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Analysis of Biodegradable and Tensile Strength of Yarn from Polycaprolactone (PCL) with Wet Spinning Method

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***Abstract* - Polycaprolactone (PCL) is a biodegradable polymer widely utilized in biomedical and environmentally friendly textile applications due to its excellent biocompatibility, mechanical strength, and ability to degrade naturally in biological environments. This study aims to analyze the biodegradability and tensile strength of PCL yarn produced through the wet spinning process. A 20% w/v PCL solution was prepared by dissolving PCL pellets in chloroform and extruded through a 21G needle tip into a 96% ethanol coagulation bath at room temperature. The solidified filaments were dried and twisted into yarns with variations of 2-ply, 3-ply, and 4-ply configurations. Biodegradation was evaluated by immersing the yarn samples in a saline (NaCl) infusion solution for several weeks to measure mass loss, while tensile strength was measured following ASTM D2256 standards using a universal testing machine. The results revealed a gradual reduction in yarn mass over the immersion period, indicating effective biodegradation. Tensile strength increased proportionally with the number of plies, where the 4-ply yarn exhibited the highest strength and elongation performance. The findings confirm that wet-spun PCL yarn maintains sufficient mechanical integrity while demonstrating significant biodegradability, making it a promising candidate for biomedical sutures, bio-textiles, and sustainable polymer products. Overall, this research provides a practical understanding of the relationship between spinning parameters, mechanical properties, and biodegradation behavior in PCL-based yarns.**

Keywords: Degradation, Density, Fiber Formation, Polylactic Acid (PLA), Tensile Strength.

I. INTRODUCTION

The growing concern over plastic pollution and environmental sustainability has driven extensive research into biodegradable polymers as alternatives to conventional synthetic materials [1]. Among them, polycaprolactone (PCL) has gained significant attention for its combination of flexibility, low melting temperature, and biocompatibility [2-4]. As a semi-crystalline aliphatic polyester, PCL can be synthesized through ring-opening polymerization of ε-caprolactone, resulting in a polymer that degrades slowly through hydrolysis of its ester bonds [5-6]. These properties make it suitable for various applications, particularly in the biomedical field and environmentally friendly textiles [7-8].

In the textile and materials engineering sectors, the development of biodegradable fibers is essential to reduce the ecological footprint of synthetic fibers [9]. The ability of PCL to form continuous filaments makes it a potential alternative to petroleum-based fibers. However, the success of its application depends largely on the optimization of spinning techniques, as the microstructure of the fiber directly influences its mechanical performance and degradation rate[10].

Wet spinning is a traditional yet effective technique for producing fibers from polymers that are soluble in organic solvents [11]. The process involves dissolving the polymer, extruding it through a spinneret into a non-solvent coagulation bath, and forming solid filaments through phase inversion [12]. Control over parameters such as solvent selection, extrusion rate, and bath composition determines the final fiber morphology and strength. In this study, chloroform served as the solvent and ethanol as the coagulation medium due to their compatibility with PCL.

Furthermore, the structural integrity of the spun fibers is influenced by post-processing techniques such as twisting or plying. Twisting multiple single strands into multi-ply yarns enhances mechanical strength by redistributing stress and improving load transfer among filaments. Therefore, investigating how ply variation affects the tensile properties of PCL yarn provides valuable insight into its applicability in practical use [13].

From an environmental perspective, PCL's biodegradation behavior in saline conditions simulates its degradation in biological or physiological environments [14]. Monitoring the rate of mass loss during immersion helps to understand the polymer's lifetime and suitability for temporary biomedical applications, such as absorbable sutures or tissue scaffolds [15]. This also provides valuable data for its use in green textile industries.

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Hence, this research focuses on two main objectives: (1) to analyze the biodegradation behavior of wet-spun PCL yarn through immersion testing, and (2) to determine its tensile properties under different ply configurations. The results are expected to serve as a foundation for further material optimization and potential industrial application of PCL-based yarns.

II. METHODS

The research process began with a comprehensive literature review from reliable sources such as Google Scholar and ScienceDirect, focusing on the fabrication of Polycaprolactone (PCL) fibers using the wet spinning method. Following this, the necessary tools and materials were prepared, starting with the creation of a polymer solution by dissolving PCL in selected solvents, including acetone, dichloromethane, dimethyl fumarate, ethyl acetate, and chloroform, using a magnetic stirrer at specific concentrations. A custom-built wet spinning apparatus was then assembled to extrude the polymer solution into fibers, which were subsequently spun into yarns. The produced samples underwent several tests, including density, macro photo analysis, and biodegradation rate testing, to evaluate the effectiveness of the wet spinning process in producing high-quality PCL fibers. The overall workflow of the study is illustrated in Figure 3.1.

