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Studies on epoxy-coated waste fishing nets for exploration as reinforcement in cementitious composite

Aiswarya Kesh[a] & Smitha Gopinath[b*]

Advanced Protective Structures and Mechanics Laboratory,
CSIR- Structural Engineering Research Centre, Chennai 600 113, India

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Comprehensive investigations have been carried out to understand the chemical resistance of nylon-based waste fishing nets for use as reinforcement in cementitious composites. The study has aimed to promote a circular economy by converting waste fishing nets into construction materials. Epoxy coatings have been applied to two types of waste fishing nets, and characterization studies have been conducted. Chemical characterization has involved exposing coated and uncoated nets to alkali solutions to simulate the cementitious environment. Advanced techniques, including scanning electron microscopy (SEM), thermogravimetric analysis (TGA), and Fourier transform infrared spectroscopy (FTIR), have been used to assess morphological and elemental changes before and after alkali exposure. Uniaxial tensile tests have been performed to evaluate the influence of epoxy coating on mechanical properties and its suitability for reinforcement. Coated nets have shown minimal degradation compared to uncoated ones, with damage primarily involving the formation and expansion of etch holes. The tensile response of coated nets has demonstrated promising strength, stiffness, and strain values, qualifying them for reinforcement applications. The findings suggest that epoxy-coated waste fishing nets offer a durable and sustainable alternative for cementitious composites, supporting the broader goal of waste recycling in construction.

Keywords: Chemical resistance, Tensile characterization, SEM, FTIR, TGA, Nylon fiber durability, Uniaxial tension, Degradation, Alkali exposure

1 Introduction

Waste fishing nets have been contributing majorly to ocean pollution and recognizing the urgency to overcome this issue, research groups globally have initiated to mobilize their efforts to find sustainable solutions[1–4]. Presently, there has been limited study available on the reuse of waste fishing net fibers, particularly in the commercial sector where waste fibers are readily available. The construction sector has emerged as one of the segments that can open up the scope for the use of waste fishing nets in various product applications[5–11]. Utilizing waste fishing net fibers in brittle matrices, such as concrete, has demonstrated significant improvements in mechanical properties, including tensile strength, flexural strength, impact resistance, deformation capacity, and load-bearing capacity. These fibers have found potential for application in fiber-reinforced concrete[5,12–15], fiber-reinforced polymer-reinforced concrete, and textile-reinforced concrete[12,16] as reported in some of the literature. However, for the successful implementation of such materials in various product applications, it has been crucial for the composite materials to maintain their strength and toughness over time, without experiencing significant degradation[6,17,18]. It is important to note that the concrete matrix creates an environment with strong alkalinity, characterized by a pH level above 12.5. These environmental factors have potentially react with waste fishing net fibers, leading to degradation, mass loss, and a reduction in fiber strength. Therefore, it has been imperative to thoroughly investigate the alkali resistance of such fibers before using in cementitious applications. Comprehensive studies on the alkali resistance of waste fishing net fibers have provide insights into their performance and potential susceptibility to degradation in highly susceptible environments[6,19,20]. This investigation has been crucial for ensuring composite materials' continued integrity and reliability, mitigating the potential risks associated with fiber deterioration[21,22]. To evaluate the alkaline resistance of fibers, accelerated aging tests have been commonly employed. These tests have involved exposing the fibers to NaOH solutions to assess their degradation rate. Several key factors have significantly influenced the rate of degradation

*Corresponding author (E-mail: smithag@serc.res.in)

observed in the solutions, including the temperature of the test, duration of the aging process, presence of fiber coatings, and specific chemical compositions of fibers and solutions used. The degradation of fibers in these solutions has primarily occured through two mechanisms: leaching of the fiber in water and degradation of the fiber within the specific alkaline conditions provided by the solutions[13,23]. Among these mechanisms, the degradation process has played a pivotal role[3]. By conducting comprehensive investigations using accelerated aging tests, researchers have gained valuable insights into the alkaline resilience of fibers. Carefully considering factors such as temperature, aging duration, fiber coating, and chemical composition of both the fiber and solution has allowed for a systematic evaluation of the identification of specific degradation mechanisms. Understanding these factors has been essential in developing strategies to enhance the durability and performance of fibers, ensuring their suitability for a range of applications in adverse environments. Based on the aforementioned reviews, it has become apparent that the existing body of research on the alkali resistance of waste fishing net fibers, specifically regarding the degradation mechanisms, has been insufficient.

To advance the application of waste fishing net fibers in construction, it has been essential to conduct a comprehensive investigation into the resistance of these fibers. As for the materials of the waste fishing nets, they have typically been made of synthetic polymers such as nylon, polyethylene, or polypropylene. These materials have been chosen for their durability, flexibility, and resistance to degradation, making them suitable for use in various applications, including construction and marine industries. Hence, present study has aimed to fill the knowledge gap by undertaking a fundamental examination of the feasibility of use of waste fishing net fibers in cementitious system. One of the potential application has been in textile reinforced concrete wherein non-metallic textile have already been used as reinforcement. It seeks to explore the resistance of the fiber net itself beforehand. In the above context, the primary objective of this study has been to identify the type of waste fish net, explore the applicability of an epoxy coating on waste fishing net to enhance the characteristics for qualification as reinforcement in cementitious system called textile reinforced concrete (TRC) that uses non-metallic textiles as reinforcement, to understand the underlying degradation mechanisms to evaluate the resistance of waste fishing net fibers, and also arrive at the strength and ductility parameters of the waste fishing net. By undertaking such an investigation, it is supposed to provide a proof of concept for the development of use of waste fishing net in cementitious applications. In order to achieve these objectives, the resistance of waste fishing net fibers have been evaluated through a series of experiments designed to simulate real-world conditions by subjecting the fibers to an alkaline solution to observe and measure their performance and resistance to degradation[24]. Results from advanced instrumentation techniques such as SEM, FTIR and TGA[25–27] will be carefully analysed, and the degradation mechanisms have been identified based on the empirical data. Further, uniaxial tensile characterisation has been carried out to understand the tensile response of waste fishing nets for qualification as reinforcement in cementations composite called TRC.

