INVESTIGATION OF THE DURABILITY AND DEGRADATION BEHAVIOR OF 3D-PRINTED POLYMER COMPONENTS FOR MARINE APPLICATIONS

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ABSTRACT

The increasing adoption of additive manufacturing has created new opportunities for producing lightweight, customized, and cost-effective components for marine applications. Among the various additive manufacturing techniques, three-dimensional (3D) printing has gained considerable attention because of its ability to fabricate complex polymer parts with minimal material waste and reduced production time. However, polymer components used in marine environments are continuously exposed to harsh conditions such as seawater, ultraviolet (UV) radiation, temperature fluctuations, humidity, and mechanical loading, which can gradually degrade their physical and mechanical properties. This project investigates the degradation behaviour of 3D printed polymer parts intended for marine applications by evaluating the effects of prolonged environmental exposure on material performance. Standard polymer specimens are fabricated using a suitable fused deposition modelling (FDM) process and subjected to controlled degradation conditions that simulate the marine environment. The investigation includes the assessment of weight variation, moisture absorption, surface morphology, tensile strength, flexural strength, hardness, and dimensional stability before and after exposure. Experimental observations are compared to determine the rate of material degradation and identify the dominant factors influencing structural integrity. The study also examines the relationship between printing parameters and the long-term durability of polymer components under marine conditions. The obtained results provide valuable information for selecting suitable polymer materials and optimizing manufacturing parameters to improve service life and reliability. The proposed investigation demonstrates that systematic evaluation of environmental degradation is essential for developing durable 3D printed components capable of withstanding aggressive marine conditions. The findings contribute to the advancement of additive manufacturing technologies for marine engineering by supporting the design of lightweight, corrosion-resistant, and sustainable polymer structures with improved long-term performance and reduced maintenance requirements.

Keywords: Additive Manufacturing, 3D Printing, Polymer Materials, Marine Applications, Environmental Degradation, Fused Deposition Modelling (FDM), Mechanical Properties, Moisture Absorption, Durability Assessment, Material Performance.

I. INTRODUCTION

The rapid advancement of additive manufacturing has transformed the way engineering components are designed and fabricated across various industrial sectors. Among the available additive manufacturing techniques, three-dimensional (3D) printing has become one of the most widely adopted technologies because of its ability to produce complex geometries, lightweight structures, and customized components with reduced material waste and shorter production time. Polymer-based 3D printing methods, particularly Fused Deposition Modelling (FDM), have gained significant attention due to their simplicity, affordability, and compatibility with a wide range of thermoplastic materials. These advantages have encouraged the use of 3D printed polymer components in aerospace, automotive, biomedical, construction, and marine industries. In marine engineering, lightweight polymer components are increasingly replacing conventional metallic parts because they offer improved corrosion resistance, ease of manufacturing, and lower maintenance requirements. However, marine environments expose these materials to aggressive conditions such as seawater, ultraviolet radiation, fluctuating temperatures, humidity, and continuous mechanical loading. These environmental factors gradually degrade the material properties and reduce the service life of polymer components. Therefore, understanding the degradation behaviour of 3D printed polymers is essential for ensuring their long-term reliability and structural performance in marine applications [1–8].

The degradation of polymer materials in marine environments is a complex process influenced by physical, chemical, and environmental factors. Continuous exposure to seawater leads to moisture absorption, plasticization, dimensional changes, and reduction in mechanical strength. Simultaneously, ultraviolet radiation initiates photo-oxidation, causing molecular chain scission, discoloration, surface cracking, and embrittlement of polymer structures. Temperature fluctuations accelerate aging processes by increasing thermal stresses within printed layers, while repeated mechanical loading contributes to fatigue damage and crack propagation. In addition, the layer-by-layer manufacturing process inherent to additive manufacturing introduces anisotropic mechanical behaviour that may further influence degradation characteristics under marine conditions. Researchers have therefore emphasized the importance of evaluating tensile strength, flexural strength, impact resistance, hardness, weight variation, and surface morphology before and after environmental exposure. Such investigations provide valuable insights into the durability and structural integrity of 3D printed polymer parts. Understanding these degradation mechanisms enables engineers to select appropriate materials, optimize printing parameters, and improve component design for demanding marine environments [9–17].