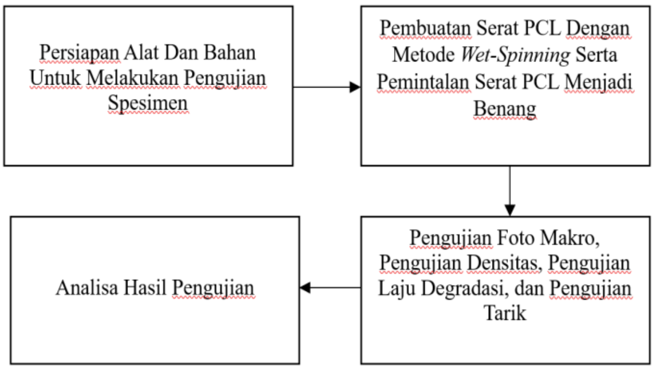

Figure 1: Block Diagram

2.1 Governing Equations

Density testing is a method used to determine the mass per unit volume of a material. This parameter plays a vital role in material characterization because it directly relates to physical properties such as strength, hardness, and structural stability. In polymer and fiber materials, density values can be influenced by the production process and environmental conditions during or after fabrication. The measured density provides insight into porosity, crystallinity, and homogeneity of the material.

The density (ρ) is calculated using the general formula:

$$\rho = \frac{m}{V}$$

where ρ is density (kg/m³), m is mass (kg), and V is volume (m³).

For a **mixture or composite**, density can be obtained by dividing the total mass by the total volume of all components, expressed as:

$$\rho = \frac{(m_1 + m_2 + \dots + m_n)}{(V_1 + V_2 + \dots + V_n)}$$

where $m_1, m_2, \dots, m_n$ are the individual masses and $V_1, V_2, \dots, V_n$ are the corresponding volumes of each component.

2.2 Testing Procedure

The specimen preparation in this study involved the fabrication of PCL fibers and PCL yarns using the wet spinning method. The process began with weighing the PCL polymer according to the predetermined 20% concentration, followed by dissolving it in 10 mL of solvent using a magnetic stirrer at 25 °C for one hour until a homogeneous solution was obtained. The polymer solution was then loaded into a syringe and extruded slowly into a coagulation bath, where solid fibers were formed and collected onto a spool. The produced PCL fibers were subsequently twisted into yarns with variations of 2-ply, 3-ply, and 4-ply configurations using a drop spindle to enhance uniformity and mechanical strength.

Material testing was conducted to evaluate the effectiveness of the wet spinning process, focusing on density, macro photo, degradation rate, and tensile strength. The density test was carried out using a digital density meter to measure mass and volume, providing data on the compactness and homogeneity of the fibers. The macro photo analysis utilized a macro microscope to observe the surface morphology and fiber uniformity under controlled lighting conditions. The biodegradation test aimed to determine the degradation rate of PCL fibers by immersing samples in 0.9% NaCl solution for up to five weeks, with periodic drying and weighing each week to record mass loss. Finally, the tensile test followed the ASTM D2256 procedure using a universal testing machine, where yarn specimens were clamped, tensioned, and pulled until failure to measure tensile strength, elongation, and Young's modulus.

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III. RESULTS AND DISCUSSIONS

3.1 Yarn Formation Process

The spinning process of polycaprolactone (PCL) fibers using the twisting method with a spindle was performed to convert individual filaments into yarns with improved strength and cohesion. The procedure began by preparing several dried PCL fibers of uniform length, which were aligned parallel to ensure even stress distribution during spinning. The aligned fibers were then placed on a spindle, a rotating device that applies a continuous twist along the fiber axis. As the spindle rotated at a controlled speed, the fibers experienced torsional forces that caused them to intertwine and bond mechanically. Gentle tension was maintained throughout the process to ensure uniform twisting and prevent fiber entanglement. The resulting twisted yarn exhibited a more compact structure, enhanced tensile strength, and greater dimensional stability. The number of twists per unit length played a critical role in determining the mechanical properties and elasticity of the produced PCL yarn. The morphology of the twisted PCL fiber is shown in Figure 2.

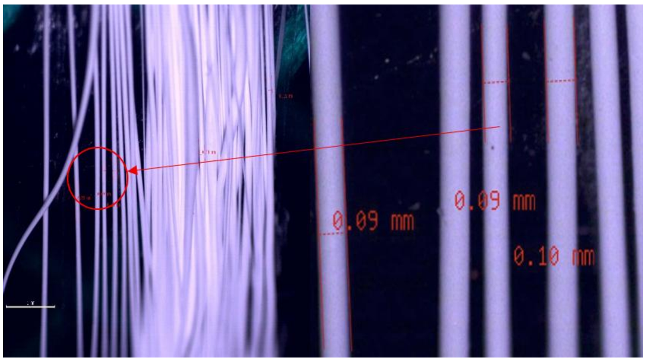

Figure 2: PCL Fiber Shape and Diameter

3.2 Macro Photo Test Results and Analysis

The macro photo examination of the polycaprolactone (PCL) fibers was conducted to analyze the surface morphology and macroscopic structure of the produced filaments. Through this test, the diameter of both the single-strand fibers and the twisted yarns could be observed, along with their diameter uniformity and surface smoothness resulting from the extrusion and spinning processes. The macro images also provided visual confirmation of fiber continuity and structural consistency. The morphology of the single-strand PCL fiber extruded using a 21G needle tip can be seen in Figure 3.