2 Materials and Methods

2.1 Materials and sample preparation

In this study, discarded waste fishing nets were gathered from a fishing location in India with the help of local fishermen. The two types of fishing nets collected were deep-sea (green) waste fishing nets and anchovy (red) waste fishing nets, both made of nylon, as shown in Fig. 1. The properties of the collected waste fishing nets are listed in Table 1. The waste fishing net fibers underwent a meticulous cleaning process to ensure their suitability. This process began with multiple washings using running water to effectively remove impurities and surface salts. To further prepare the fishing net fibers for subsequent experimentation, the nets were immersed in tap water for 30 minutes, effectively rinsing away any remaining contaminants. This soaking procedure was repeated four times, utilizing fresh tap water on each occasion. The water's conductivity was measured using a conductivity meter after each rinse to confirm the removal of contaminants. After the fourth soaking, the water conductivity was similar to that of the original tap water, confirming that the fibers were thoroughly cleaned. Following cleaning, the fibers were subjected to uniform drying in an air-circulating oven at 100°C for 24 hours to ensure consistent weight measurements and maintain their integrity. These cleaning and preparation procedures were

Fig. 1 — a) Uncoated Anchovy fishing net (Red net), (b) Deep sea fishing net (Green net) (c) coating of Anchovy red net (d) coating of green net (e) Dipping of Anchovy and Deep sea net in alkali (NaOH) Solution for 5 days, 28 days and 56 days.

Table 1 — Properties of collected waste fishing nets.

Properties	Mesh Size (mm)	Yarn thickness (mm)	Knot thickness (mm)
Deep sea (Green) fishing net	15	0.88 to 0.90	t_x: 3.25; t_y: 2.76
Anchovy (Red) fishing net	5	0.22 to 0.26	t_x: 0.96; t_y: 0.78

essential to guarantee the fibers' optimal performance when integrated into the TRC system, enhancing their potential as effective reinforcement elements.

From the collected nets, it is noted that the positioning of nets in any cementitious system needs a particular stiffness for practicality in product prefabrications. In such scenarios additional coating on such nets can be of benefit. Along this line the SBR and epoxy coating has been done to glass textiles in some of the studies reported in literature. Hence, to investigate the influence of additional epoxy coating on collected waste fishing net, a coating procedure was employed using a roller brush as shown in Figs. 1c and 1d. The ratio of resin to hardener in the epoxy system was determined based on the manufacturer's instructions and recommendations for the Rotex EP-821/Rotex EH-369 system. This ratio is critical for achieving the desired properties of the epoxy coating, such as adhesion, strength, and durability. The uniformity of the coating was maintained by carefully mixing the resin and hardener components and applying them evenly to the waste fishing nets using a roller brush. The resin and hardener components were mixed in a weight ratio of 10:4. The resin-hardener mixture was uniformly applied to the samples using a roller brush, and the coated specimens were subsequently left to cure at room temperature for approximately 24 hours, following the manufacturer's recommended curing time

The coated and uncoated waste fishing net fiber used were multi filamented in nature, as depicted in Fig. 1 (a - b). These were used to examine the resistance to various environments, an accelerated aging test was conducted by submerging them in NaOH solution as shown in Fig. 1(e). Throughout the process, the treatment duration ranged from 5 days to 56 days, with the solution temperature consistently maintained at 25° (normal room temperature). The coated and uncoated waste fishing net fiber was completely submerged in the NaOH solution, with a depth of 25 mm, and the container housing the solution was sealed to prevent any evaporation.

For conducting uniaxial tensile test on coated and uncoated waste fishing nets, samples were prepared with standardized dimensions, measuring 200mm in length and 50mm in width. The textile samples were designated with the following nomenclature: GC for green net coated, GU for green net uncoated, RC for red net coated, and RU for red net uncoated.

2.2 Testing methods

Identifying the material in waste fishing nets is pivotal for a comprehensive understanding of their environmental impact and determining the appropriate coating for further usage. Additionally, assessing the type of fiber used is crucial for determining the material's durability, influencing decisions on its suitability for TRC applications. To delve deeper into these aspects, a combination of experimental techniques was employed to evaluate the physical properties of coated and uncoated waste fishing net fibers exposed to alkali solutions. The samples underwent thorough analysis using advanced methods such as scanning electron microscopy (SEM), Thermogravimetric Analysis (TGA), and Fourier transform infrared spectroscopy (FTIR) to examine morphological, elemental, and phase composition changes. Furthermore, uniaxial tensile tests were conducted following the ISO 1806-2002 procedure for both coated and uncoated waste fishing nets. This comprehensive approach provides valuable insights into the material's behaviour under different duration in alkali environmental conditions, aiding in the development of informed strategies for TRC applications.

2.2.1 Physical properties

Scanning electron microscopy (SEM) images were used to estimate the diameter of both coated and uncoated waste fishing net fibers. Fourier transform infrared spectroscopy-Attenuated Total Reflectance (FTIR-ATR) was utilized to confirm the polymer type of the waste fishing net. Thermal gravimetric analysis (TGA) were conducted to investigate the thermal degradation behaviour. In the TGA test, a 10 mg fiber sample was heated from room temperature (20°C) to 800°C at a rate of 10°C/min using a TA Q500 instrument. Furthermore, a comprehensive series of experimental investigations were carried out to assess the disparities in physical properties between coated/uncoated and new/waste fishing net fibers. SEM was used to examine the surface morphology of both coated and uncoated waste fishing net fibers, both before and after immersion in NaOH solution. Moreover, FTIR spectroscopy, equipped with a microscope attachment, was employed to record the infrared spectra within the range of 400-4000 cm^{-1}, allowing for a detailed analysis of the fibers.

2.2.2 Alkali conditioning of Waste fishing net fibers

This study investigates the response of Waste fishing net fiber’s monofilaments to alkali conditioning, adhering to the ASTM D543-06 standard. The conditioning process involved immersing 200 mm fishing net fibers monofilaments in an alkaline solution for an extended duration of 5 to 56 days. The alkaline solution was meticulously prepared by dissolving 10.4 g of sodium hydroxide in 999 ml of distilled water. A molarity of 0.26 M and pH of 12.41 is achieved using the above preparation. Crucially, the conditioning process was conducted under strict temperature control to ensure a constant and controlled environment. This research provides valuable insights into the behaviour of fishing net fiber’s monofilaments under alkali exposure, with implications for their potential use in various applications, particularly where resistance to alkaline environments is essential.

