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INVESTIGATION OF THE MECHANICAL AND TRIBOLOGICAL BEHAVIOURS OF CUPOLA SLAG AND MWCNT-REINFORCED EPOXY HYBRID NANOCOMPOSITES: A SUSTAINABLE APPROACH FOR ENVIRONMENTAL PRESERVATION

DOLOČITEV TRIBOLOŠKIH IN MEHANSKIH LASTNOSTI HIBRIDNEGA KOMPOZITA SESTAVLJENEGA IZ KUPOLNE ŽLINDRE IN VEČ-STENSKIH OGLJIKOVIH NANOCEVK: PRIJAZNI IN TRAJNOSTNI PRISTOP VAROVANJA OKOLJA

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This experimental investigation explores the mechanical and tribological characteristics of cupola slag (CS) and multiwall carbon nanotubes (MWCNTs) reinforced hybrid nanofiller epoxy composites. Cupola slag is an industrial by-product that is generated during the melting of cast iron. The disposal of slag residues in landfills results in environmental pollution. In the context of environmental preserving as well developing new engineering composites material from waste to resource. MWCNTs possess an excellent strength-to-weight ratio, high stiffness, and thermal properties. The mechanical and tribological characteristics of the hybrid nanocomposites comprising epoxy were examined by varying the weight fraction of fillers composed of CS and MWCNTs. The experimental results indicated that the ECSM3 hybrid nanocomposites have superior tensile strength and the flexural modulus improved by 92 % and 78 % respectively when compared with epoxy. Similarly, the tribology performance of the ECSM3 exhibited improved specific wear resistance of 97 %, 106 % and 88 % on the dry-sliding loads of 10 N, 20 N and 30N, respectively. A morphological analysis was carried out on fractured and worn surfaces of the specimen to understand the homogeneous dispersion and matrix-interlocking mechanism between the hybrid nanofillers and the epoxy matrix. The integration of CS alongside MWCNTs for the fabrication of epoxy hybrid nanocomposites represents a stride towards sustainable and eco-friendly technology in the production of multifunctional composite materials for diverse engineering applications.

Keywords: tribology, wear, cupola slag, mwcnts, epoxy, hybrid, nanocomposites

V članku avtorji opisujejo eksperimentalno raziskavo mehanskih in triboloških lastnosti hibridnega epoksidnega kompozita z ojačitvijo iz delcev kupolne žlindre (CS; angl.: cupola slag) in večstenskih ogljikovih nano cevčic (MWCNTs; angl.: multiwall carbon nanotubes). Kupolna žlindra je stranski produkt, ki nastaja med proizvodnjo sive litine. Odlaganje ostankov kupolne žlindre na raznih odlagalnih poljih predstavlja velik okoljski problem. Zato raziskovalci poizkušajo najti oziroma razviti nove inženirske kompozitne materiale, ki vsebujejo določen delež te vrste odpadkov. Po drugi strani imajo MWCNTs odlično mehansko trdnost in trdoto, odlično razmerje med trdnostjo in specifično masno gostoto, veliko togost in dobre termične lastnosti. Izdelanim hibridnim kompozitom z epoksidno osnovo in različnimi masnimi deleži dodanih MWCNTs in CS so avtorji določili mehanske in tribološke lastnosti. Rezultati mehanskih preiskav ECSM3 (3 % CS in 0,3 % MWCNTs) hibridnih kompozitov so pokazali, da imajo le-ti odlično natezno trnost in upogibni modul v primerjavi z epoksidno smolo. Natezna trdnost ECSM3 se je povečala z dodatkoma za 92 % in upogibni modul se je izboljšal za 78 %. Podobno se je odpornost proti drsni obrabi tega hibridnega kompozita izboljšala za 97 % pri obremenitvi 10 N, za 106 % pri obremenitvi 20N in za 88 % pri obremenitvi 30 N. Izvršena morfološka analiza je na prelomih preizkušancev in na drsno obrabljenih površinah preizkušancev pokazala, da imajo izdelani kompoziti homogeno dispergirane delce MWCNTs in CS v epoksidni matrici. Ti so dobro medsebojno mehansko povezani z izbrano polimerno matrico. Integracija kupolne žlindre in več stenskih ogljikovih nano cevčic v epoksidno smolo predstavlja pomemben napredek v smeri trajne in ekološke tehnologije izdelave večfunkcionalnih kompozitnih materialov za različne inženirske aplikacije.

Ključne besede: tribologija, obraba, kupolna žlindra (CS), večstenske ogljikove nano cevčice (MWCNTs), epoksidna smola, hibridni nanokompoziti

1 INTRODUCTION

Industrial solid waste, comprising various by-products and residues from manufacturing processes, poses a significant environmental challenge when disposed of in landfills. Such waste materials frequently encompass harmful elements like heavy metals, hazardous chemicals, and materials that do not decompose naturally. These substances have the potential to seep into the soil and underground water, leading to the pollution of nearby ecosystems and presenting environmental hazards. To reduce these adverse effects, it is imperative to prioritize sustainable waste-management approaches, including recycling, composting, waste-to-energy conver-