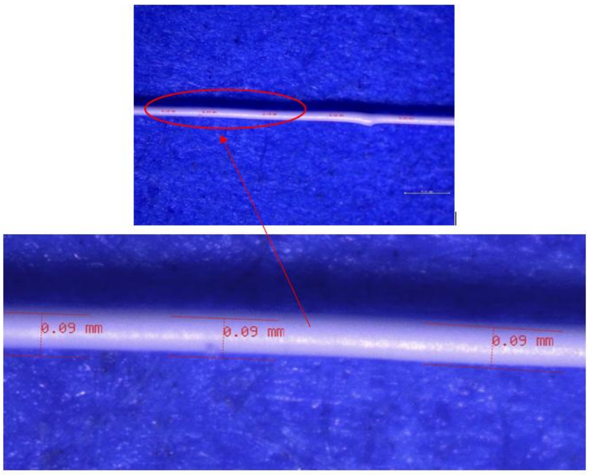

Figure 3: Single Strand PCL Fiber

The PCL fiber produced using a 21G needle showed a consistent diameter of about 0.9 mm. This single fiber was then twisted to improve its mechanical strength and form yarn. The PCL yarn was made in three variations2-ply, 3-ply, and 4-plywhich are shown in Figures 4, 5, and 6.

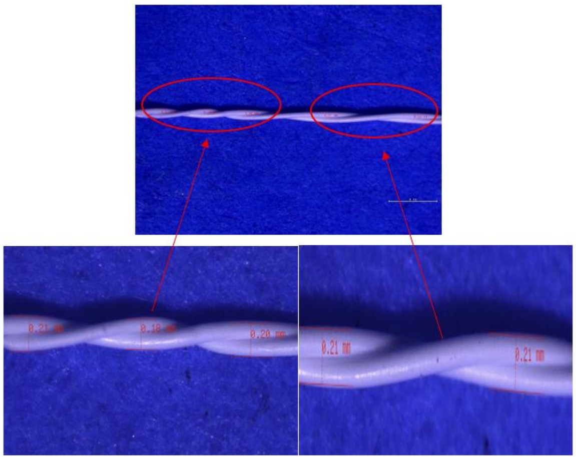

Figure 4: 2 Ply PCL thread Diameter 0.20 mm

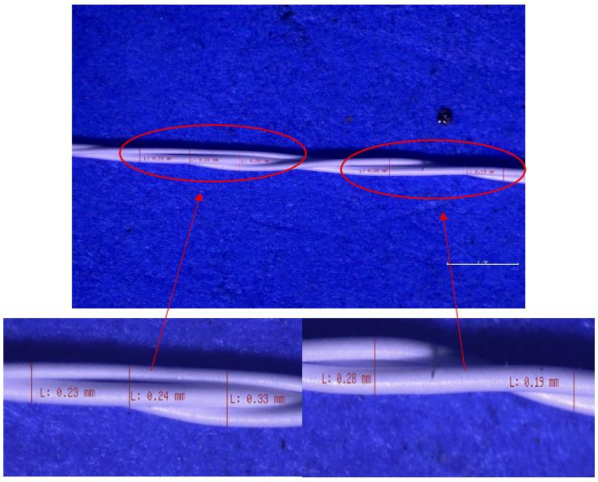

Figure 5: 3 Ply PCL thread Diameter 0.25 mm

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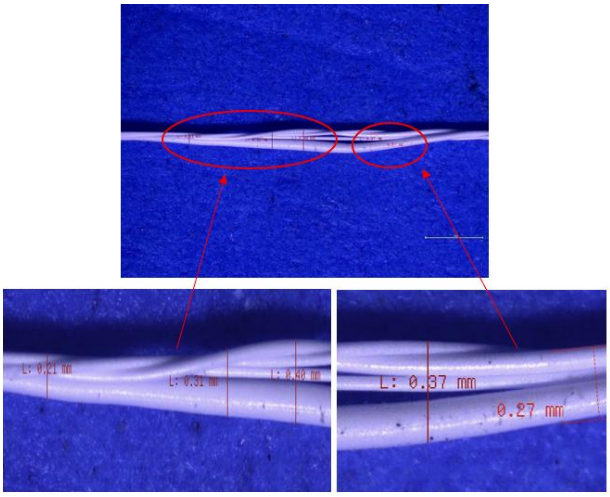

Figure 6: 4 Ply PCL thread Diameter 0.31 mm

From the macro photo results of the 2-ply, 3-ply, and 4-ply PCL yarns, the measured diameters were approximately 0.20 mm, 0.25 mm, and 0.31 mm, respectively. The images also show that the yarn diameter varies across the five measured points. This variation occurs because the spinning process was done manually using a simple hand-twisting method, which leads to uneven twisting and results in non-uniform yarn diameters.