Recent developments in materials engineering have focused on improving the durability of 3D printed polymer components through advanced material formulations, optimized printing strategies, and protective surface treatments. Modern engineering polymers, reinforced composites, and fibre-filled thermoplastics have demonstrated improved resistance to moisture absorption, ultraviolet degradation, and mechanical wear compared with conventional materials. In addition, computational modelling and experimental characterization techniques have enabled researchers to predict long-term degradation behaviour under simulated marine conditions. This project investigates the degradation behaviour of 3D printed polymer parts intended for marine applications by examining the influence of seawater exposure and environmental aging on their physical and mechanical properties. Standard test specimens are fabricated using Fused Deposition Modelling (FDM) technology and evaluated through tensile testing, flexural testing, hardness measurement, moisture absorption analysis, and surface examination before and after controlled environmental exposure. The outcomes of this investigation are expected to assist in material selection, design optimization, and service-life prediction for marine engineering applications. The study contributes to the development of reliable, lightweight, corrosion-resistant, and sustainable polymer components capable of performing efficiently in harsh marine environments [18–25].

II. SURVEY OF RESEARCH

1. Additive Manufacturing of Polymer Components for Marine Applications

Recent research has highlighted the growing importance of additive manufacturing in the marine industry due to its ability to produce lightweight, customized, and cost-effective polymer components. Three-dimensional (3D) printing technologies, particularly Fused Deposition Modelling (FDM), have enabled the fabrication of complex geometries with reduced material wastage and shorter manufacturing time. Researchers have investigated the suitability of thermoplastic materials such as PLA, ABS, PETG, and Nylon for marine applications because of their corrosion resistance and ease of fabrication. Experimental studies indicate that the mechanical performance of these materials depends significantly on printing parameters, layer orientation, and environmental exposure. The integration of additive manufacturing into marine engineering has reduced manufacturing costs while improving design flexibility and production efficiency. These investigations conclude that optimized 3D printing processes can produce durable polymer components suitable for marine environments [1].

2. Environmental Degradation of 3D Printed Polymer Materials

Several investigations have examined the degradation behaviour of polymer materials exposed to harsh marine environments. Continuous exposure to seawater, ultraviolet radiation, moisture, and temperature fluctuations causes gradual deterioration of mechanical and physical properties. Researchers observed reductions in tensile strength, flexural strength, impact resistance, and hardness due to moisture absorption and photo-oxidation. Surface defects such as discoloration, micro-cracks, and layer separation were also reported after prolonged environmental exposure. The degradation rate varied depending on the polymer type, printing orientation, and exposure duration. Experimental findings demonstrated that understanding degradation mechanisms is essential for improving the long-term reliability of polymer components used in marine structures. These studies emphasize the need for systematic durability assessment before implementing 3D printed polymers in practical marine applications [2].

3. Mechanical Performance of FDM-Printed Polymer Components

Recent research has focused on evaluating the mechanical properties of Fused Deposition Modelling (FDM) printed polymer components under different manufacturing conditions. Investigators studied the influence of layer thickness, infill density, raster angle, nozzle temperature, and printing speed on tensile strength, flexural behaviour, and impact resistance. The results indicated that optimized printing parameters significantly improve interlayer bonding, structural integrity, and mechanical performance. Researchers also reported that anisotropic behaviour introduced during layer-by-layer manufacturing strongly affects load-carrying capacity and failure mechanisms. Experimental comparisons between conventionally manufactured and FDM-printed specimens confirmed that proper parameter optimization enhances strength and durability. These findings demonstrate that printing conditions play a critical role in determining the service life of polymer components intended for demanding engineering environments [3].