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sion, and the adoption of innovative reuse methods. These initiatives aim to decrease the quantity of waste destined for landfills, while simultaneously fostering resource conservation and preventing pollution. Effective waste-management practices are essential for attaining optimal reuse outcomes. Cupola slag is a by-product of cast-iron production, characterized by its high silica content and diverse chemical composition. It is commonly generated in cupola slag during the melting of metal scrap and iron ore. The primary disposal method for cupola slag is landfilling, wherein the slag is buried in designated areas. However, the practice of landfilling can result in detrimental environmental consequences such as the contamination of soil and groundwater, air pollution, and disruption of habitats. This underscores the urgency of implementing sustainable waste-management solutions. Epoxy resins are widely recognized for their remarkable mechanical strength, resistance to chemicals, and adhesive properties, making them essential in the realm of polymer composite production. These thermosetting polymers, characterized by a complex three-dimensional network, demonstrate exceptional dimensional stability and minimal shrinkage upon curing.[1] Their capacity to adhere to various substrates and undergo customizable formulations renders them indispensable in composite manufacturing processes.[2] Additionally, epoxy resins offer tailored mechanical and thermal characteristics, contributing to the superior performance of polymer composites in diverse applications, ranging from aerospace to automotive.[3] Their versatile nature allows for the production of lightweight, durable, and high-performance composite materials tailored to specific engineering requirements. Multiwall carbon nanotubes (MWCNTs) exhibit outstanding mechanical, electrical, and thermal characteristics, making them indispensable in various polymer-composite applications. Their high aspect ratio, extraordinary tensile strength, and superior conductivity make them ideal candidates for enhancing the mechanical and electrical properties of polymer matrices.[4] Furthermore, MWCNTs exhibit excellent chemical stability and resistance to environmental degradation, ensuring the longevity and durability of composite materials.[5] Their ability to form strong interfacial interactions with polymer matrices enhances the load transfer and dispersion, leading to improved mechanical reinforcement and electrical conductivity in polymer composites.[6] As a result, MWCNTs are pivotal in enhancing the performance and functionality of polymer composites across diverse industrial sectors.[7] The incorporation of carbon nanotubes (CNTs) in fly-ash-based geopolymer composites has been shown to enhance their mechanical properties, thereby improving the strength and durability of these composites for construction applications.[8] The incorporation of fly ash into polyester composites is to enhance their mechanical and thermal properties.[9] Optimizing the filler size and dispersion of fly ash is crucial for improving the mechanical properties of epoxy-based composites. This optimization aims to enhance the structural properties of the composites by investigating the influence of fly-ash particle size on their mechanical behavior.[10] Evaluating the mechanical properties of epoxy composites containing fly-ash particles aims to determine the viability of utilizing fly ash as an economical filler material in epoxy-matrix composites.[11] Thermal conductivity and mechanical properties of fly-ash/epoxy composites through the incorporation of functionalized graphene nanoplatelets (GNPs) to develop high-performance composites for thermal management applications.[12] The enhancement of mechanical properties in blast furnace slag-based polymer composites by incorporating carbon nanotubes (CNTs) to enhance the composites for structural applications.[13] The thermal conductivity enhancement of foundry sand-filled epoxy composites using boron nitride (BN) nanoparticles to enhance the heat-transfer properties of the composites for thermal management applications.[14] The structural and temperature characteristics of polypropylene composites filled with electronic waste to evaluate the feasibility of utilizing E-waste as a filler material in polymer composites for various engineering applications.[15] The study provides insights into sustainable approaches for recycling waste and reducing environmental impact in composite manufacturing.[16] The environmental sustainability of waste-derived polymer composites assesses the lifecycle impacts and environmental benefits of utilizing waste materials in composite manufacturing, highlighting the importance of sustainable materials' development for mitigating environmental concerns.[17] The research outlined on leveraging cupola slag to enhance the mechanical and environmental properties of polymer composites, contributing to sustainable materials development. Incorporating recycled waste and industrial by-products into construction materials is now essential to preserve natural resources and address waste-disposal environmental issues[18].

In this research work, epoxy-matrix composites reinforced by CS-MWCNTs hybrid nanofillers, in which the CNTs are dispersed homogeneously and at the same time strongly attached with the CS nanofillers. CNTs exhibiting high tensile strength, low density, high aspect ratio and rigidity, superior electrical and thermal conductivity are widely used for structural applications. Combining CNTs with cupola slag may ensure the following advantages. First, CNTs effectively attached on the surface of the CS which will lead to easy dispersion during the sonication process and eliminate the agglomeration in the host matrix. Second, both CS and CNT particles have mechanical characteristics and their hybridization may improve the tribological properties. Third, CNTs surface tangle on the CS particle can make surface interlocks and thus enhance the epoxy/hybrid nanofiller interface phenomenon.

2 MATERIALS AND METHODS

2.1 Materials

The epoxy Diglycidyl Ether of Bisphenol A (DGEBA) was used in this study, while the curing agent selected was HTDA (4-methylcyclohexane-1,3-diamine), with a ratio of 10:1. The density of procured epoxy is 1200 kg/m^3. The MWCNTs external diameter of 30–40 nm and a length of 4–5 µm with purity greater than 95 %. Both the materials were purchased from Bottomup Technologies, Bangalore, India. The raw form of cupola slag collected from Bakgiyam Engineering – Iron Casting Foundry, Coimbatore, India. The slag was taken into various desizing and cleaning process for composites preparation process.