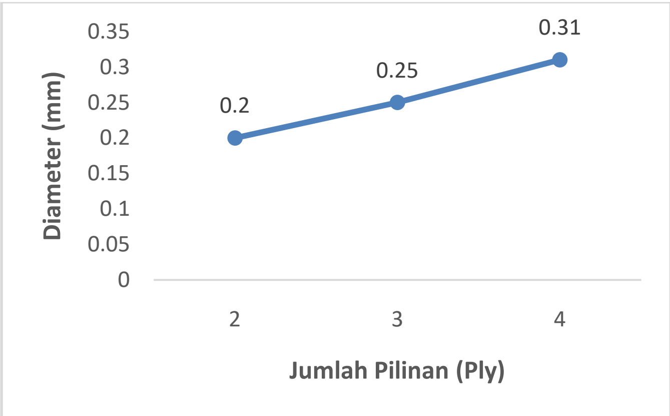

Figure 7: Graph of Change in Mass of Yarn

The graph shows the relationship between the number of plies and the resulting yarn diameter. As observed, an increase in the number of plies leads to a larger yarn diameter. This occurs because adding more plies combines more individual filaments into a single structure. During twisting, the filaments form a spiral arrangement and press against each other, but the pressure is not enough to fully compress the total material volume. As a result, multi-ply yarns naturally have a larger diameter due to the increased filament volume. The spiral structure also creates small gaps between fibers, expanding the radial dimension of the yarn. Since polycaprolactone (PCL) is a thermoplastic and elastic material, the fibers tend to recover their shape after twisting, further contributing to the diameter increase. Therefore, the higher the number of plies, the larger the yarn diameter becomes due to the combined effects of added material volume, spiral arrangement, and the elastic nature of the polymer.

3.3 Degradation Rate Test Results and Analysis

The degradation rate test was carried out to determine how quickly the produced PCL yarn breaks down over time. The yarn samples were immersed in a 0.9% NaCl solution for five consecutive weeks, with each cycle lasting seven days. After every immersion period, the samples were dried and weighed to measure the percentage of weight loss. The NaCl solution was chosen because it mimics the composition of human body fluids, allowing the test to simulate a relevant biological environment without causing chemical reactions with the polymer. This means the observed degradation comes purely from the natural hydrolysis of PCL. At the end of the test, the yarn samples were also observed using a macro microscope to identify any shrinkage or visible structural changes. The results provide an indication of how PCL yarn would behave in biomedical applications such as biodegradable sutures or implants.

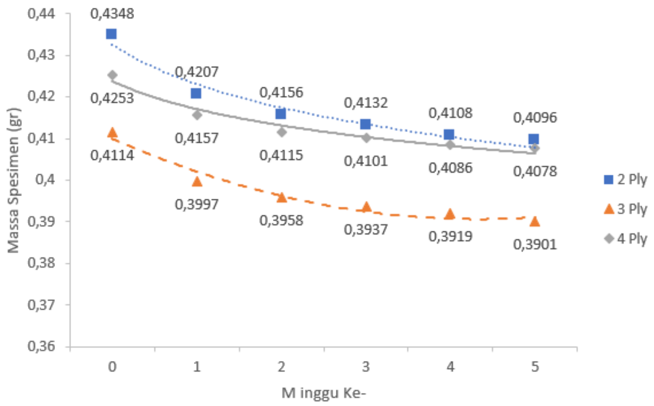

Figure 8: Week by Week Mass Loss Graph

The graph shows the change in mass of the 2-ply, 3-ply, and 4-ply PCL yarns during five weeks of immersion in a 0.9% NaCl solution. All samples experienced a gradual mass decrease, indicating ongoing polymer degradation. The highest mass loss occurred in the 2-ply yarn, which decreased from 0.4348 g to 0.4096 g (5.78%) by week five, followed by the 3-ply and 4-ply yarns, with mass losses of 5.18% and 4.12%. The largest decrease happened during the first two weeks due to rapid water penetration into the pores and gaps between filaments, causing softening and removal of unstable polymer fragments or residual solvent. As the outer layer degraded and the yarn structure became more compact, water penetration slowed, resulting in smaller and more stable mass reductions in the later weeks. Overall, yarns with more plies or larger diameters showed slower degradation because their

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denser structure limits water diffusion and has a lower surface-to-volume ratio, reducing the area exposed to the solution. This denser morphology restricts hydrolysis, leading to a slower and more controlled degradation rate in thicker or higher-ply PCL yarns.