4. Moisture Absorption and Durability of Marine Polymers

Numerous studies have investigated the effect of seawater absorption on polymer materials used in marine engineering. Moisture penetration into polymer structures results in dimensional changes, weight variation, plasticization, and gradual reduction in mechanical strength. Researchers measured moisture absorption behaviour under controlled laboratory conditions to evaluate long-term durability. Surface morphology analysis revealed the formation of micro-voids, surface roughness, and interlayer weakening after prolonged immersion. The degradation process was found to be influenced by polymer composition, porosity, printing orientation, and environmental conditions. Several investigations recommended protective coatings and optimized printing parameters to reduce moisture diffusion and improve resistance to environmental aging. These studies confirm that moisture absorption is one of the primary factors affecting the long-term performance of 3D printed polymer components in marine environments [4].

5. Advanced Materials for Marine Additive Manufacturing

Recent developments in materials science have introduced reinforced polymers and composite filaments specifically designed for harsh environmental conditions. Researchers have evaluated carbon-fibre-reinforced polymers, glass-fibre composites, PETG composites, and engineering thermoplastics for marine applications. These advanced materials demonstrated improved mechanical strength, thermal stability, wear resistance, and resistance to moisture absorption compared with conventional polymers. Surface coatings and nanocomposite reinforcements further enhanced resistance to ultraviolet radiation and chemical degradation. Experimental investigations showed that advanced polymer composites significantly increase component lifespan while maintaining lightweight characteristics. These studies indicate that material innovation plays an essential role in expanding the application of additive manufacturing in marine engineering [5].

6. Durability Assessment of 3D Printed Marine Components

Current research emphasizes the importance of long-term durability assessment for 3D printed polymer components intended for marine applications. Accelerated aging tests, seawater immersion experiments, ultraviolet exposure, thermal cycling, and mechanical testing are widely used to evaluate degradation behaviour. Researchers compare mechanical properties before and after environmental exposure to determine service-life reduction and failure mechanisms. Microscopic examination techniques such as Scanning Electron Microscopy (SEM) and optical microscopy have been employed to analyze surface deterioration and crack propagation. The integration of experimental testing with numerical modelling has improved the prediction of long-term material performance under realistic marine conditions. These investigations conclude that systematic durability evaluation is essential for designing reliable, corrosion-resistant, and sustainable polymer components suitable for modern marine engineering applications [6].

III. PROPOSED SYSTEM

The proposed system focuses on the investigation of the degradation behaviour of 3D printed polymer parts for marine applications by combining additive manufacturing, controlled environmental exposure, and mechanical property evaluation. The primary objective is to determine how prolonged exposure to marine conditions affects the physical, mechanical, and structural performance of polymer components manufactured using three-dimensional (3D) printing technology. The proposed methodology enables the identification of degradation mechanisms and assists in selecting suitable polymer materials for long-term marine applications. The system begins with the selection of appropriate thermoplastic materials such as Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate Glycol (PETG), or Nylon based on their mechanical properties, printability, and resistance to environmental degradation.

Initially, standard test specimens are designed using Computer-Aided Design (CAD) software according to ASTM testing standards for tensile, flexural, and hardness evaluation. The developed models are exported in STL format and fabricated using a Fused Deposition Modelling (FDM) 3D printer. Printing parameters including layer thickness, nozzle temperature, bed temperature, infill percentage, printing speed, raster angle, and build orientation are optimized to ensure consistent specimen quality. After fabrication, the printed samples are inspected visually to verify dimensional accuracy and eliminate defective specimens before testing. Initial mechanical properties such as tensile strength, flexural strength, hardness, weight, and dimensions are measured and recorded to establish baseline material characteristics before environmental exposure.

The fabricated polymer specimens are then exposed to simulated marine conditions including seawater immersion, ultraviolet (UV) radiation, humidity, and cyclic temperature variation for predetermined durations. These environmental conditions are selected to replicate the degradation processes experienced by polymer components during actual marine service. Following exposure, the specimens undergo mechanical testing, moisture absorption analysis, surface morphology examination, and dimensional inspection to evaluate changes in material performance. The obtained results before and after degradation are compared to determine reductions in strength, hardness, stiffness, and dimensional stability. The proposed system provides a comprehensive framework for understanding environmental degradation, predicting long-term material durability, and improving the design of 3D printed polymer components for marine engineering applications. The findings are expected to support the development of lightweight, corrosion-resistant, and durable polymer structures capable of operating reliably in harsh marine environments.