2.2 Production of nano dimension cupola slag

High-energy ball milling was used to achieve nano-scale dimensions of cupola slag. Utilizing a high-energy ball milling setup, the slag particles are subjected to mechanical forces generated by the collision of milling balls. The process parameters, including milling balls with the diameter of 10 mm and the canister were made of carbon steel. The ball to powder ratio is 10:1 in weight. After completion of 5 h of milling process, the machine shutdown for 0.5 h to cool the canister. During milling the 200 min^{-1} speed is set to constant for 8h with 5:1 as ball to powder ratio is to be maintained for efficient size reduction. The repetitive impact and grinding action gradually reduce the particle size of the slag. Moreover, the selection of ball material is pivotal to influencing the efficacy of the milling process. Through careful control of the milling conditions, the cupola slag is progressively transformed into nano-sized particles in the range 150 nm ± 20 nm, exhibiting enhanced reactivity and surface area. **Figure 1a** shows the SEM images of milled cupola slag. This methodology enables the production of nanostructured cupola slag, offering promising prospects for its utilization in various advanced materials and engineering applications. The chemical components of the cupola slag are listed in **Table 1**.

Table 1: Cupola slag chemical composition in weight fraction

Chemical composition	*w*/%
Silicon	49.7
Iron oxide	17.9
Alumina	10.9
Calcium oxide	11.1
Manganese oxide	3.41
Magnesium oxide	2.04
Titanium dioxide	1.39
Potassium oxide	0.98

2.3 Synthesis of MWCNTs

The carbon nanotubes (CNTs) utilized in this investigation were produced via thermal decomposition of hydrocarbon gas using chemical vapor deposition (CVD) as shown in **Figure 1b**. Benzene served as the source of carbon, thiophene as a growth catalyst, ferrocene as the catalyst, and hydrogen as the carrier gas. The proportions of these components in the reaction system were adjusted by controlling the flow rate of the carrier gas. By manipulating the reaction duration and the relative amounts of benzene, thiophene, and ferrocene, carbon nanotubes and carbon nanofibers with diverse diameters and structures were synthesized.

2.4 Preparation of CS-CNTs epoxy nanocomposites

The dispersion of CS-MWCNTs in the epoxy resin Diglycidyl Ether of Bisphenol A was achieved by means of a sonicator machine operating at a frequency of 30 kHz for a duration of 20 min. To lower the viscosity of the epoxy and to enable better wetting of the particle during the sonication process the temperature was maintained between 70 °C and 80 °C. The MWCNTs in their initial state taken into purification and functionalization through heat treatment, resulting in the introduction of carboxylic acid groups. This process involved immersing 1 g of MWCNTs in a solution consisting of 500 mL of H_2SO_4 and HNO_3 in a volume ratio of 3:2, followed by

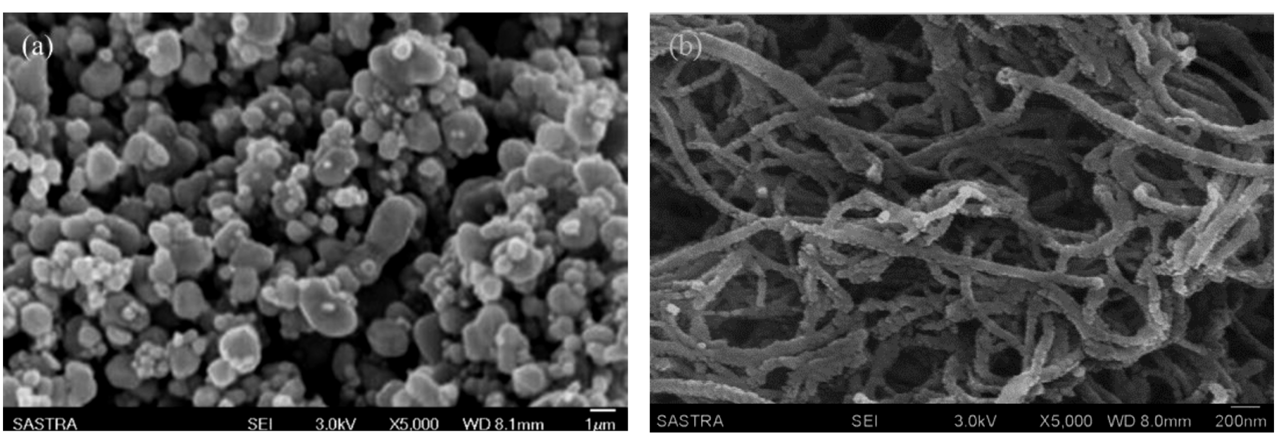


Figure 1: FESEM images of a) cupola slag and b) MWCNTs used in this experiment

ultrasonic treatment for 12 h at ambient temperature to prepare a suspension. Subsequently, the prepared solution is heated at 80 °C and stirred for 18 h before undergoing filtration through a nylon membrane. The MWCNTs, after filtration, experienced extensive washing with water, repeating the process to attain a neutral pH. The treatment with HNO_3 resulted in functionalization of the MWCNTs surface without significantly affecting their length. The MWCNTs were dried in a vacuum chamber at ambient conditions for 24 h. The second filler material, cupola slag (CS) is in a size range a little bigger than the MWCNTs. The particles are irregular ball shaped and the specific area was also considerably large. The cupola slag consisted of silicon oxide layers that hold strongly together. The cupola-slag surface was treated with carboxylic acid groups. An ultrasonicator was used to disperse the CS in the $SOCl_2$ and the stirring process continued for 5 h under ambient conditions. Furthermore, the suspension was filter dried for 18 hours at ambient temperature.