2.2.3 Textile sample preparation for Uniaxial Tensile Test

Using a computer-controlled electro-hydraulic universal servo testing machine with a 75kN capacity (Tinius Olsen), Uniaxial tensile test was carried out on each textile sample at a rate of 0.5mm/minute. To evenly distribute the load without experiencing any fastening troubles, the textile was gripped for a length of 25mm at the top and 25mm at the bottom. A minimum of 10 samples were tested in each case as specified in Indian Standard ISO 1806-2002. Average of the best three results from each case were reported as the tensile strength. To find the influence of additional epoxy coating on the waste fishing net, tensile test results of coated waste fishing net and uncoated waste fishing net were compared.

3 Results and Discussion

3.1 Degaration of coated and uncoated waste fishing net fiber in NaOH solution

3.1.1. Morphological Changes In Fibers – SEM

The comprehensive examination of both the waste anchovy sea net and the deep-sea net, both before after treatment undergoing an alkali treatment for durations of 5, 28, and 56 days, highlighted significant differences in their diameter and coating quality. Initially, the red anchovy fishing net exhibited a diameter measuring 283.1 μm, while the deep-sea green net exhibited a larger diameter of 958.1 μm. In the initial observation, as depicted in Fig. (2a) for the red anchovy coated net and Fig. (2d) for the green deep-sea coated net, both nets were meticulously and evenly coated, showing a minimal number of pores visible at an observation scale of about 10 μm. Following 5 days of treatment, both the red Fig. (2b) and green Fig. (2f) nets displayed no discernible differences. Neither showed visible pores or any degradation in the coating quality. However, after prolonged treatment for 28 and 56 days, distinctive differences became apparent. The green-coated net began to exhibit signs of degradation, with fibers becoming visible and starting to detach, as evidenced in Fig. (2g) and (2h). Contrarily, the red- coated net, as seen

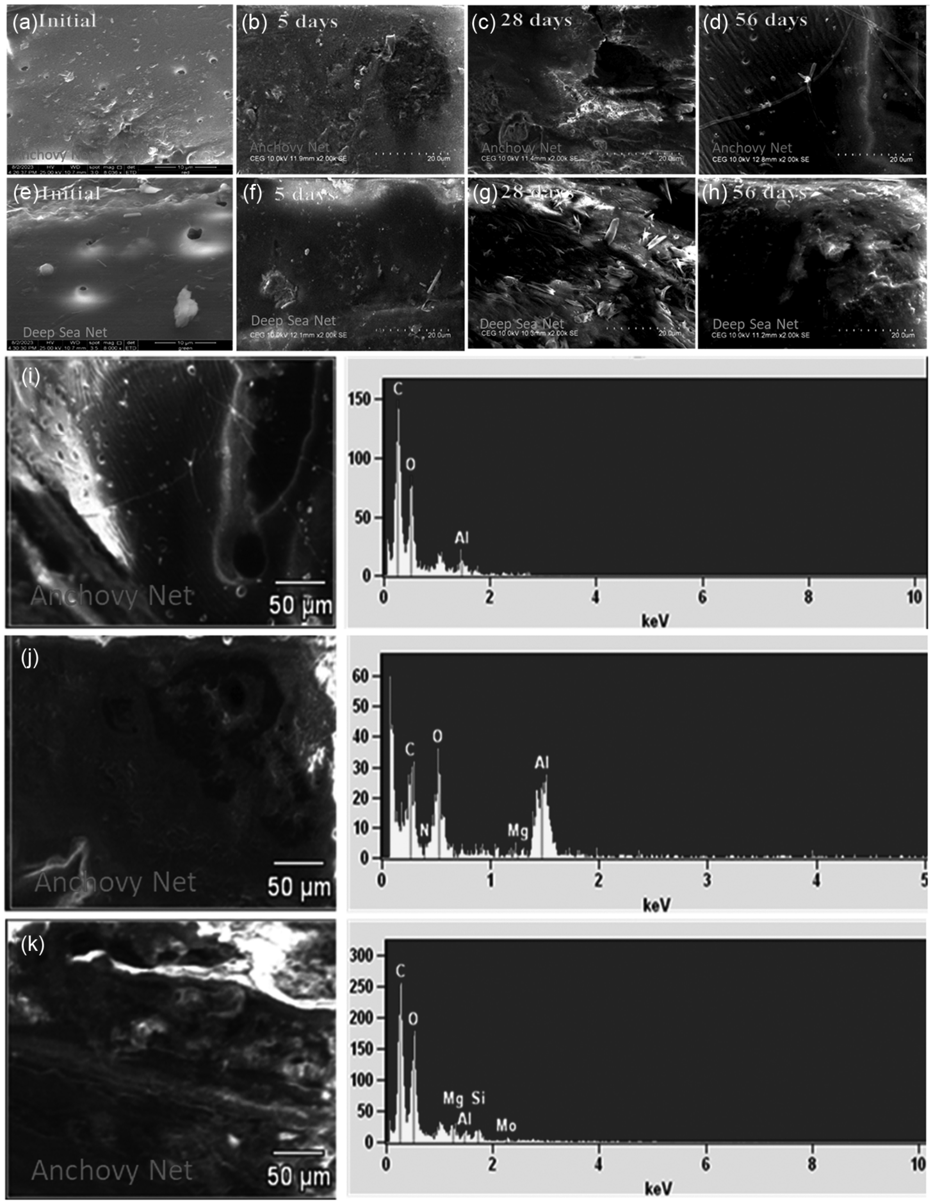

Fig. 2 — SEM images illustrating the coated (a-d) Anchovy and (e- h) Deep sea waste fishing net fiber before and after dipping in NaOH solution. (a, e) Before dipping in NaOH solution. After dipping in NaOH solution for (b, f) 5 days (c, g) 28 days and (d, h) 56 days. and (i, j and k) EDS of Anchovy Sea net after 5, 28 and 56 Days of alkali treatment respectively.

in Fig. 2 (c & d), remained resilient without any apparent signs of degradation or fiber loss. Although both nets exhibited a similar level of coating quality initially, the prolonged alkali treatment caused significant degradation in the green net, leading to fiber loss, while the red net remained unaffected by such issues. After 28 days, evident degradation areas develop due to the breakdown of Si-O-Si bonds by OH^- ions, causing silicates to migrate into the solution, particularly in the case of the green net. These degraded areas are then covered by a loose and porous gel layer. In addition, particles made up of insoluble metal oxides (Fe, Ca, and Mg) and hydroxides, originating from the fiber core beneath the gel layer, adhere to this gel layer. With time, the gel layer fully forms, leading to an increased concentration of these particles on its surface, which eventually coalesce into larger flaky coatings. This progression signifies the formation of a deposition layer and the development of a brittle shell-like

Table 2 — Chemical composition of the Fishing net Fiber.