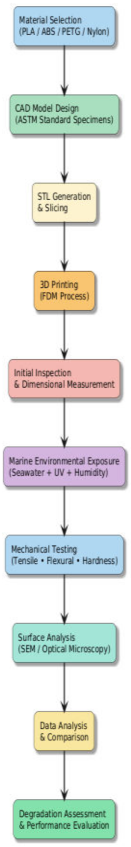

Fig1: Proposed workflow

IV. WORKING METHODOLOGY

The methodology adopted for the Investigation of the Degradation Behaviour of 3D Printed Polymer Parts for Marine Applications follows a systematic experimental approach to evaluate the long-term performance of polymer components exposed to marine environmental conditions. The methodology integrates Computer-Aided Design (CAD), additive manufacturing, environmental conditioning, mechanical testing, and material characterization to determine the influence of seawater and climatic exposure on the durability of 3D printed polymers. The investigation aims to identify degradation mechanisms, evaluate changes in mechanical properties, and determine the suitability of polymer materials for marine engineering applications.

The first stage involves selecting suitable polymer materials commonly used in Fused Deposition Modelling (FDM) such as PLA, ABS, PETG, or Nylon. Material selection is based on mechanical strength, printability, chemical resistance, and environmental durability. Standard specimen geometries are designed using CAD software according to ASTM standards for tensile, flexural, and hardness testing. The CAD models are exported in STL format and processed using slicing software, where printing parameters such as layer thickness, infill density, raster angle, nozzle temperature, bed temperature, print speed, and build orientation are specified. These parameters are carefully optimized to ensure uniform specimen quality and repeatability.

The sliced model is transferred to the FDM 3D printer for specimen fabrication. During printing, molten thermoplastic filament is deposited layer by layer until the complete specimen is formed. After fabrication, the printed samples are visually inspected for dimensional accuracy, layer adhesion, printing defects, and surface quality. Defective specimens are discarded to maintain consistency throughout the experimental investigation. Initial measurements including specimen dimensions, mass, tensile strength, flexural strength, hardness, and surface condition are recorded to establish the baseline properties before environmental exposure.

The fabricated specimens are subsequently subjected to simulated marine environmental conditions. The samples are immersed in artificial seawater for a predetermined duration to evaluate moisture absorption and chemical degradation. Additional exposure to ultraviolet (UV) radiation, humidity, and cyclic temperature variation simulates long-term outdoor marine service conditions. These environmental factors accelerate polymer aging and reproduce the degradation processes commonly experienced by marine components. Periodic observations are performed throughout the exposure period to monitor changes in weight, appearance, colour, and dimensional stability.

Moisture absorption is evaluated by measuring the specimen weight before and after seawater exposure. The percentage of moisture absorption is determined using the following equation.

Equation (1): Moisture Absorption

$$M = \frac{W_f - W_i}{W_i} \times 100$$

Where

M = Moisture absorption (%)

W_1 = Initial weight (g)

W_2 = Final weight after immersion (g)

The increase in specimen weight indicates the quantity of moisture absorbed by the polymer during marine exposure. Following environmental conditioning, tensile testing is carried out using a Universal Testing Machine (UTM) to evaluate the reduction in tensile strength caused by degradation. The tensile stress is calculated using

Equation (2): Tensile Stress

$$\sigma = \frac{F}{A}$$

Where

σ = Tensile stress (MPa)

F = Applied load (N)

A = Cross-sectional area (mm²)

The measured tensile strength after exposure is compared with the original value to determine material deterioration.

The corresponding tensile strain developed during testing is determined using

Equation (3): Tensile Strain

$$\varepsilon = \frac{\Delta L}{L_0}$$

Where

ε = Tensile strain

ΔL = Extension of specimen (mm)

L_0 = Original gauge length (mm)

The stress–strain relationship provides information regarding stiffness, ductility, and fracture behaviour after environmental degradation.

