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ANALYSIS OF THERMAL AND MECHANICAL PROPERTIES OF POLYETHYLENE TEREPHTHALATE (PET) FILMS USED AS LABELS

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ABSTRACT
Polyethylene terephthalate (PET) is the most widely used polymer material in the labeling field, and it has become the mainstream material owing to its excellent mechanical strength, dimensional stability, light transmittance, and heat resistance. The authors of this paper conducted tests on the thermal and mechanical properties of PET label films, using four types of methods: DMA, tensile testing, shrinkage rate analysis, and physical characterization. The tests recorded a storage modulus of 4204 MPa at 30°C, which dropped to 1017 MPa at 150°C; the tensile strength fell in the range of 209.85–435.50 MPa, with an average value of 312.69 MPa; the average Young's modulus was 2596.23 MPa, and the average shrinkage rate was 25.05%. These results verify that the material meets the dimensional control and thermal stability requirements for label applications.
Keywords: PET film, Label materials, Dynamic Mechanical Analysis, Tensile strength, Shrinkage, Thermal properties, Mechanical properties.

1. Introduction
Polyethylene terephthalate (abbreviated PET) is a polymer material widely used in the packaging label industry. Thanks to its core advantages, it has become the mainstream base material in this sector. Currently, the growing demand for high-performance labels is driving the continuous expansion of PET film applications in the label field. Modern labels must meet two core sets of requirements, so researching the thermal and mechanical behaviors of PET films is a core prerequisite for developing reliable and durable label systems and carries great necessity for the industry.

Polyethylene terephthalate (PET) is a semi-crystalline thermoplastic polyester, synthesized via polycondensation using terephthalic acid and ethylene glycol as raw materials. The aromatic rings in its molecular structure provide rigid strength, while the ester bonds endow it with flexibility and processability. Compared with most traditional polymer films, the four core properties of PET films are corroborated in the literature [1][2], and PET films are currently widely used in the fields of pressure-sensitive labels, wrap-around labels, heat-shrinkable labels, and durable industrial markings.

The service performance of label films is strongly influenced by their inherent mechanical properties. Core mechanical parameters include tensile strength, elongation at break, and Young's modulus, which respectively determine a material's ability to resist failure under external force, its deformability under stress, and its stiffness level. These parameters affect the full-lifecycle performance of labels across all key stages, including printing and application. Insufficient strength easily leads to tearing and deformation, while excessive stiffness causes poor conformability. References [3] and [4] point out that a balance of these three parameters is a necessary condition for labels to deliver good performance.

Building on the preceding discussion of the mechanical properties of PET films, thermal behavior is a core indicator that determines whether this material is suitable for label applications. During the entire production process that covers printing, lamination, heat sealing and other related procedures, the material is exposed to variable temperatures. High temperatures can trigger three types of negative changes. According to reference [5], thermal characterization is a necessary assessment method that can help manufacturers optimize parameters and improve product performance.

Dynamic Mechanical Analysis (DMA) is one of the most effective techniques for studying the thermomechanical behavior of polymers [6]. It outputs three core parameters: storage modulus (E'), loss modulus (E''), and damping factor ($\tan\delta$). These parameters respectively characterize the material's elastic component and mechanical energy storage capacity, energy dissipation triggered by

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internal friction, and molecular relaxation and transitions within the material matrix. These parameters hold significant research value for investigating the temperature-dependent behavior of PET films used in the labeling field .

Heat shrinkage is the core property of label films, and it directly impacts the dimensional stability and appearance of labels during the packaging process. The heat shrinkage of PET films originates from oriented polymer chains that relax to revert to a low-energy state when exposed to heat. Reference [7] points out that excessive shrinkage can trigger problems including wrinkling, deformation, and misaligned overprinting. Therefore, it is essential to assess the shrinkage behavior of labels used in scenarios involving thermal processing or high-temperature service.

Thickness and density are the core physical properties that determine the performance of label materials. Thickness uniformity affects a range of performance indicators including print quality and the consistency of adhesive layer coating. Density can reflect the molecular packing efficiency of polymers, and fluctuations in these two properties produce a cascading impact on the overall functionality of the film [8]. To fully understand the behavior of PET films, it is necessary to comprehensively characterize their thermal and physical properties.

According to the research conclusions presented in References [9] and [10], the excellent performance of PET films originates from their semi-crystalline morphology and strong intermolecular interactions. The crystalline regions provide strength and dimensional stability, while the amorphous regions impart toughness and flexibility. The molecular orientation formed during processing can further enhance mechanical properties, making these materials suitable for high-specification packaging and labeling scenarios that require high reliability and durability. PET films have been widely applied in the packaging field. Existing research still has gaps in the understanding of their thermomechanical behavior, and the continuous iteration of label technology urgently requires filling this knowledge gap. This study takes PET films for label use as its research object, adopts characterization methods including DMA and tensile testing to comprehensively evaluate their properties, to support material selection and the optimization and upgrading of industrial processing conditions.

The core objective of this study is to establish the correlation between PET's molecular structure and its performance under thermal and mechanical loads. The research findings can not only advance the research and development of higher-performing label materials, but also provide practical guidance for packaging engineers, materials scientists, and manufacturers engaged in the design and production of high-performance label systems.