Elements → / Days of Treatment ↓	C	N	O	Mg	Al	Si	Mo
5 Days	52.3	Nil	44.2	1.1	0.6	1.4	0.4
28 Days	56.8	Nil	41.7	Nil	1.4	Nil	Nil
56 Days	70.3	0	0.05	0.6	29.1	Nil	Nil

structure. The emergence of cracks and exfoliation of fragments from the surface of the fiber becomes noticeable, facilitated by water molecules that cause swelling of the surface layer, resulting in volume expansion. By the 56-day mark, the deposition layer completely covers the gel layer, and reaches a saturation point. The thickness of the degradation zone at 56 days exceeds what was observed at 28 days. In certain filaments, it is partially or completely detached, revealing a smooth and uncorroded fishing net fiber core. At 56 days, specific filaments undergo considerable degradation, evident from a significant amount of exfoliated degradation between them. Moreover, erosion starts anew in other filaments, indicated by complete delamination and the appearance of fresh degradation marks on the fiber core surface which is clearly seen in Fig. 2(h). Throughout this progression, the fiber's residual diameter gradually diminishes with time.

In analyzing Fig. 2 (i, j, and k), through Energy Dispersive Spectroscopy (EDS) of the anchovy sea net, the initial chemical composition of the fishing net fiber was determined and is outlined in Table 2. The elements detected include C, N, O, Si, Mg, Al and Mo where carbon (C) is the predominant element, comprising the majority of the composition. Over the treatment period of 5, 28, and 56 days, there are notable changes in the elemental composition, especially in the carbon content. Nitrogen content is not explicitly present for the 5-day and 28-day treatments, but it becomes detectable at 56 days but in very minimal percentage which is almost ~ 0. The oxygen content decreases from 44.2% to 41.7% by the 28th day, and then there is a sharp decrease to 0.05% at 56 days. This could indicate oxidation or other chemical reactions affecting the oxygen content. Silicon (Si), Magnesium (Mg), Aluminium (Al), and Molybdenum (Mo) are present in varying amounts. Aluminium shows a noticeable increase from 0.6% at 5 days to 29.1% at 56 days, suggesting a potential influence of NaOH on the already presence of material on the net during the treatment period. The observed changes in elemental composition over time may be indicative of chemical processes such as oxidation, degradation, or interaction with environmental factors (alkali conditioning). The release of certain elements or the transformation of the material could have implications for aquatic ecosystems or other environments where these nets are disposed of.

3.1.2. Fourier-Transform Infrared (FTIR) spectroscopy

A Fourier-Transform Infrared (FTIR) spectroscopy serves as a pivotal method for the identification and determination of functional groups within adsorbent samples, exerting significant influence on the adsorption processes. The FTIR spectra depicted in Fig. 3 exhibit the characteristic signatures of Nylon 6, 6. In Fig. 3, the results of samples before dipping in NaOH solution and after dipping in NaOH solution are for (c, h) 5 days , (d, i) 28 days, and (e, j) 56 days.

According to the obtained results, nylon 6,6 exhibits a noteworthy medium-intensity band at peaks 3292 cm^{-1}(Anchovy Uncoated Fig. 3(a), and 3292 cm^{-1} (Deep Sea Uncoated Fig. 3(f) which can be attributed to the N-H stretching vibrations originating from amino groups. Subsequently, a distinct C-H stretching vibration associated with alkanes groups manifests itself as a medium-intensity peak at 2940 cm^{-1} (Deep Sea Uncoated) and 2857, 2926 cm^{-1} (Anchovy Uncoated). These vibrations are associated with the hydrocarbon chains in the nylon structure. Two prominent and strong peaks are observed at peaks 1640 cm^{-1} and 1519 cm^{-1} (Deep Sea Uncoated) and peaks 1630 cm^{-1} and 1533 cm^{-1} (Anchovy Uncoated). These are the Amide I and Amide II band associated with the stretching vibration of the carbon-oxygen (C=O) bond, the bending of nitrogen-hydrogen (N-H) bonds and the stretching of carbon-nitrogen (C-N) bonds within the amide functional group present in the nylon polymer. The peak at 1630 cm^{-1} (Fig. 3a) includes both the Amide I band associated with C=O stretching and N-H bending vibrations. To confirm the molecular structure of the epoxy resin coating, Fourier-Transform Infrared (FT-IR) spectroscopy was employed within the wavelength