For the fabrication of the CS-MWCNTs epoxy nanocomposites, the procedure commenced with the addition of designated weight fractions of MWCNTs and cupola slag (CS) (**Table 2**) fillers into an ethanol solvent, followed by continuous stirring for 15 min. Subsequently, polyvinylpyrrolidone (PVP) dispersant was introduced and stirred for an additional 10 min. Next, preheated epoxy was incorporated into the solution and sonicated for 2 h to achieve a homogeneous distribution of the fillers within the matrix. To eliminate the solvents, the suspension was kept at 100 °C in an oil container for 3 h. Upon cooling to room temperature, the corresponding curing agent was added, and sonication continued for another 5 min. For tribological and mechanical characterization, the solution was poured into designed acrylic moulds to manufacture the test specimens as per the standards. Subsequently, all test specimens are cured at room temperature for 12 h, followed by maintenance at 50°C for 18 h for post-curing. The designated weight fraction of cupola slag and MWCNTs with various weight fractions is presented in **Table 2** and the composites sample were analysed by X-ray diffractometer (XRD).

Table 2: Description and label of MWCNTs and cupola slag weight fraction

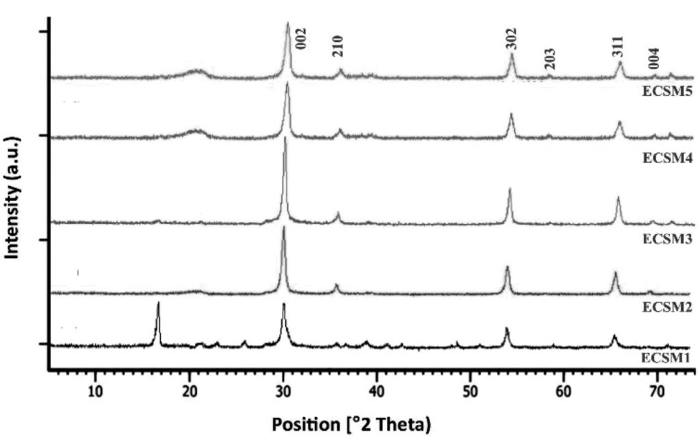
Sample Description	Label
Epoxy + Cupola slag 1.0 *w*/% + MWNCTs 0.1 *w*/%	ECSM1
Epoxy + Cupola slag 2.0 *w*/% + MWNCTs 0.2 *w*/%	ECSM2
Epoxy + Cupola slag 3.0 *w*/% + MWNCTs 0.3 *w*/%	ECSM3
Epoxy + Cupola slag 4.0 *w*/% + MWNCTs 0.4 *w*/%	ECSM4
Epoxy + Cupola slag 5.0 *w*/% + MWNCTs 0.5 *w*/%	ECSM5

2.5 Characterization techniques

Microstructure characterizations of the CS-MWCNTs nano fillers and composites fracture surface and worn surface were examine by field-emission scanning electron microscope (FESEM) and X-ray diffractometer (XRD) (**Figure 2a** and **2b**). The aim was to understand the influence of nanofillers on the reinforcing mechanism and wear mechanism.

2.6 Mechanical characterization

Tensile examinations of epoxy resin and CS-MWCNTs filler-reinforced hybrid epoxy composites were performed utilizing a universal tensile test apparatus (Instron, USA) in accordance with ASTM D-638 standards. Specimens were shaped into dumbbell configurations for assessment purposes. The varying lengths of the specimens were measured by an extensometer at a crosshead movement speed of 1 mm/min. To ensure statistical robustness, five specimens were utilized to derive the mean value and recorded. In accordance with ASTM D7264 guidelines, flexural characteristics were performed on epoxy and CS-MWCNTs filler-reinforced hybrid epoxy composites. The samples were shaped into rectangular dimensions measuring (60 × 13 × 4) mm^3. The crosshead movement of the jaw set to 1 mm/min to measure the displacement rate. The test specimen both the ends knurled for excellent gripping actions. Each test was repeated five times to ensure statistical accuracy, al-