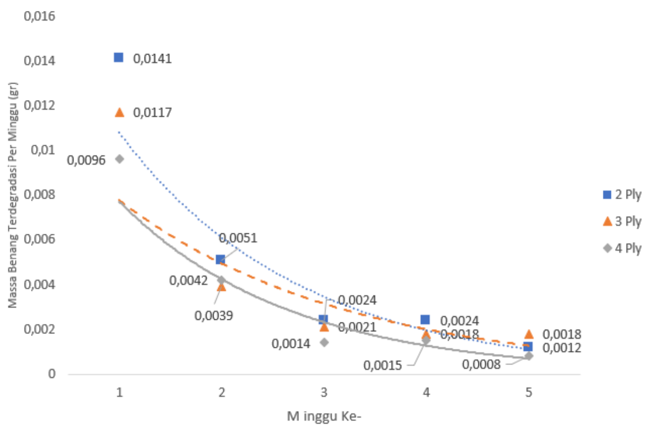

Figure 9: Week by Week Mass Loss Graph

The graph shows the weekly degraded mass of 2-ply, 3-ply, and 4-ply PCL yarns over five weeks of immersion in a 0.9% NaCl solution. All yarn types experienced the highest mass loss during the early weeks, followed by a gradual decrease in the later weeks, indicating a fast initial degradation phase that slowed over time. In the first week, the largest degradation occurred in the 2-ply yarn (0.0141 g), followed by 3-ply (0.0117 g) and 4-ply (0.0096 g). By the second and third weeks, the degraded mass continued to decline, and during weeks four and five the values became relatively small and stable. This pattern shows that yarns with more plies degrade more slowly because the denser and tighter structure of 4-ply fibers limits the penetration of the NaCl solution compared to the looser 2-ply structure. The high initial degradation reflects rapid surface dissolution, while the slower rates in later weeks indicate limited diffusion into the inner layers. Overall, the degradation rate decreases exponentially over time and is strongly influenced by yarn density and ply configuration.

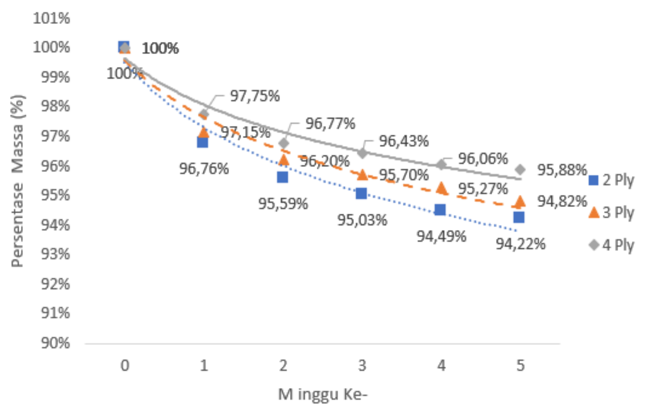

Figure 10: Percentage Mass Decrease Graph from Week to Week

The graph illustrates the percentage of mass loss of 2-ply, 3-ply, and 4-ply PCL yarns during five weeks of immersion in a 0.9% NaCl solution. All samples showed a consistent decrease in mass each week, confirming ongoing material degradation. After the first week, the remaining mass of the yarns dropped to 96.76% for 2-ply, 97.15% for 3-ply, and 97.75% for 4-ply, indicating that degradation occurred fastest in the 2-ply sample and slowest in the 4-ply sample. This trend continued until week five, where the remaining mass reached 94.22% for 2-ply, 94.82% for 3-ply, and 95.88% for 4-ply. The total mass loss was therefore highest for 2-ply (5.78%) and lowest for 4-ply (4.12%). These differences are caused by structural variations, as the looser and more porous structure of the 2-ply yarn allows easier penetration of the NaCl solution, accelerating degradation, while the denser structure of the 4-ply yarn restricts diffusion and slows the process. The gradually flattening curve after week two shows the reduced degradation rate as the easily degradable outer layers break down first, leaving the tighter inner structure to degrade more slowly. Overall, the number of plies significantly affects degradation behavior: fewer plies degrade faster, making them suitable for applications requiring rapid breakdown, while higher-ply yarns offer slower, more stable degradation for longer-lasting applications.