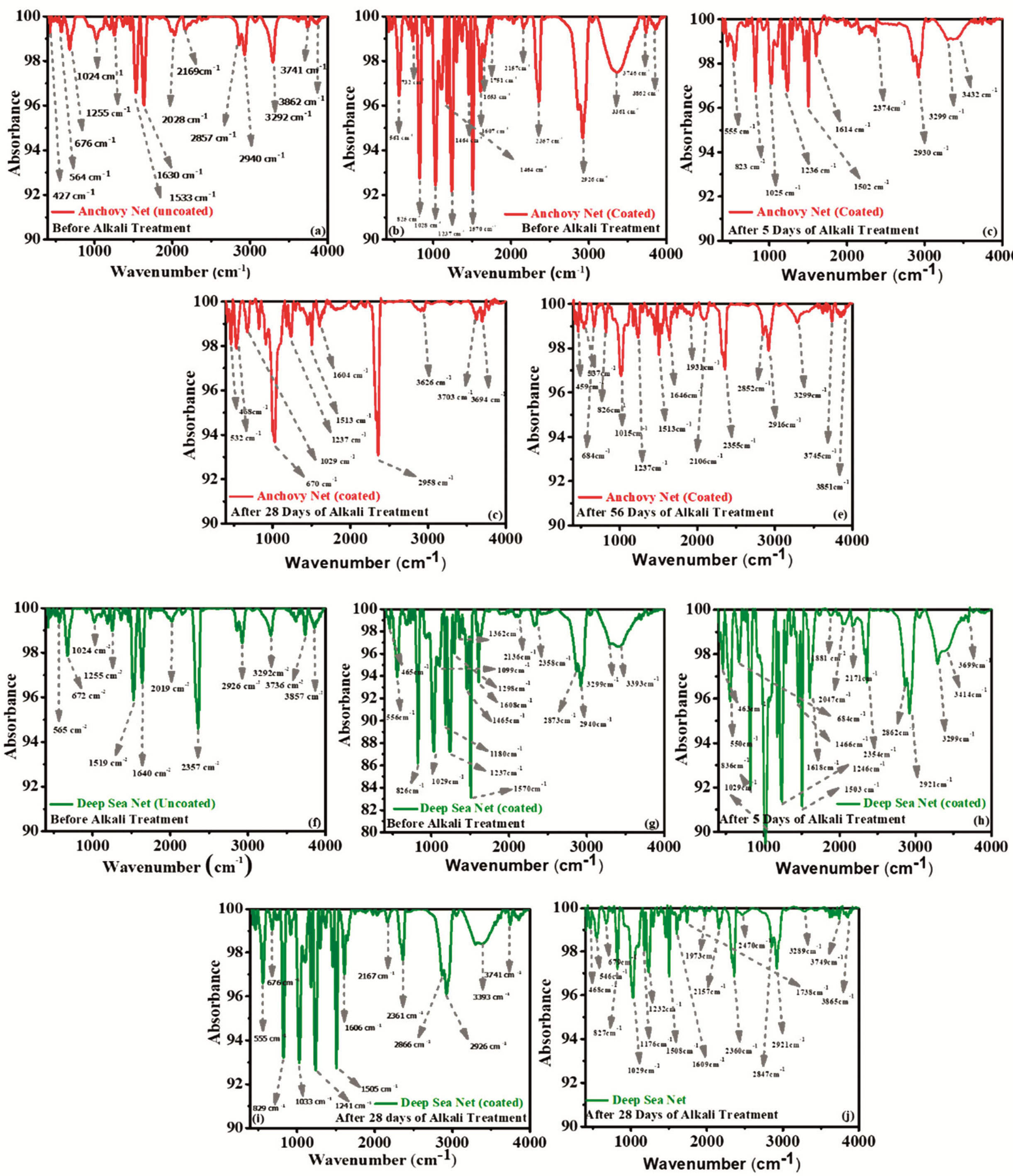

Fig. 3 — Annulated infrared (ATR) (a-e) Anchovy and (f- j) deep sea waste fishing net fiber before and after dipping in NaOH solution. (a, b, f and g).

range of 4000–400 cm^{-1}. The FT-IR spectra obtained for the epoxy resin-coated red and green nets are presented in Fig. 3b, g. The primary functional group of interest in this compound is the epoxy group, characterized by absorption peaks at 1028 cm^{-1} (Fig. 3b) and 1029 cm^{-1} (Fig. 3g). These observations confirm the presence of epoxy rings within the coating material. Importantly, the intensity of this peak is sharp, signifying a moderate concentration of epoxy groups integrated into the net's coating.

Additionally, significant absorption bands at 1168 cm^{-1} Fig. 3(b) and 1180 cm^{-1} Fig. 3(g) are attributed to the C–O stretching vibrations of aromatic rings. Moreover, the peak around 3000 cm^{-1} to 3500 cm^{-1} (3361 cm^{-1} for Fig. 3 (b) and 3393 cm^{-1} for Fig. 3 (g) signifies the presence of hydroxyl groups originating from the epoxy resin. The shift in the Amide II peak from 1533 cm^{-1} to 1517 cm^{-1} Fig. 3 (b) and from 1519 to 1511 cm^{-1} Fig. 3 (g) suggests an interaction between the nylon 6,6 and the epoxy coating indicative of changes in the N-H bending and C-N stretching vibrations within the amide groups. The shift to lower wave numbers via 1607 cm^{-1} (Anchovy coated) from 1630 cm^{-1} (Anchovy Uncoated) and 1608 cm^{-1}(Deep sea coated) from 1630 cm^{-1}(Deep sea Uncoated) may imply a change in the hydrogen bonding environment or conformation of the amide groups. This shift suggests that the epoxy coating has affected the amide bonds in the nylon 6,6 polymer. Moreover, the C-H stretching vibrations (CH_2 and CH of aromatic and aliphatic respectively) at 2926 $cm^{-1}$and 3292 cm^{-1} Fig. 3 (b) remain almost similar to the anchovy uncoated Fig. 3 (a) suggesting that the aliphatic C-H stretching bands associated with the nylon 6,6 polymer remain relatively unchanged after the epoxy coating whereas for deep sea uncoated net Fig. 3 (f) it shifts from 2926 cm^{-1} and 3292 cm^{-1} to 2940 cm^{-1} and 3299 cm^{-1} Fig. 3 (g) respectively suggesting the deep sea net having a larger diameter to anchovy net has absorbed more epoxy inside changing the nylon 6,6 bonding. Notably, absorption peaks within the range of 1500–1607 cm^{-1} and 1200–1250 cm^{-1}, common to both Anchovy and Deep sea coated nets, corresponding to characteristic features of aromatic C=C bonds and phenolic C–O groups, respectively. Additionally, peaks at 1029 cm^{-1} and 829 cm^{-1} (Deep sea coated) and at 1028 cm^{-1} and 825 cm^{-1} (Anchovy coated net) are indicative of the stretching vibrations of C–O–C in ether groups and C–O–C in oxirane groups, respectively. Furthermore, the presence of methylene groups is confirmed by vibration bands at 1464 cm^{-1} (Anchovy coated net) and 1465 cm^{-1} (Deep sea coated net).