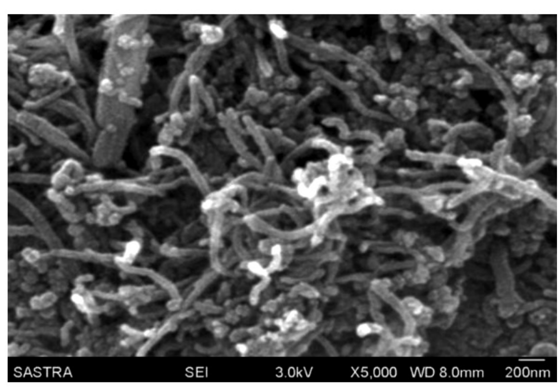


Figure 2: XRD pattern and SEM images of CS-MWCNTs hybrid nanocomposites

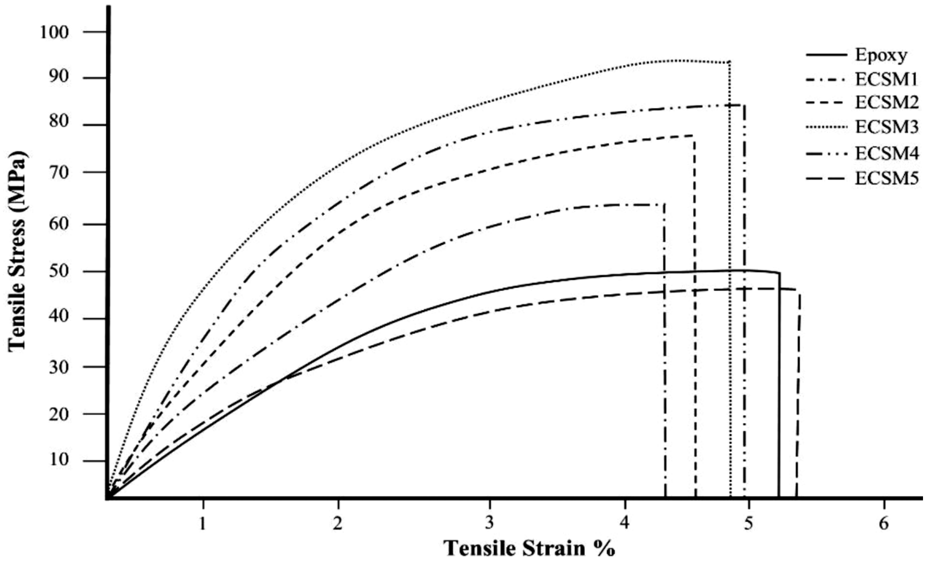


Figure 3: Stress–strain curve for epoxy and the epoxy-hybrid nanocomposites with various weight fractions

lowing for the calculation of the mean value and standard deviation.

2.7 Tribology characterization

Dry-sliding wear tests were carried out on a pin-on-disc machine to determine the tribological characteristics of the epoxy and epoxy-hybrid nanocomposites. A rotating counterpart was made up of a commercially available steel disc (EN8) with a surface roughness of Ra = 0.6 µm, hardness 60 HRc and diameter of 100 mm. The test specimen held against the high-speed rotating counterpart with the radius of 25 mm, rotating speed of 250 min^{-1} and running in period and distance of 1000 m and 0.5 h, respectively. During this test, the sample was under 10 N (low), 20 N (moderate), and 30 N (high) loads against the steel disc counterpart. During the wear process the material remove from the sample which leads to mass reduction occurred on the sample specimen. The mass reduction was estimated by measuring the material removed from the test specimen before and after the wear test. The specific wear rate, which demonstrate the wear characteristics under the predetermined condition for the tribosystem from the calculated value.

$$w_s = \frac{\Delta m}{\rho \cdot Fn \cdot L} \quad (\text{mm}^3/\text{Nm}) \qquad (1)$$

where w_s = specific wear rate, Δm = change in the mass of the wear test specimen (g), ρ = density of the composites (g/cm^3), Fn = Load acting on the specimen and L = distance of sliding (m).

3 RESULT AND DISCUSSION

3.1 Mechanical characteristics

3.1.1 Tensile characteristics

Epoxy and CS-MWCNTs with various weight fraction of filler loading hybrid nanocomposites tensile stress-strain typical curve is presented in **Figure 3**. Interestingly, nanofiller reinforced epoxy hybrid composites exhibit an improvement of the tensile characteristics compared to the epoxy. It can be shown that the epoxy hybrid nanocomposites exhibit higher tensile strength and higher flexural modulus compared to the epoxy. The ECSM3 composites exhibit the highest tensile strength, achieving an increase of approximately 94.3 MPa, corresponding to a 92 % enhancement compared to the pure epoxy. Similarly, ECSM4 also exhibits an increase in tensile strength as compared to epoxy matrix but lower than ECSM3 about 70 % and 31 %, respectively. The matrix material strength, fillers particle shape and size, interfacial adhesion and homogeneous dispersion in the matrix are significant parameters in the tensile strength of polymer composites materials. In our formulation, the

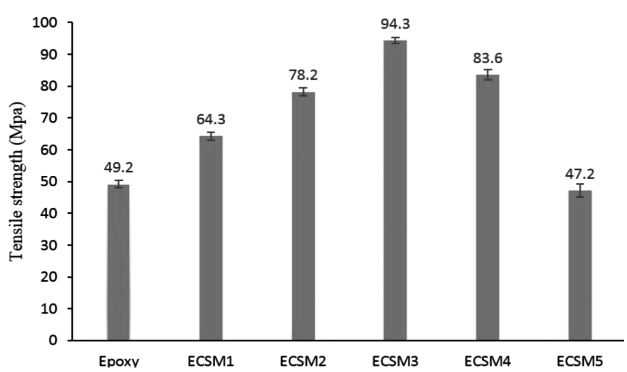


Figure 4: Tensile strength of epoxy and the epoxy-hybrid nanocomposites with various weight fractions

