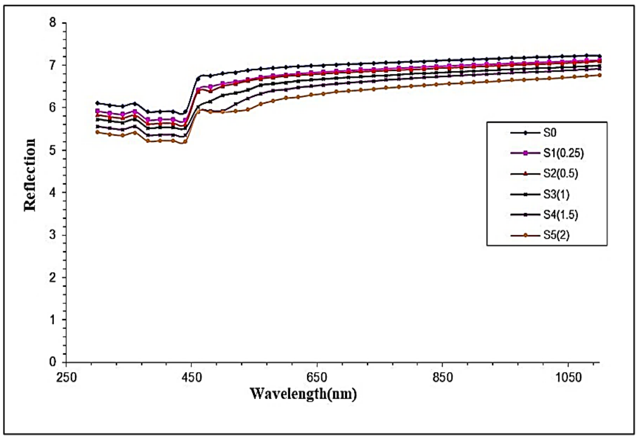

Figure 15. Optical features (reflection) of neat epoxy and epoxy-ZnO nanocomposites

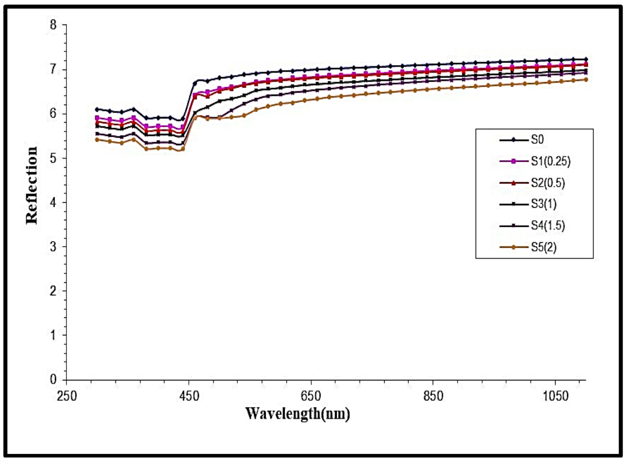

Figure 16. Optical features (reflection) of neat epoxy and epoxy-TiO_2 nanocomposites

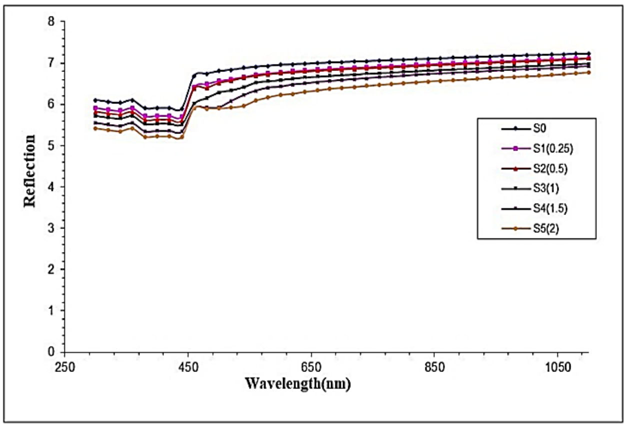

Figure 17. Optical features (reflection) of neat epoxy and epoxy-MMT nanocomposites

Figure 16 demonstrates the influence of the Titanium Dioxide addition ratios on the reflection spectrum of epoxy coatings compared to neat EP (S0). The results showed that reflectivity decreased with increasing TiO_2 concentration compared to pure epoxy. At a wavelength of 300 nm, the reflectivity of pure epoxy (S0) was approximately 5.9, while it decreased to 5.3 at the highest concentration (S5, 2 wt.%). It was also observed that all samples exhibited the lowest reflectivity near the 440–450 nm region, followed by a gradual increase with increasing wavelength, reaching 6.2 for the 2 wt.% sample at 1050 nm. This behavior is attributed to the effective role of TiO_2 nanoparticles in absorbing and scattering a portion of the incident radiation and reducing its surface reflectivity, which leads to enhancing the overall absorbance of the coating, increasing its efficiency in blocking ultraviolet rays, and protecting the epoxy layer from photodegradation.

Figure 17 demonstrates the influence of the montmorillonite nano-clay addition ratios on the reflection spectrum of epoxy coatings compared to neat EP (S0). The findings demonstrate that as the filler amount increases, the reflectivity reductions occur, with the most pronounced reduction happening in the 450–1050 nm range, i.e., the visible and near-infrared range. At 650 nm, the filler-free specimen, representing pure epoxy (S0), produced a reflectance of approximately 7.1, and this reflectance magnitude reduced to approximately 6.1 for specimen S5 containing 2 wt.% MMT. This reduction is due to the light scattering impact of the nanoparticles in the epoxy matrix, while the internal reflection at the surface is reduced to a lesser extent. This behavior enhances the light absorption impacts and helps reduce UV-induced damage to the coatings. Thus, the reduction in reflectivity with increasing nanofiller loading is a good indication of the beneficial role of these particles in enhancing the optical and mechanical stability of the manufactured epoxy coatings.