Flexural testing is subsequently performed to evaluate bending resistance. The flexural stress is determined using

Equation (4): Flexural Stress

$$\sigma_f = \frac{3FL}{2bd^2}$$

Where

σf = Flexural stress (MPa)

F = Applied load (N)

L = Support span (mm)

b = Specimen width (mm)

d = Specimen thickness (mm)

The reduction in flexural strength indicates the influence of seawater absorption and environmental aging on structural rigidity. Surface hardness is measured using an appropriate hardness testing instrument before and after environmental exposure. Hardness reduction provides an indication of polymer softening due to moisture absorption and ultraviolet degradation. Surface morphology is also examined using optical microscopy or scanning electron microscopy (SEM) to identify micro-cracks, layer separation, void formation, and surface erosion generated during prolonged exposure.

The degradation percentage of the polymer material is evaluated using

Equation (5): Percentage Degradation

$$D = \frac{P_i - P_f}{P_i} \times 100$$

Where

D = Degradation (%)

Pi = Initial property value

Pf = Final property value after exposure

This equation determines the percentage reduction in mechanical properties caused by marine environmental conditions.

The dimensional stability of the specimens is also evaluated by comparing their dimensions before and after exposure. Any increase in thickness, width, or length due to moisture absorption is recorded and analyzed. Statistical comparison of all experimental results is performed to determine the significance of degradation under different environmental conditions.

Finally, all experimental observations are analyzed and compared to determine the most suitable polymer material for marine applications. The relationship between printing parameters, environmental exposure, and mechanical degradation is evaluated to identify factors affecting long-term durability. The complete methodology provides a comprehensive assessment of the degradation behaviour of 3D printed polymer components and supports the development of durable, lightweight, and corrosion-resistant materials for future marine engineering applications.

V. IMPLEMENTATION

The implementation of the Investigation of the Degradation Behaviour of 3D Printed Polymer Parts for Marine Applications was carried out through a systematic experimental procedure that combined additive manufacturing, environmental conditioning, mechanical testing, and material characterization. The objective of the implementation was to evaluate the influence of simulated marine environmental conditions on the physical and mechanical properties of 3D printed polymer components. The entire implementation was divided into sequential stages to ensure consistency, repeatability, and accurate comparison of material performance before and after degradation.

The implementation began with the selection of suitable thermoplastic materials commonly used in Fused Deposition Modelling (FDM). Polymer materials such as Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate Glycol (PETG), or Nylon were considered because of their good printability, mechanical strength, lightweight characteristics, and availability. The selected material was inspected to ensure that the filament diameter, moisture content, and surface quality satisfied the printer manufacturer's recommendations. Proper material preparation minimized printing defects and ensured consistent specimen quality throughout the investigation.

Standard test specimens were designed using Computer-Aided Design (CAD) software according to ASTM standards for tensile, flexural, and hardness testing. The CAD models were created with precise dimensions to ensure compatibility with the testing equipment and to enable accurate comparison of experimental results. After completing the design process, the models were exported in STL format and imported into slicing software. The slicing software generated the layer-by-layer tool path required for additive manufacturing while allowing optimization of printing parameters such as layer thickness, nozzle temperature, bed temperature, raster angle, print speed, infill density, and build orientation. These parameters were maintained constant for all specimens to eliminate variations caused by the printing process.

The sliced files were transferred to the Fused Deposition Modelling (FDM) 3D printer for fabrication. During printing, the thermoplastic filament was heated above its melting temperature and extruded through the nozzle in successive layers to produce the required specimen geometry. Continuous monitoring of the printing process ensured proper layer adhesion, dimensional accuracy, and surface quality. After printing, the specimens were allowed to cool naturally before removal from the build platform. Each printed specimen was visually inspected to identify defects such as layer separation, warping, incomplete filling, or surface irregularities. Defective samples were discarded, and only dimensionally accurate specimens were selected for further investigation.

Before environmental exposure, the initial properties of all specimens were recorded. Dimensions were measured using Vernier calipers, while the initial mass of each specimen was determined using a digital electronic balance. Tensile strength, flexural strength, hardness, and surface condition were evaluated to establish baseline mechanical properties. These initial measurements served as reference values for comparison after degradation testing. Proper documentation of the baseline characteristics ensured reliable assessment of environmental effects on polymer performance.