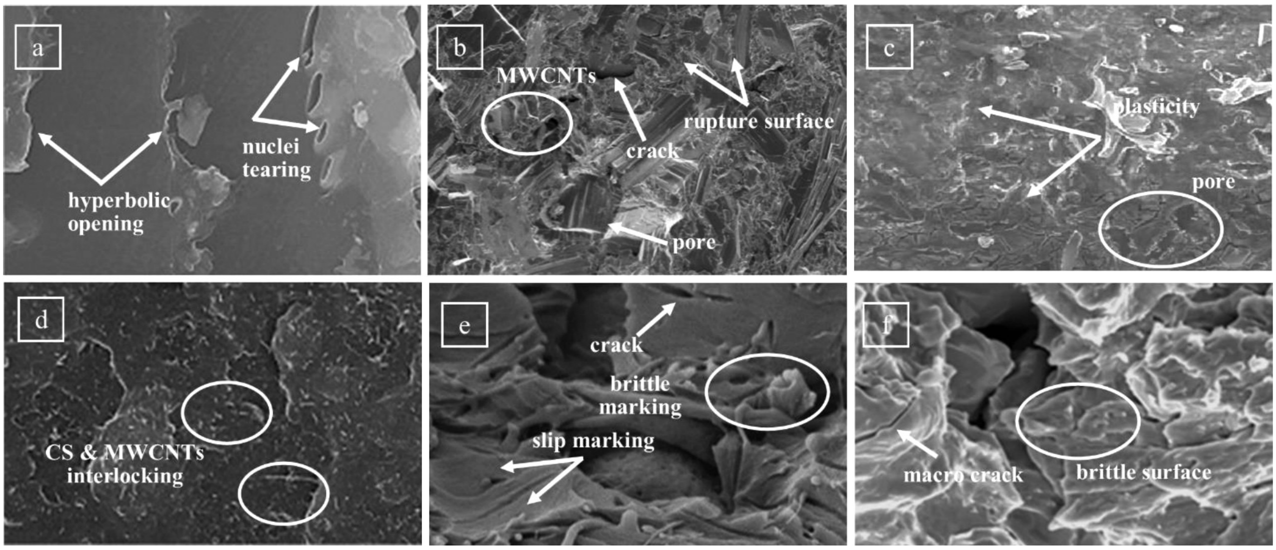


Figure 5: SEM morphology analysis of epoxy and CS-MWCNTs hybrid nanocomposites fractured surface

CS-MWCNTs reinforced epoxy demonstrates an enhancement in tensile strength when contrasted with pure epoxy. The cupola slag serves as a conduit for the dispersion of CNTs into the matrix, while concurrently facilitating the formation of CNT networks instead of agglomeration. These networks effectively absorb the applied tensile loads from the matrix during loading.

However, a further increase of filler content of the pure epoxy on 0.4 *w*/% and 0.5 *w*/% of MWCNTs and 4 *w*/% and 5 *w*/% of cupola slag decreasing trend of tensile strength as shown in **Figure 4**. This occurrence is anticipated and primarily attributed to the agglomeration of CNTs, particularly at higher filler loadings, exacerbated by the substantial surface area of the CNTs. The weak van der Waals' forces between the CNTs lead to their interconnection, resulting in agglomeration. Therefore, the strength and modulus of the composites can serve as indicators for pre-evaluating the extent of filler dispersion within the composite materials.

The impacts and significance of a substantial enhancement in tensile strength, the fractured surface of the nanofillers reinforced epoxy composites were analysed using FESEM, as shown in **Figure 5**. The morphology analysis found that the epoxy fractured surface exhibits hyperbolic opening and nuclei tearing. This will indicate the material fracture occurred with a brittle nature. Further, ECSM1 and ECSM2 fracture surface exhibits micro cracks, pore, rupture and plasticity surface on the fracture surface, which indicates the material tends from brittle to ductile in nature. Similarly, the ECSM3 hybrid composites fracture morphology shown larger smoother surface, CS-MWCNTs interlocking reveals material tends to elongate during the fracture, which means materials tends to be ductile in nature. Furthermore, ECSM4 and ECSM5 fractured surface demonstrated macro crack, slip and brittle marking and fillers pull out exhibits reform of the material ductile to brittle in nature, as well the nonuniform distribution of fillers tends to local failure within the matrix, which leads the composites to fail and transfer the load by the filler.

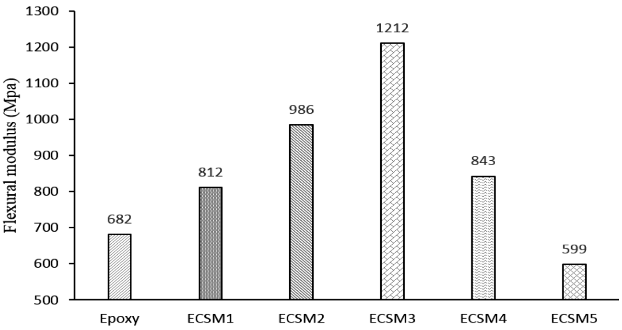


Figure 6: Flexural modulus of epoxy and the epoxy-hybrid nanocomposites with various weight fractions

3.1.2 Flexural modulus

The significant improvement achieved in stress-strain behaviour of the nanofiller-loaded epoxy-hybrid nanocomposites due to the filler natural characteristics as well the optimum level of incorporation in the host matrix. Well-known materials science revealed that when the filler content exceeds the optimum level this leads to lower performance of the matrix properties. Surprisingly, the flexural modulus results are in incremental value with respect to increasing the filler loading, which means that the flexural modulus value increase linearly until the filler content reaches the optimum level, as shown in **Figure 6**. Certain critical attributes of the composites must be considered to describe this phenomenon. The interface between filler and matrix is inadequate, the particles fail to bear any portion of the external load. Consequently, the strength of the composite cannot surpass that of the pure polymer matrix. In contrast, when the bonding between fillers and matrix is sufficiently robust, the yield strength of a particulate composite can exceed that