From the UV results above, we conclude that the addition of TiO_2 to the epoxy coating resulted in the greatest improvement in response in the UV region, with absorbance values increasing significantly with a decrease in transmittance, indicating its high UV blocking effectiveness. ZnO followed, which showed a good improvement with an additional contribution to reflectivity. However, MMT had the least effect in enhancing UV protection. Therefore, TiO_2 represents the most effective additive for enhancing the UV resistance of coatings; its high refractive index contributes to improving light dispersion and protecting the epoxy network from photodegradation.

4.4 Differential Scanning Calorimetry (DSC)

The results of the DSC analysis, as shown in Figures 18-24 and Table 7, indicate that the addition of different nanoparticles gradually enhanced the thermal properties of the epoxy matrix. The glass transition temperature (Tg) of pure epoxy reached 66.68°C. However, upon the addition of 0.25 wt. of ZnO to the epoxy matrix, a significant increase in the glass transition temperature (Tg) to 67.59°C was observed, indicating an effective interaction between the nanoparticles and the polymer chains, and a restriction on their relative mobility. At a concentration of 2%, the glass transition temperature (Tg) increased to 67.99°C. This reflects the role of ZnO in improving the structural cross-linking within the epoxy matrix through surface interactions that reduce chain flexibility and increase the density of the polymer network. When MMT was added at a concentration of 0.25%, there was a significant increase in Tg to 69.37°C compared to pure epoxy (the reference sample), indicating the material's effectiveness in reducing polymer chain mobility through the regular interpenetration of the nano clay layers within the structure. In contrast, the Tg value decreased to 67.72°C when MMT was added at a high concentration of 2%. This is attributed to the aggregation of nanoparticles within the epoxy matrix, which disrupts the structural distribution and reduces the effectiveness of restricting mobility. When the addition of TiO_2 exhibited a different behavior. The Tg value decreased to

65.97°C at a concentration of 0.25% compared to pure epoxy. This was due to weaker interactions between the particles and the polymer chains, allowing for a relative increase in molecular movement. Conversely, at a concentration of 2%, the Tg value increased significantly to 73.18°C compared to pure epoxy. This increase is attributed to improved particle dispersion and enhanced interactions between the titanium dioxide surfaces and the epoxy structure, which contribute to restricting molecular motion, thereby improving the network structure and increasing thermal stability. These changes in Tg values indicate a direct relationship between the type and concentration of the additive and the level of cross-linking within the epoxy matrix. Higher Tg reflects more effective restriction of chain motion, improving stiffness and thermal stability. A decrease in the free volume, which consequently requires high thermal energy to initiate molecular motion. While lower Tg indicates a less compact structure and greater freedom of movement, increased free volume and increased spaces between polymer chains, which weakens the material's resistance to heat and load. These findings are consistent with those of Saeed et al. [33].