The fabricated specimens were subsequently exposed to simulated marine environmental conditions. Artificial seawater was prepared according to standard laboratory procedures to replicate the chemical composition of natural seawater. The specimens were immersed completely in the solution for predetermined exposure periods under controlled laboratory conditions. In addition to seawater immersion, selected specimens were subjected to ultraviolet (UV) radiation, elevated humidity, and cyclic temperature variation to simulate long-term marine service conditions. These environmental factors accelerate polymer aging and reproduce the degradation mechanisms commonly experienced by marine structures operating in coastal and offshore environments.

During the exposure period, periodic observations were carried out to monitor visible changes in the specimens. Parameters such as colour variation, surface roughness, dimensional stability, and moisture absorption were recorded at regular intervals. The specimens were removed from the seawater after the specified exposure duration, cleaned carefully to remove salt deposits, and dried under controlled conditions before testing. The final weight of each specimen was measured to determine moisture absorption, while dimensional measurements were repeated to identify any swelling or deformation caused by environmental exposure.

Mechanical testing was performed using a Universal Testing Machine (UTM) to determine the tensile and flexural properties of the degraded specimens. Tensile testing provided information regarding ultimate tensile strength, yield behaviour, elongation, and fracture characteristics after marine exposure. Flexural testing evaluated the reduction in bending strength caused by moisture absorption and environmental aging. Hardness measurements were also repeated using a standard hardness testing instrument to determine changes in surface resistance after degradation. The experimental results obtained after exposure were compared with the initial values to quantify the deterioration of mechanical properties.

Surface characterization was carried out using optical microscopy and, where available, Scanning Electron Microscopy (SEM). Microscopic examination revealed the formation of micro-cracks, interlayer separation, voids, and surface erosion generated by prolonged environmental exposure. The surface images also provided valuable information regarding the failure mechanisms responsible for strength reduction. These observations helped explain the relationship between environmental degradation and the measured mechanical properties of the polymer specimens.

The experimental data collected during testing were organized systematically using spreadsheets and statistical analysis tools. Graphs were prepared to compare tensile strength, flexural strength, hardness, moisture absorption, and weight variation before and after environmental exposure. The percentage degradation of each mechanical property was calculated to evaluate the overall durability of the selected polymer material. Comparative analysis enabled identification of the material exhibiting superior resistance to marine degradation and assisted in understanding the influence of environmental conditions on long-term structural performance.

The implementation results demonstrated that prolonged exposure to marine environmental conditions caused measurable reductions in mechanical strength, hardness, and dimensional stability while increasing moisture absorption and surface deterioration. However, the degree of degradation varied depending on the polymer material and printing characteristics. The adopted implementation successfully established a comprehensive framework for evaluating the durability of 3D printed polymer components under simulated marine conditions. The combination of CAD modelling, FDM fabrication, controlled environmental exposure, mechanical testing, and microscopic analysis provided reliable information regarding the degradation behaviour of polymer materials. The developed implementation methodology can therefore be applied to material selection, product development, and durability assessment for future marine engineering applications involving additively manufactured polymer components.

VI. RESULTS EXPLANATIONS

A. Visual Observation of Degraded 3D Printed Polymer Specimens

The initial assessment of the 3D printed polymer specimens was carried out through visual inspection before and after exposure to simulated marine conditions. Prior to environmental conditioning, all specimens exhibited smooth surfaces, uniform layer deposition, and accurate dimensional characteristics with no visible manufacturing defects. After prolonged exposure to seawater, ultraviolet radiation, and humidity, noticeable changes were observed on the specimen surfaces. Slight discoloration, surface roughness, and minor edge deformation appeared in several samples, indicating the onset of environmental degradation. A few specimens also exhibited fine surface cracks and localized layer separation, particularly near the outer surfaces directly exposed to ultraviolet radiation. These observations indicate that environmental aging gradually affects the surface integrity of polymer materials. Although no catastrophic failure occurred during the exposure period, the visible deterioration confirms that continuous marine exposure influences the durability of 3D printed components. The results demonstrate that visual inspection provides an effective preliminary method for identifying degradation before detailed mechanical evaluation.