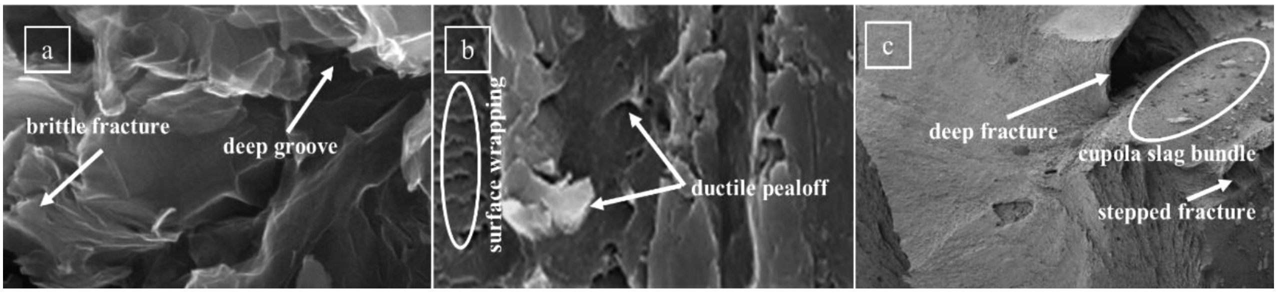


Figure 7: SEM morphology analysis of epoxy, ECSM3 and ECSM5 hybrid nanocomposites flexural fractured surface

of the matrix polymer. The morphology analysis explores the conclusions regarding the dissipation of energy during fracture, understanding the path of traveling cracks through the material and the influence of particles on crack propagation is crucial, as shown in **Figure 7**. Cracks interact with particles as obstacles, potentially altering the crack front by deviation or branching, or even pinning it, thereby necessitating increased energy absorption in the composite. Additionally, significant energy may be expended at the interface between particles and matrix, particularly under conditions of strong bonding. The interface explores a significance in the deformation behavior of the composite materials.

3.2 Tribological characteristics

The tribological systems of epoxy and nanofiller-reinforced epoxy-hybrid nanocomposites were described with wear and friction characteristics. The sample material, rotating counterpart and ambient conations are the important functional parts of the tribology system. To attain the constant level of the frictional force and coefficient, the specimen has taken into initial running time period to attain the steady-state level. The temperature between the test sample and counterparts is not to exceed 45 °C during the entire process of the wear-test experiments. This present study was to explore the influence of cupola slag and MWCNTs nano particle in the epoxy matrix. In the previous literature it is found that small particles exhibit good wear resistance, and it can shield the polymer surface and restrict the filler pull outs. The pin-on-disc machine was used for conducting the wear experiments. The experiment results plotted in Figure 8. The specific wear resistance is plotted as a function of various filler compositions. A high resistance to wear phenomena on the material means a decrease in wear rate. The improvement in the specific wear resistance of the CS-MWCNTs nano-filler-loaded epoxy nano composites observed on ECSM1 and ECSM2 composition compared with epoxy. Furthermore, ECSM3 composition demonstrated remarkable specific wear resistance and recorded 97 %, 106 %, 88 % higher than the epoxy matrix on the dry-sliding load of 10 N, 20 N and 30 N, respectively. Similarly, increasing the filler content, the specific wear resistance considerably decreased for the ECSM4 and ECSM 5 composites. Interestingly, it is observed that the ECSM 4 wear resistance was higher than the epoxy, but lower than the ECSM 3 composites. The phenomena reveals that the matrix reached the saturation level of the optimized level of weight fraction. Furthermore, increasing the filler content, i.e., ECSM 5 deterioration of wear behaviour and the wear resistance lower than the epoxy matrix.

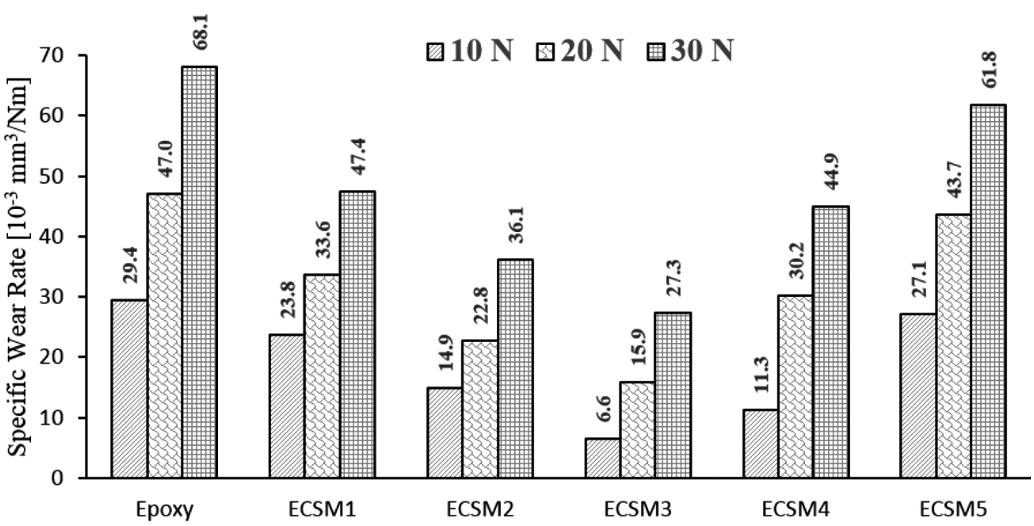


Figure 8: specific wear rate of epoxy and the epoxy hybrid nanocomposites with various weight fraction