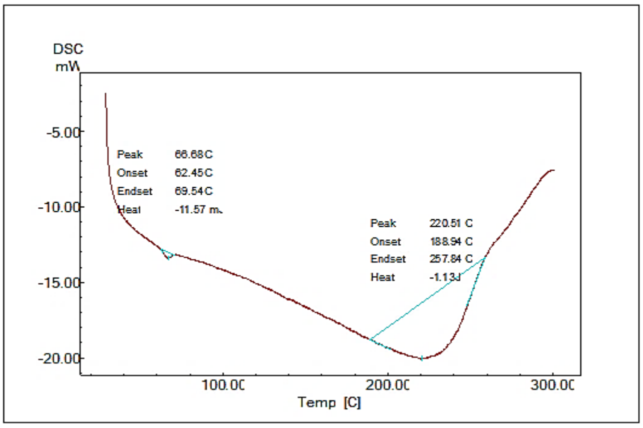

Figure 18. DSc thermograms of neat epoxy

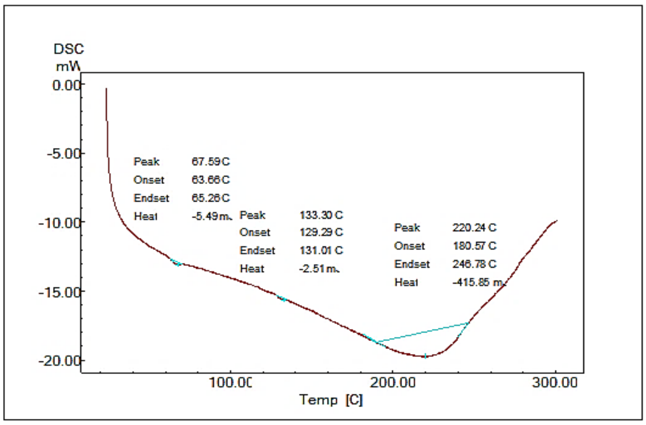

Figure 19. DSc thermograms of epoxy-ZnO with 0.25%

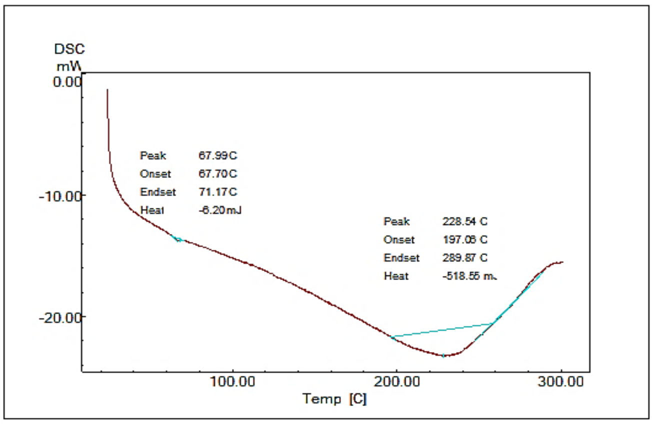

Figure 20. DSc thermograms of epoxy-ZnO with 2%

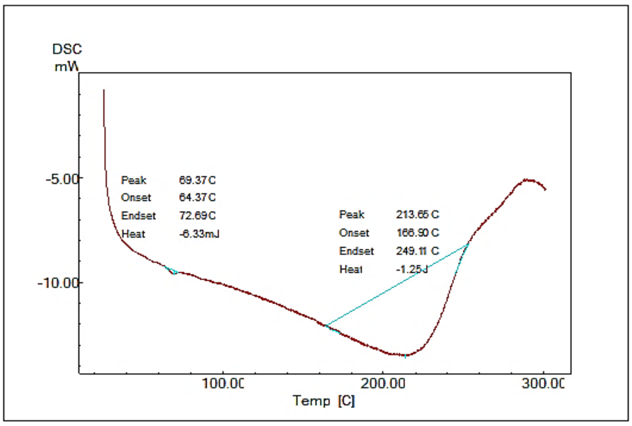

Figure 21. DSc thermograms of epoxy-MMT with 0.25%

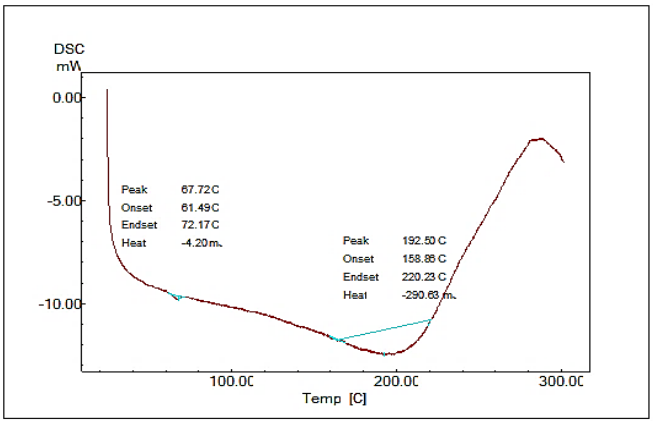

Figure 22. DSc thermograms of epoxy-MMT with 2%

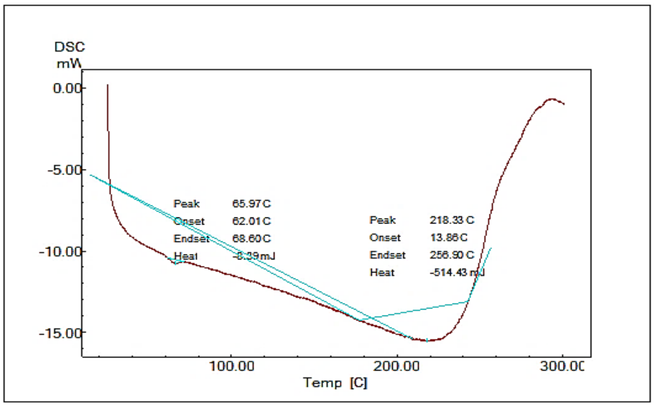

Figure 23. DSc thermograms of epoxy-TiO_2 with 0.25%

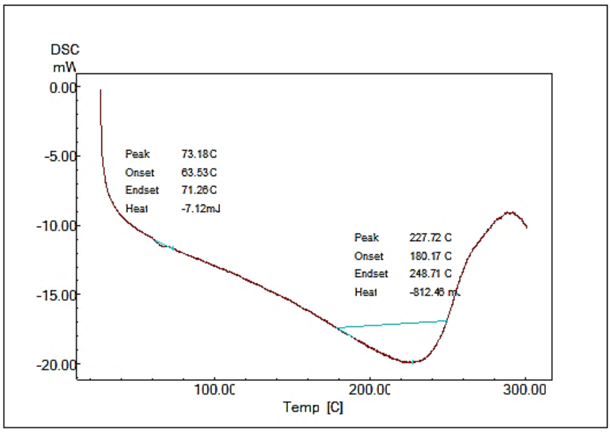

Figure 24. DSc thermograms of epoxy-TiO_2 with 2%

Table 7. Values of glass transition and degree of degradation for epoxy and nanomaterials

Specimen	Tg	Td
Neat Epoxy	66.68	220.51
0.25% ZnO	67.59	220.24
2% ZnO	67.99	228.54
0.25% MMT	69.37	213.65
2% MMT	67.72	192.50
0.25% TiO_2	65.97	218.33
2% TiO_2	73.18	227.72

5. CONCLUSION

This research focused on understanding the response of epoxy coatings to enhancement through various nano-additives, aiming to improve coating performance and increase durability under diverse application conditions. This approach helped elucidate changes in the coating's UV durability, thermal behavior, and surface adhesion. Consequently, it provided a deeper and clearer understanding of the effectiveness of nano-modification in developing epoxy coatings with enhanced properties. The key findings are summarized below:

- The addition of zinc oxide had the greatest effect in terms of improving impact strength, as this is due to zinc oxide's ability to absorb and distribute mechanical energy well, which reduces crack growth and improves the durability of the epoxy.
- The addition of nanoparticles to the epoxy matrix enhances the pull-off adhesion strength compared with pure epoxy, and the addition of MMT is more effective in improving adhesion compared with other fillers.
- Absorbance increases with increasing filler amount of ZnO, MMT, and TiO_2, while transmittance reduces with increasing amount. In addition, TiO_2 represents the most effective additive for enhancing the UV resistance of coatings.