After subjecting the epoxy-coated Nylon 6,6 nets, both Anchovy and Deep Sea varieties, to alkali treatment for different durations, notable changes in their infrared spectra were observed. In the case of Anchovy nets Fig. 3 (c-e) following 5 days of NaOH exposure, the Amide II band shifted to 1502 cm^{-1}, and the Amide I band appeared at 1614 cm^{-1}. The C-H stretching vibration exhibited a peak at 2930 cm^{-1}, while an aliphatic peak emerged at 3299 cm^{-1}. After 28 days, the Amide II band shifted slightly to 1513 cm^{-1}, the Amide I band appeared at 1604 cm^{-1}, and the C-H stretching vibration showed a peak at 2958 cm^{-1}. After 56 days, the Amide II band remained at 1513 cm^{-1}, but the Amide I band shifted to 1646 cm^{-1}. The C-H stretching vibration exhibited a peak at 2916 cm^{-1}.For Deep Sea n ets (Fig. 3(h-i), after 5 days of NaOH exposure, the Amide II band shifted to 1503 cm^{-1}, and the Amide I band appeared at 1618 cm^{-1}. The C-H stretching vibration exhibited a peak at 2921 cm^{-1}, and an aliphatic peak emerged at 3299 cm^{-1}. After 28 days, the Amide II band shifted slightly to 1505 cm^{-1}, the Amide I band appeared at 1606 cm^{-1}, and the C-H stretching vibration showed a peak at 2926 cm^{-1}. After 56 days, the Amide II band shifted to 1508 cm^{-1}, the Amide I band appeared at 1609 cm^{-1}, and the C-H stretching vibration exhibited a peak at 2921 cm^-1. In interpreting these changes, it can be noted that the shifts in the Amide I and II bands suggest alterations in the amide bonds, possibly indicative of interactions between the epoxy coating and the nylon polymer. The variations in the C-H stretching vibrations further indicate modifications in the molecular structure of the coated nylon nets over time. The differences observed between Anchovy and Deep Sea nets may be attributed to variations in the initial characteristics of the nets or the absorption capacity of the coatings. The data indicates that the Deep Sea coated net absorbed a higher quantity of NaOH as the duration increased from 5 to 56 days. This increased absorption had discernible consequences on the epoxy coating, subsequently influencing the Nylon 6,6 structure. Although there may not be pronounced visible differences in peak positions, the progressive decrease in peak intensity in the green net, aligns with the inference drawn from the IR studies. A careful examination of the IR peak studies reveals that, despite not exhibiting significant differences in peak positions, the intensity of peaks in the Deep Sea (green) net consistently decreased over the observed time period. This decline in peak intensity is indicative of structural changes within the coated net, emphasizing the impact of prolonged exposure to alkali conditions. Visual evidence suggests that the epoxy coating on the Deep Sea net experienced a more substantial alteration, likely due to its increased absorption of NaOH over the 5 to 56-day

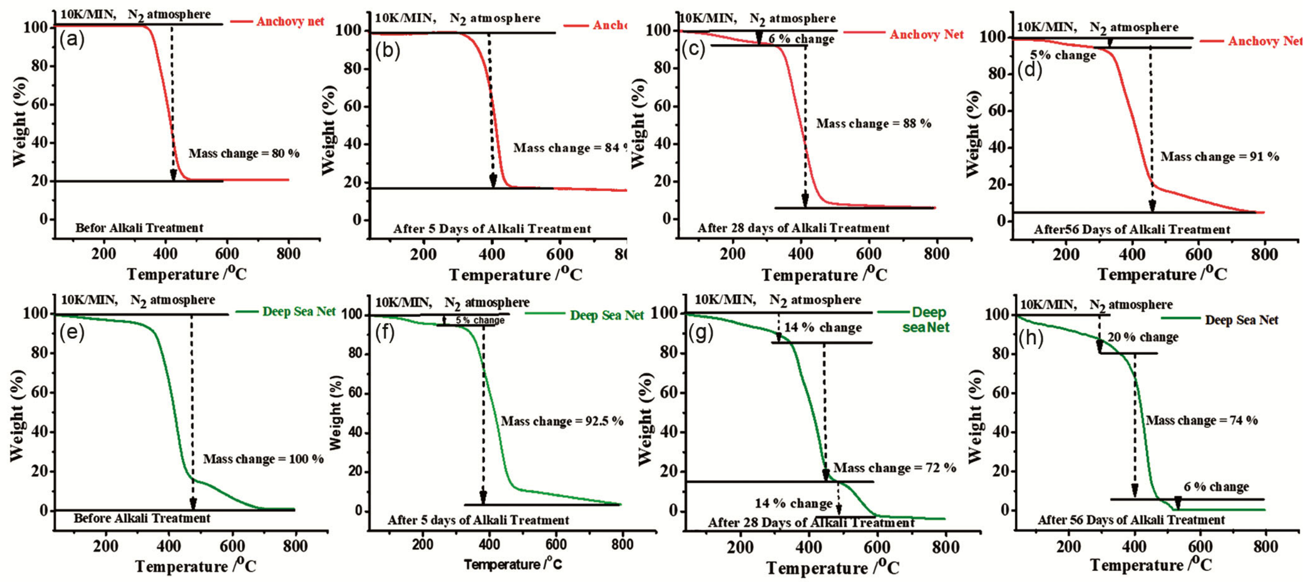

Fig. 4 — Thermogravimetric analysis (TGA) images of coated (a-d) Anchovy sea net and (e- h) Deep sea net at a temperature range of 40° C to 900° C.

period. In summary, the combined analysis of IR and SEM studies supports the conclusion that the red net (Anchovy) exhibits superior performance compared to the green net (Deep Sea) under the conditions of alkali treatment.

3.1.3 Thermogravimetric Analysis (TGA)

Thermo gravimetric Analysis (TGA) was employed elucidate the thermal stability and decomposition behaviour of material. Figure 4 shows the TGA images of Coated (a, b, c and d) deep sea net and (e, f, g and h) Deep sea net at a temperature range of 40° C to 900° C.