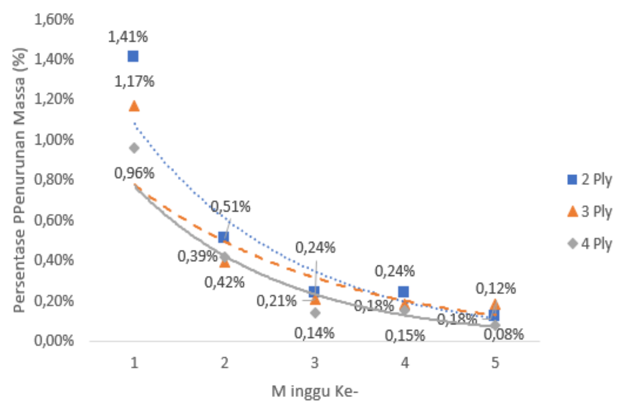

Figure 11: Graph of Percentage of Mass Lost Week by Week

The graph shows the weekly mass loss rate of PCL yarn specimens with different ply numbers. Overall, the degradation rate decreases over time, indicating that the process slows after the initial weeks. In the first week, the highest mass loss occurred in the 2-ply yarn (1.41%), followed by 3-ply (1.17%) and 4-ply (0.96%), showing that yarns with fewer plies degrade faster at the beginning. By the second week, the degradation rate dropped to 0.51% for 2-ply, 0.39% for 3-ply, and 0.42% for 4-ply, and continued to decrease until week five, reaching only 0.12%, 0.18%, and 0.08% respectively. This pattern indicates that yarns with more plies have a denser and tighter structure, which slows the penetration of the solution and reduces the degradation rate. Therefore, the number of plies significantly influences

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degradation behavior, with fewer-ply yarns degrading faster than yarns with higher ply counts.

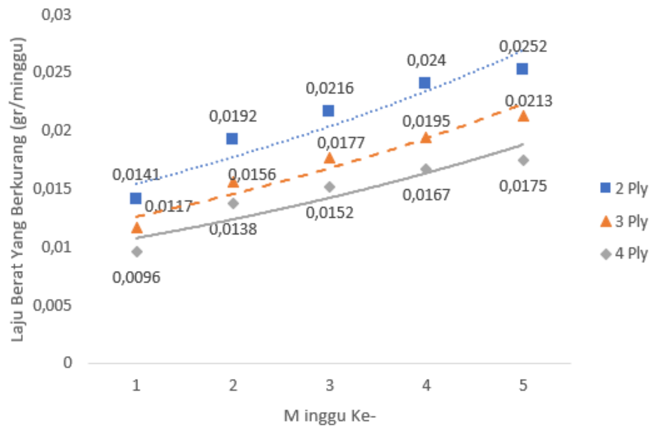

Figure 12: Week-by-Week Mass Loss Rate Graph

The graph shows the relationship between ply number and the weekly mass loss rate of PCL yarn during five weeks of immersion. Yarns with fewer plies experienced higher mass loss compared to yarns with more plies. In the first week, the mass loss rates were 0.0141 g/week for 2-ply, 0.0117 g/week for 3-ply, and 0.0096 g/week for 4-ply. By the fifth week, these values increased to 0.0252 g/week, 0.0213 g/week, and 0.0175 g/week, respectively. This trend shows that lower-ply yarns have a looser structure, allowing more solution penetration and faster degradation, while higher-ply yarns are denser and degrade more slowly. Overall, the number of plies has a significant effect on degradation, with fewer plies leading to higher mass loss rates.

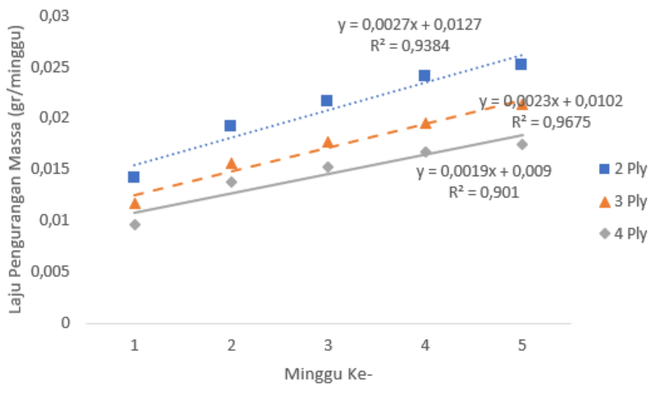

Figure 13: Linear Regression Analysis Graph on PCL Yarn

The linear regression analysis shows that the difference in slopes among the ply variations indicates a clear influence of yarn structure on degradation rate, where higher ply numbers lead to slower degradation. The 2-ply yarn has a regression equation of $y = 0.0027x + 0.0127$ with an R^2 of 0.9384, meaning that each additional week increases the degradation rate by about 0.0027 g/week and that the model explains over 93% of the data variation. This reflects the looser structure of 2-ply yarn, which allows water to diffuse more easily into the fibers. The 3-ply yarn shows a regression equation of $y = 0.0023x + 0.0102$ with $R^2 = 0.9675$, indicating a slightly slower but more stable degradation due to its denser structure. Meanwhile, the 4-ply yarn has the slowest degradation, with a regression equation of $y = 0.0019x + 0.0090$ and $R^2 = 0.901$, caused by its tighter and more compact structure that restricts water penetration. Overall, the results confirm that increasing the number of plies reduces the degradation rate of PCL yarn.