- Adding nanoparticles to the epoxy matrix has a positive role in improving the stability of the epoxy coating when exposed to ultraviolet radiation for a period of time. They act as light dispersants that help reduce the disintegration of the polymer network and maintain the mechanical properties of the epoxy coating.
- DSC results demonstrated that the effect of nanoparticles on the glass transition temperature (Tg) depends not only on their concentration but is also influenced by the type of additive. Some nanomaterials, such as ZnO and MMT, increased their glass transition temperature at certain concentrations due to improved structural bonding, while others, such as TiO_2, decreased their glass transition temperature at lower concentrations due to particle agglomeration and weaker interaction with the epoxy matrix.
- When thermal changes occur, the nanoparticles cause expansion in the thermal coating and improve its stability, leading to an increased service life.

As a future proposal, hybrid nanoparticles could be incorporated into the epoxy matrix to enhance the interaction between the nanoparticles and the epoxy matrix, thereby improving the mechanical and thermal properties of the coating and increasing its resistance to UV degradation in electric motor applications.

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NOMENCLATURE

A	absorbance (Dimensionless)
Aa	adhesion area (mm^2)
acU	impact strength (J/mm^2)
b	thickness of specimen (mm)
f	pull force (KN)
h	width of specimen (mm)
I	intensity of transmitted (W/m^2)
I_0	intensity of incident light at a given wavelength (W/m^2)
R	reflection (Dimensionless)
T	transmittance (Dimensionless)
W_B	energy at break (J)
X	specimen of thickness through which light passes (mm)
L	length of specimen (mm)

Abbreviations

DSc	Differential Scanning Calorimetry
MMT	montmorillonite clay
Tg	glass transition temperature
TiO_2	titanium dioxide
UV	ultraviolet
ZnO	zinc oxide
CdS	Cadmium Sulfide
EP	neat epoxy