In Fig. 4(a), representing the thermo-gravimetric analysis (TGA) of the coated Anchovy sea net before alkali conditioning, during the initial stage (40°C to 200°C), no discernible weight loss is observed, indicative of thorough drying and absence of moisture content in the thin net. Subsequently, in the temperature range of 200 °C to 400 °C, the epoxy resin undergoes distinct thermal degradation with an 80% weight loss, emphasizing its contribution to the overall composite's thermal behaviour. Simultaneously, between approximately 300 °C to 450 °C, the primary decomposition of nylon 66 and the coated epoxy material occurs, with no significant weight loss, underscoring the interplay of resin behavior and its impact on the composite's thermal stability. Moving to Fig. 4(b), where the Anchovy net is subjected to alkali solution for 5 days, negligible moisture absorption is evident in the 40 °C to 200 °C range. However, a notable 84% mass loss occurs between 200 °C and 400 °C, and no mass change is observed from 300°C to 450°C and beyond, signifying the influence of alkali treatment on thermal stability. In Fig. 4(c), with a 28-day alkali treatment, a visible mass change (6%) in the 40 °C to 200 °C range indicates NaOH absorption. Subsequently, an 88% mass loss is observed between 200 °C and 400 °C, while no mass change is detected in the 300 °C to 450 °C range and above, highlighting the continued impact of alkali conditioning on thermal properties. Finally, in Fig. 4(d), following a 56-day alkali treatment, a 5% mass change in the 40 °C to 200 °C range indicates NaOH absorption. Notably, there is a significant 91% mass loss between 200 °C and 400 °C, coupled with a decrease in cure, emphasizing the prolonged influence of alkali conditioning on the material's thermal stability, particularly in the 300 °C to 450 °C temperature range and above.

In Fig. 4(e), prior to alkali conditioning, TGA reveals a weight loss of approximately 2-3% in the initial stage, attributed to inadequate drying of the thicker deep sea net, resulting in residual moisture. Subsequently, between 200°C and 400°C, the coated net undergoes distinct thermal degradation, leading to a 100% weight loss. Concurrently, in the temperature range of 300°C to 450°C, the primary decomposition of nylon 66 and the coated epoxy material occurs. Moving to Fig. 4(f), after the deep sea net is

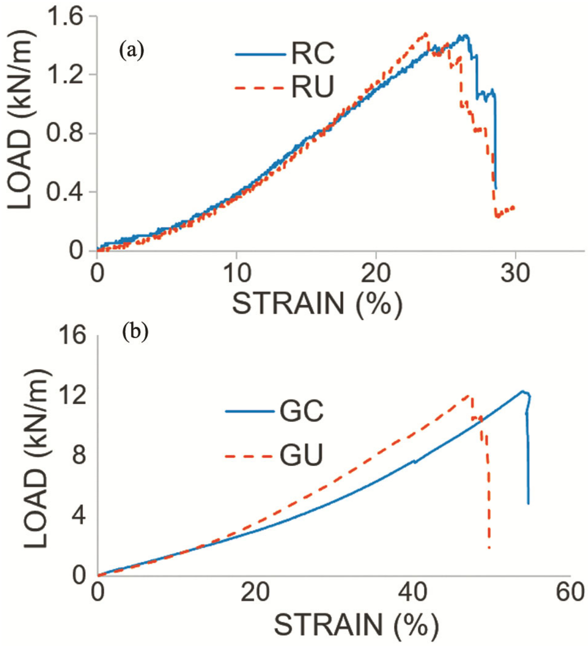

Fig. 5 — Load versus strain curve of (a) Anchovy red fishing net, and (b) Deep sea Green fishing net.

immersed in alkali solution for 5 days, a 5% mass loss from 40 °C to 200 °C is observed due to moisture absorption. A significant 92.5% mass loss in the 200-400°C range indicates extensive thermal degradation, while no mass change in the 300 °C to 450 °C range signifies stability. In Fig. 4(g), after 28 days of alkali exposure, a 14% mass change from 40 °C to 200 °C suggests increased NaOH absorption. A notable 72% mass loss in the 200-400°C range signifies continued degradation, with a 14% mass change in the 300 °C to 450 °C range. Fig. 4(h), depicting 56 days of alkali exposure, reveals a 20% mass change from 40 °C to 200 °C due to NaOH absorption. A 74% mass loss in the 200-400°C range indicates sustained degradation, accompanied by a 6% mass change in the 300°C to 450°C range, suggesting a decrease in the cure process. Here, a substantial weight loss is observed as the polymer chains within nylon 66 begin to break down. This decomposition process may generate volatile by-products such as ammonia (NH3) and caprolactam ((CH2)2CNH). These findings underscore the material's thermal behavior, emphasizing the influence of resin type and formulation on overall composite performance.

3.1.4 Uniaxial tensile response of coated and uncoated waste fishing nets

The results of the uniaxial tensile tests conducted on Anchovy red fishing nets have provided valuable insights into the impact of epoxy coating on their mechanical properties. In Fig. 5, the load vs. strain response of both Anchovy red and Deep sea coated and uncoated waste fishing nets are shown. The anchovy red uncoated fishing net is denoted as RU and anchovy red coated net is denoted as RC in Fig. 5(a). Further the nomenclature used for Deep sea green uncoated is GU and that of coated is GC in Fig. 5(b).The uncoated anchovy red fishing net Fig. 5(a) exhibited a maximum load at failure of 1.48 kN/m and a corresponding strain of 23.7%. Upon the application of epoxy coating, the maximum load at failure marginally decreased to 1.47 kN/m, indicating a reduction of 0.7%. However, a notable improvement in stiffness was observed, with the strain in the coated red net decreasing to 1.05% of that in the uncoated net. This enhanced stiffness is attributed to the epoxy coating.

A careful examination of the failure patterns further elucidates the differences between the uncoated and coated anchovy red fishing nets. In the uncoated net anchovy red net as seen in Fig. 6, the failure was characterized by uneven breakage of yarns and knots at various locations, suggesting a less predictable failure mode. In contrast, the coated red net exhibited a more brittle and even failure pattern, indicative of increased stiffness resulting from the epoxy coating. Thus, the coating's application to the red fishing net has not only led to a slight reduction in maximum load at failure but has significantly improved the net's overall stiffness and structural integrity.