3.4 Density Test Results and Analysis

Based on the table 1and 2, the density of the PCL fibers measured using the Quantachrome Ultrapyc 1200e shows consistent results across three runs. The first test, with a volume of 6.7476 cc, produced a density of 0.1626 g/cc. The second test, with a volume of 6.6564 cc, resulted in a density of 0.1648 g/cc, and the third test, with a volume of 6.7319 cc, produced a density of 0.1630 g/cc. From these results, the average density of the PCL fiber is 0.1635 g/cc. Since all yarn variations were made from the same composition—2 grams of PCL dissolved in 10 mL of chloroform (20% concentration)—their densities are expected to remain similar.

Table 1: Analysis Results of PCL Yarn Density Testing

Analysis Results	
Weight	1,0972 g
Deviation Achieved	0,5518%
Average Volume	6,7120 cc
Volume Std. Dev	0,0398 cc
Average Density	0,1635 g/cc
Density Std. Dev	0,0010 g/cc
Coefficient of Variation	0,5930%

Table 2: Analysis Results of PCL Yarn Density Testing

Run Data		
Run	*Volume (cc)*	*Density (g/cc)*
1	6,7476	0,1626
2	6,6564	0,1648
3	6,7319	0,1630
Total		0,1635

3.5 Tensile Test Results and Analysis

The tensile test results show that the yarn with the largest diameter (0.31 mm) has the highest tensile strength at 6.87 N/mm², indicating a greater ability to withstand load before deforming or breaking. However, this yarn also has a lower elongation value of 119.24% compared to the smaller-diameter yarns. In contrast, the 0.25 mm and 0.20 mm yarns exhibit much higher elongation values of 136.85% and

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146.82%, showing that thinner yarns are more elastic and can stretch further before breaking, although they have lower tensile strengths of 4.55 N/mm² and 4.00 N/mm². This indicates a trade-off between strength and elasticity depending on yarn diameter.

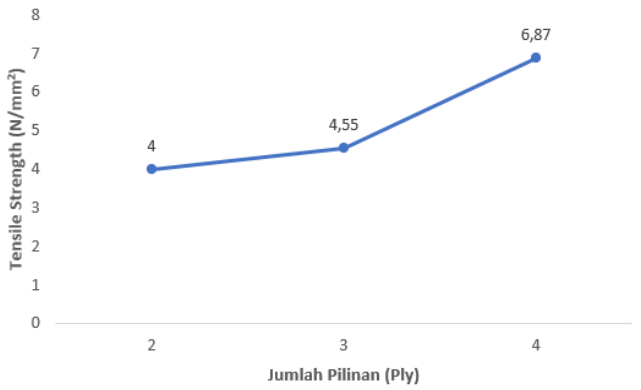

Figure 14: Graph of the Relationship between the Number of Twists of Yarn and the Tensile Strength of Yarn

The graph shows the relationship between the number of plies and the resulting tensile strength of the PCL yarn. As the ply increases from 2 to 4, the tensile strength rises noticeably, from 4 N/mm² for 2-ply to 4.55 N/mm² for 3-ply, and reaching the highest value of 6.87 N/mm² for 4-ply. This indicates that yarns with more plies can withstand greater tensile loads. Mechanically, this improvement occurs because twisting increases friction and bonding between fibers, allowing stress to be distributed more evenly throughout the yarn. As a result, the yarn becomes more compact and stronger under tension. Therefore, adding more plies plays an important role in enhancing the mechanical performance of the PCL yarn.

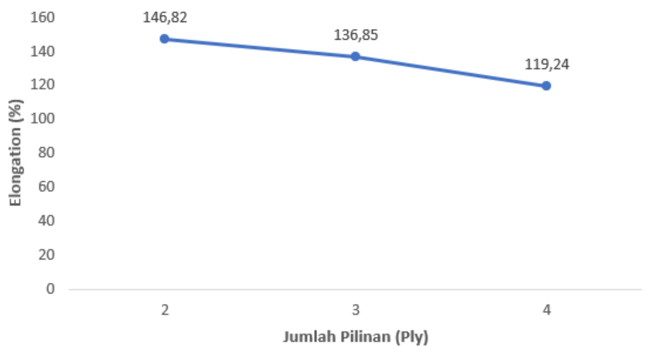

Figure 15: Graph of the Relationship of the Number of Yarn Twists with *Yarn Elongation*

The graph shows the relationship between the number of plies and the elongation of the PCL yarn. As the ply increases from 2 to 4, the elongation decreases gradually, from 146.82% for 2-ply to 136.85% for 3-ply, and reaching the lowest value of 119.24% for 4-ply. This indicates that yarns with more plies have a reduced ability to stretch before breaking. This behavior occurs because additional twisting makes the fibers more tightly packed and aligned, reducing the mobility between them. As a result, the yarn becomes stiffer and less elastic. Therefore, increasing the number of plies improves structural compactness but decreases the yarn's elasticity.