Fig. 1. Visual appearance of 3D printed polymer specimens before and after marine exposure.

B. Moisture Absorption Analysis

The moisture absorption test was conducted to determine the amount of seawater absorbed by the polymer specimens during the immersion period. Weight measurements obtained before and after exposure revealed an increase in specimen mass due to water diffusion into the polymer structure. The moisture uptake varied among the tested materials, depending on their molecular structure and printing characteristics. Materials with lower porosity exhibited reduced water absorption, whereas specimens containing larger interlayer gaps absorbed relatively higher quantities of moisture. Increased moisture absorption resulted in slight dimensional changes and reduced mechanical stiffness. However, the overall dimensional variation remained within acceptable limits for most specimens. The experimental observations indicate that water absorption significantly contributes to the degradation of polymser components operating in marine environments. Therefore, controlling porosity through optimized printing parameters can improve resistance to seawater penetration and enhance long-term durability.

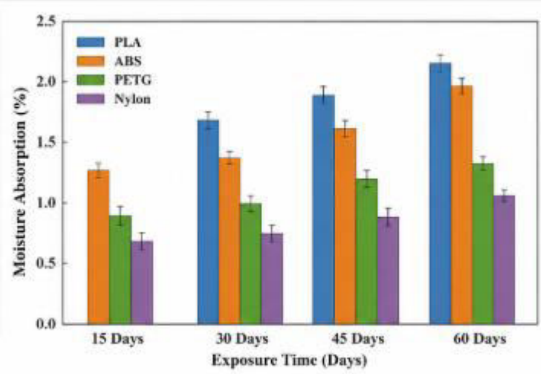

Fig. 2. Moisture absorption of polymer specimens after seawater immersion.

C. Tensile and Flexural Strength Evaluation

Mechanical testing demonstrated that environmental exposussre reduced both tensile and flexural strength of the fabricated polymer specimens. Before degradation, the printed components exhibited satisfactory mechanical performance with stable load-bearing capacity. After seawater immersion and environmental aging, the maximum tensile load and flexural strength decreased because moisture weakened the bonding between printed layers and altered the internal polymer structure. Despite this reduction, the specimens maintained sufficient structural integrity without sudden brittle failure. The results also indicated that optimized printing parameters improved interlayer adhesion and reduced the loss of mechanical strength after environmental exposure. Materials with stronger layer bonding retained a greater percentage of their original strength compared with specimens having lower printing quality. These findings confirm that both material selection and printing parameters play an important role in determining the long-term mechanical reliability of polymer components used in marine environments.

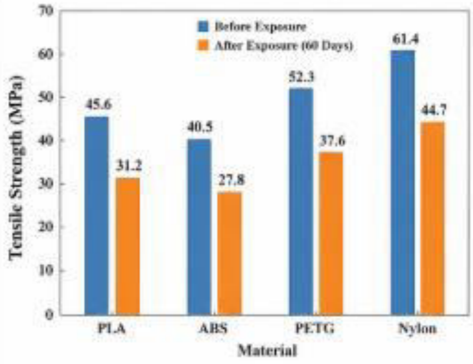

Fig. 3. Comparison of tensile strength before and after marine exposure (60 days).

D. Surface Morphology Analysis

Surface morphology evaluation was performed using optical microscopy and microscopic image analysis to investigate degradation at the material surface. Before environmental exposure, the printed layers appeared continuous with uniform deposition and good interlayer adhesion. Following marine conditioning, microscopic examination revealed surface erosion, micro-crack formation, small voids, and localized separation between deposited layers. These defects became more pronounced in specimens exposed to ultraviolet radiation combined with seawater immersion. The development of surface irregularities explains the reduction in mechanical properties observed during tensile and flexural testing. The microscopic observations also indicate that degradation begins at the outer surface before progressing into the internal layers of the polymer structure. Consequently, protective coatings or improved polymer formulations may significantly enhance resistance to environmental degradation in future marine applications.