The deepsea green fishing net (shown in Fig. 5(b)), the uncoated variant demonstrated a maximum load at failure of 12.03 kN/m and a corresponding strain of 47.5%. In comparison, the coated green net exhibited a slightly higher maximum load at failure, measuring 12.3 kN/m, signifying a 2.24% improvement. However, an unexpected increase in strain by 13.7% was observed in the coated green net, suggesting that the epoxy coating did not enhance its stiffness. This response in strain behavior between the red and green nets underlines the complex interplay of materials and coatings in different contexts. The failure patterns of the green nets offered additional insights. The uncoated green net, owing to its higher yarn and knot thickness, required more time and load to reach failure when compared to the red net. The failure in the uncoated green net (as seen in Fig. 7) primarily occurred due to the breakage of

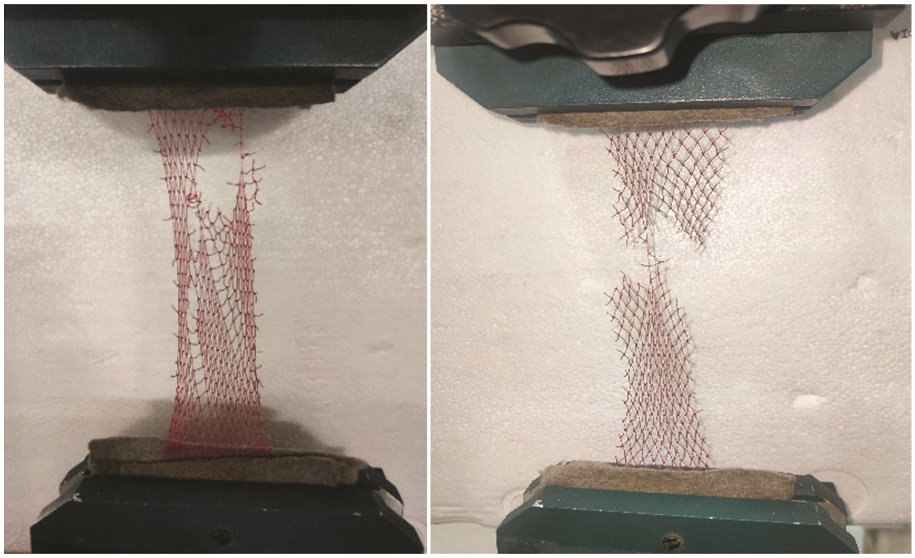

Fig. 6 — Failure patterns in Anchovy red fishing net (a) uncoated and (b) coated.

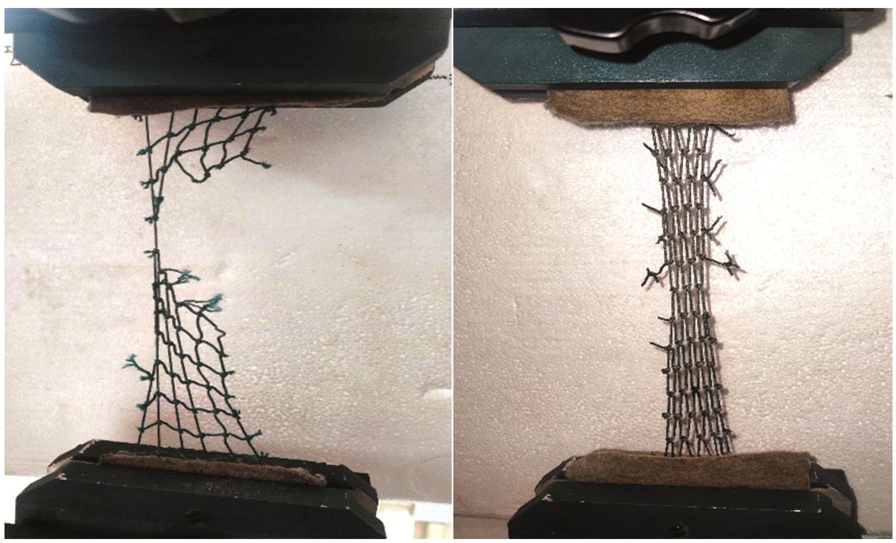

Fig. 7 — Failure patterns in deep sea green fishing net (a) uncoated and (b) coated.

yarns and knots at their weakest points. Interestingly, the presence of the epoxy coating in the green net resulted in a different response. Despite the same loading rate and time, the coated green net exhibited more extension without breakage, as illustrated in Fig. 7. This indicates that while the coating had a positive effect on the net's strength, it did not contribute to enhanced extension. The uniaxial tensile tests and failure pattern analyses have shed light on the distinct effects of epoxy coating on red and green fishing nets. The application of epoxy coating to anchovy red fishing nets yielded a marginal reduction in maximum load at failure but significantly improved stiffness, leading to a more brittle and even failure pattern. Conversely, in the case of deep-sea green fishing nets, epoxy coating resulted in a modest increase in maximum load at failure but unexpectedly increased strain, indicating no improvement in stiffness. These findings are crucial in understanding the potential advantages and limitations of epoxy coating for different types of fishing nets. It is important to note that the green net may have a higher crack width when used in TRC applications compared to the red net, based on these results. Further research may be needed to explore the specific implications of these findings for practical applications in the field.

4 Conclusion

In summary, this research has employed a comprehensive approach to unravel the potential of waste fishing nets, particularly nylon 6,6, as a sustainable and effective reinforcement in cementitious composites. The chemical characterization studies utilizing advanced techniques such as SEM, TGA, and FTIR have offered crucial insights into the morphological and compositional changes of both coated and uncoated waste fishing net fibers when exposed to alkali solutions, simulating the conditions of a cementitious system. The minimal degradation observed in coated nets, particularly in the case of anchovy compared to deep-sea nets, underscores the effectiveness of protective coatings in preserving the structural integrity of these materials. The identified degradation mechanism involving the formation, expansion, and combination of etch holes provides valuable understanding for applications in diverse environmental conditions. Moreover, uniaxial tensile characterization studies have demonstrated promising mechanical properties in coated nets, suggesting their potential as robust reinforcements in cementitious composites. This research not only sheds light on the intricate degradation behavior of waste fishing net fibers but also emphasizes the importance of meticulous coating application for enhancing their suitability in various contexts, offering a sustainable solution to address the issue of ocean pollution caused by discarded fishing nets.

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