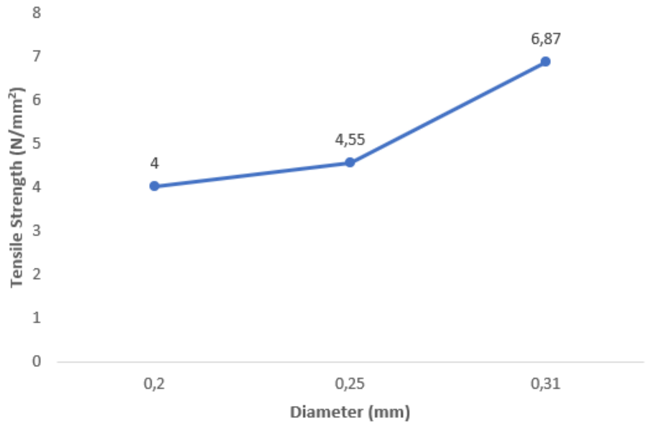

Figure 16: Graph of Thread Diameter Relationship with Thread Tensile Strength

The graph shows the relationship between yarn diameter and tensile strength. As the diameter increases from 0.20 mm to 0.31 mm, the tensile strength rises significantly. The 0.20 mm yarn has a tensile strength of 4 N/mm², which increases to 4.55 N/mm² at 0.25 mm and reaches the highest value of 6.87 N/mm² at 0.31 mm. This indicates that thicker yarns can withstand higher tensile loads. The increase in strength is likely due to a greater number of fibers and a denser structure at larger diameters, allowing stress to be distributed more evenly when the yarn is pulled. A larger diameter also enhances the interaction between filaments, creating a more compact and stronger structure. Therefore, yarns with larger diameters show better tensile performance.

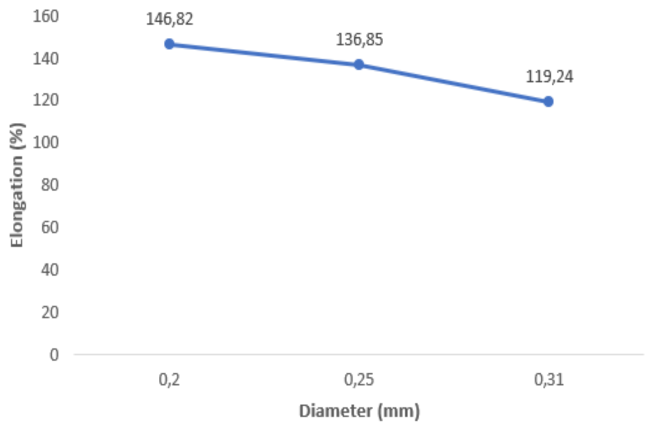

Figure 17: Graph of Thread Diameter Relationship with *Thread Elongation*

The graph shows the relationship between yarn diameter and elongation. As the diameter increases, the elongation decreases, with values dropping from 146.82% at 0.20 mm to

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136.85% at 0.25 mm, and reaching 119.24% at 0.31 mm. This indicates that larger-diameter yarns are less flexible and tend to be stiffer. The decrease in elongation occurs because a larger diameter contains more filaments and a denser structure, which limits the movement between fibers. This compact structure reduces the ability of the fibers to shift or stretch freely when subjected to tensile forces. Additionally, thicker yarns distribute stress more evenly, making plastic deformation harder to occur. Therefore, increasing the yarn diameter results in lower elongation due to higher structural compactness and stiffness.

IV. CONCLUSION

The number of plies in PCL yarn strongly affects both its mechanical properties and degradation behavior. As the ply count increases from 2 to 4, the tensile strength rises from 4.00 N/mm² to 6.87 N/mm², while elongation decreases from 146.82% to 119.24%, showing that more plies create a stronger but less elastic yarn. The degradation rate also decreases with more plies: 2-ply yarn loses 5.78% of its initial mass, 3-ply loses 5.18%, and 4-ply loses only 4.12%. This is because higher ply numbers produce a denser structure that limits solution penetration into the polymer matrix, resulting in slower degradation.

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