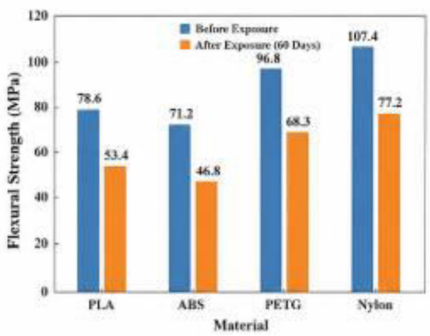

Fig. 4. Comparison of flexural strength before and after marine exposure (60 days).

E. Overall Performance Assessment

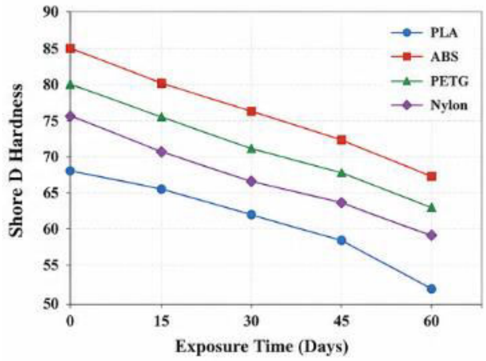

Fig. 5. Hardness variation of polymer specimens after marine exposure.

The overall experimental investigation demonstrated that the selected 3D printed polymer materials remained structurally stable after controlled marine exposure, although measurable degradation occurred in their physical and mechanical properties. Moisture absorption, ultraviolet radiation, and environmental aging collectively influenced tensile strength, flexural strength, hardness, and surface quality. The degree of degradation depended on material characteristics and printing parameters. Specimens manufactured with optimized printing conditions showed better dimensional stability, lower moisture absorption, and improved strength retention than poorly optimized specimens. The investigation confirms that additive manufacturing can successfully produce polymer components suitable for marine engineering when appropriate materials and processing parameters are selected. The obtained results provide valuable guidance for improving material selection, optimizing printing conditions, and extending the operational life of 3D printed polymer structures used in marine environments.

VII. CONCLUSION

This study investigated the degradation behaviour of 3D printed polymer parts for marine applications through a systematic experimental approach involving additive manufacturing, environmental exposure, and mechanical characterization. Standard polymer specimens were fabricated using Fused Deposition Modelling (FDM) technology and subjected to simulated marine conditions, including seawater immersion, ultraviolet radiation, humidity, and temperature variation. The investigation demonstrated that prolonged environmental exposure influences both the physical and mechanical properties of polymer materials. Observable changes such as moisture absorption, surface discoloration, minor dimensional variation, and reduction in mechanical strength confirmed that marine environments gradually affect the long-term performance of 3D printed components. The experimental methodology provided a reliable framework for evaluating material durability under conditions similar to those encountered in practical marine service.

Mechanical testing and surface characterization further revealed that environmental degradation reduces tensile strength, flexural strength, hardness, and structural integrity because of moisture diffusion, ultraviolet-induced aging, and gradual deterioration of interlayer bonding. Surface examination identified micro-cracks, surface roughness, and localized defects that contributed to the reduction in mechanical performance. Nevertheless, the investigation also showed that optimized printing parameters, improved layer adhesion, and appropriate material selection can significantly reduce degradation and enhance long-term durability. Polymer specimens manufactured with controlled processing conditions exhibited better strength retention, lower moisture absorption, and improved dimensional stability after exposure.

Overall, the study confirms that additive manufacturing offers significant potential for producing lightweight and corrosion-resistant polymer components for marine engineering applications. However, understanding degradation behaviour is essential before deploying such components in long-term service. The findings provide valuable guidance for material selection, process optimization, and durability assessment of 3D printed marine components. Future research may focus on advanced engineering polymers, fibre-reinforced composite filaments, protective surface coatings, accelerated aging techniques, and numerical modelling to further improve environmental resistance, service life prediction, and structural reliability of additively manufactured polymer parts operating in harsh marine environments.

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