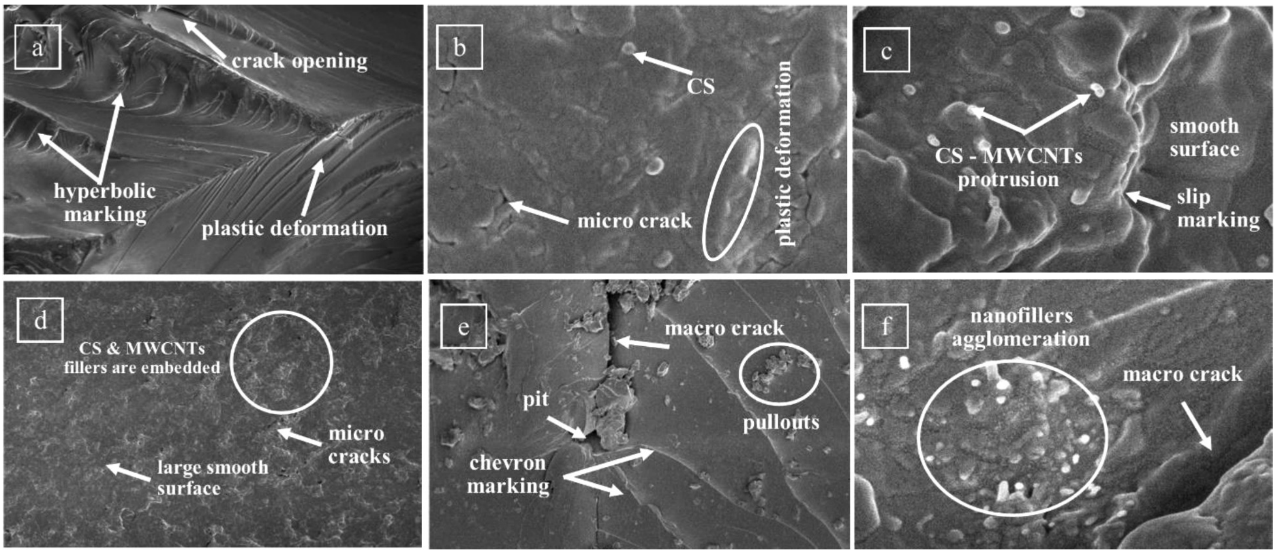


Figure 9: SEM morphology analysis of epoxy and CS-MWCNTs hybrid nanocomposites worn surface

The morphological analysis was carried out on the worn surface of the epoxy and CS-MWCNTs nanofiller-loaded hybrid nanocomposites to understand the material removal phenomena. The worn surface and its wear pattens are presented in **Figure 9**. The epoxy worn surface exhibits crack opening, hyperbolic marking and step fracture occurred on the surface. Furthermore, ECSM1 and ECSM2 shown microcrack, scars, limited smooth surface reveal that the wear mechanism transform from brittle to ductile in nature. Similarly, ECSM3 worn surface showed a smooth and even surface. In addition, ECSM4 and ECSM5 worn surfaces exhibit chevron marking, pit, macro crack, surface irregularity, delamination, filler putouts and larger pit presented on higher and excessive additions of nano fillers in the matrix, which leads lower the performance of composites. Interesting observation reveals that, under lower load (10 N) and moderate loading (20 N) and higher loading (30 N) conditions, the wear rate also gradually increased in all the compositions, which clearly indicates that the wear rate increased with an increase of the applied load due to an increase in contact pressure, which leads to an increase in temperature. Furthermore, an increase in temperature is softening the contact surface, which leads to filler pull outs. As noted earlier, the optimum weight fraction added into the matrix leas to robust improvement in the wear resistance.

4 CONCLUSIONS

The aim of developing a multifunctional hybrid nanocomposites material from industrial waste to resource has been achieved in this investigation. The epoxy-hybrid nanocomposites have been fabricated with the reinforcement of cupola slag and MWCNTs for the investigation of tribological and mechanical characteristics. Foundry industries dispose of the cupola slag through landfill, which leads to environmental pollution. Thus, developing these kinds of nanocomposites materials for multifunctional engineering applications helps to preserve the environment.

The research aims to explore the mechanical and tribological properties of epoxy composites reinforced with cupola slag (CS) and multiwall carbon nanotubes (MWCNTs), addressing environmental concerns associated with CS disposal.

Cupola slag, an industrial byproduct from cast-iron melting, is highlighted as a material of interest due to its abundance and environmental impact caused by landfill disposal.

The study underscores the dual purpose of environmental preservation and resource utilization by transforming waste materials, such as CS, into valuable engineering composites.

MWCNTs, renowned for their exceptional strength-to-weight ratio, high stiffness, and thermal properties, are utilized to enhance the mechanical performance of the composites.

Investigation of varying weight fractions of CS-MWCNTs fillers allows for the assessment of mechanical and tribological characteristics in the epoxy-hybrid nanocomposites.

Experimental findings reveal significant enhancements in the properties of ECSM3 hybrid nanocomposites, with a remarkable 92 % increase in tensile strength and a 78 % improvement in flexural modulus compared to pure epoxy.

Tribological assessments demonstrate notable improvements in specific wear resistance, with ECSM3 exhibiting enhancements of 97 %, 106 % and 88 % under dry-sliding loads of 10 N, 20 N, and 30 N, respectively.

Morphological analysis provides insights into the dispersion and interlocking mechanisms between hybrid nanofillers and the epoxy matrix, elucidating the structural integrity of the composites.

The integration of CS and MWCNTs represents a stride towards sustainable and eco-friendly composite material fabrication, offering multifunctional solutions for diverse engineering applications.

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