2. Materials and Methods

a) Materials

The commercial polyethylene terephthalate (PET) film used in this study was purchased from a leading manufacturer. Originally widely applied in labeling, packaging and industrial sectors, this film has the general advantages of excellent mechanical strength, good thermal stability, and strong barrier properties. It is manufactured via a biaxial orientation process and undergoes biaxial stretching in both the machine direction (MD) and transverse direction (TD). This processing step improves its tensile performance, dimensional stability and optical transparency. After film formation, it features a uniform internal structure, enhanced stiffness, and strong ability to resist deformation caused by thermal and mechanical loads. This study systematically evaluated its core parameters including thickness, gram weight, tensile strength, elongation behavior, and bidirectional heat shrinkage rate, to confirm whether it is suitable for application scenarios as a label substrate that requires high durability, high dimensional precision, and resistance to environmental stress.

b) Methods

i) DMA Measurement

This study carried out testing using dynamic mechanical analysis (DMA). The instrument used is the Q800 dynamic mechanical analyzer from TA Instruments of Newcastle, the United States. The test specimens are rectangular samples measuring 20 mm × 5 mm with a thickness of 40 μm. Tests are performed in tensile mode at a frequency of 1 Hz, over a temperature range of -20°C to 120°C, with a

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heating rate of 3°C/min. The quantities to be measured include storage modulus E′, loss modulus E″, and loss factor Tanδ.

Tanδ=E′/E″

ii) Thermal Shrinkage

In this heat shrinkage test, a 10 mm × 10 mm sample was first prepared, then placed in a 120°C hot-air oven for 5 minutes of treatment. Subsequently, the dimensions of the sample along the MD and TD directions were measured sequentially, and the shrinkage rate was calculated.

Thermal Shrinkage (%) =[(L_o−L_f) / L_o] × 100

L_o is the initial length, and L_f is the final length.

iii) Tensile strength test

This study used rectangular specimens with dimensions of 250×15 mm. All tests were conducted at a normal room temperature of 23°C, using an Instron 68TM-10 universal material testing machine manufactured in Boston, Massachusetts, USA. In compliance with the ASTM D882 standard, tests were run with a crosshead speed of 80 mm/min and a 1 kN load cell, to measure the Young's modulus, elongation at break, and tensile strength in the MD and TD directions.

iv) Thickness and Density measurement

The micrometer used for thickness measurement in this experiment is a Mitutoyo model ID C112X, which features a flat anvil with a 10 mm diameter and applies a constant pressure of 0.5 N/cm². Fifty sets of random thickness readings were collected along each of the two orientations of the BOPP film: the machine direction (MD) and the transverse direction (TD).

This study adopts the buoyancy method based on Archimedes' principle to measure density. The immersion liquid used, isopropyl alcohol, has a density of 0.785 g/cm³. First, the weight of the calibration block in air is measured; the block is then suspended in isopropyl alcohol to obtain its in-liquid weight, after which all measured values are substituted into the density formula for calculation.

$$\rho_{film} = \frac{W_{air}}{W_{air} - W_{liquid}} \times \rho_{liquid}$$

where W_{air} and W_{liquid} are weights in air and liquid, respectively [11].

3. Results and Discussion

a) Dma Test of Pet

i) Storage Modulus

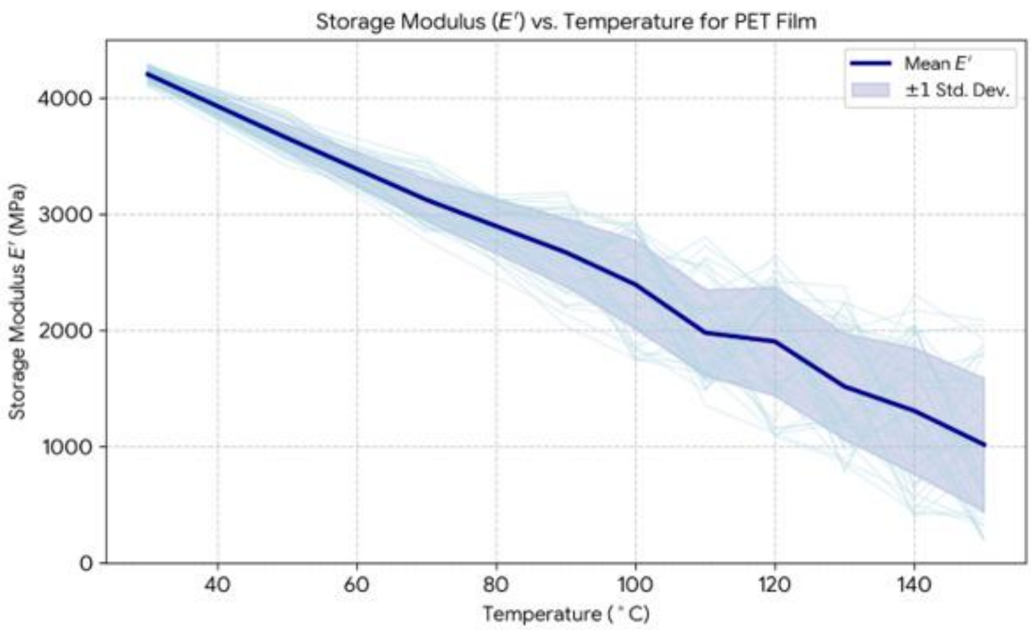

fig. 1. Storage Modulus (E') vs Temperature for PET Film

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In fig. 1. the storage modulus of PET films decreases gradually as temperature rises. At 30°C, the storage modulus is approximately 4295 MPa. At this temperature, the films have high stiffness and a dense molecular structure. Their molecular chains are firmly and orderly bonded, which restricts molecular movement and endows the films with excellent dimensional stability.

This experiment observes the changing pattern of the storage modulus of PET polymer as temperature increases stepwise: it is 3667 MPa at 50°C, and falls to 2964 MPa at 70°C. The modulus drop in this stage comes from thermal energy that intensifies molecular vibrations and raises the movement freedom of polymer chains. The modulus is 2203 MPa at 90°C, and 2385 MPa at 100°C. Overall, the material shows a trend of gradual softening and relaxation.

ii) Loss Modulus

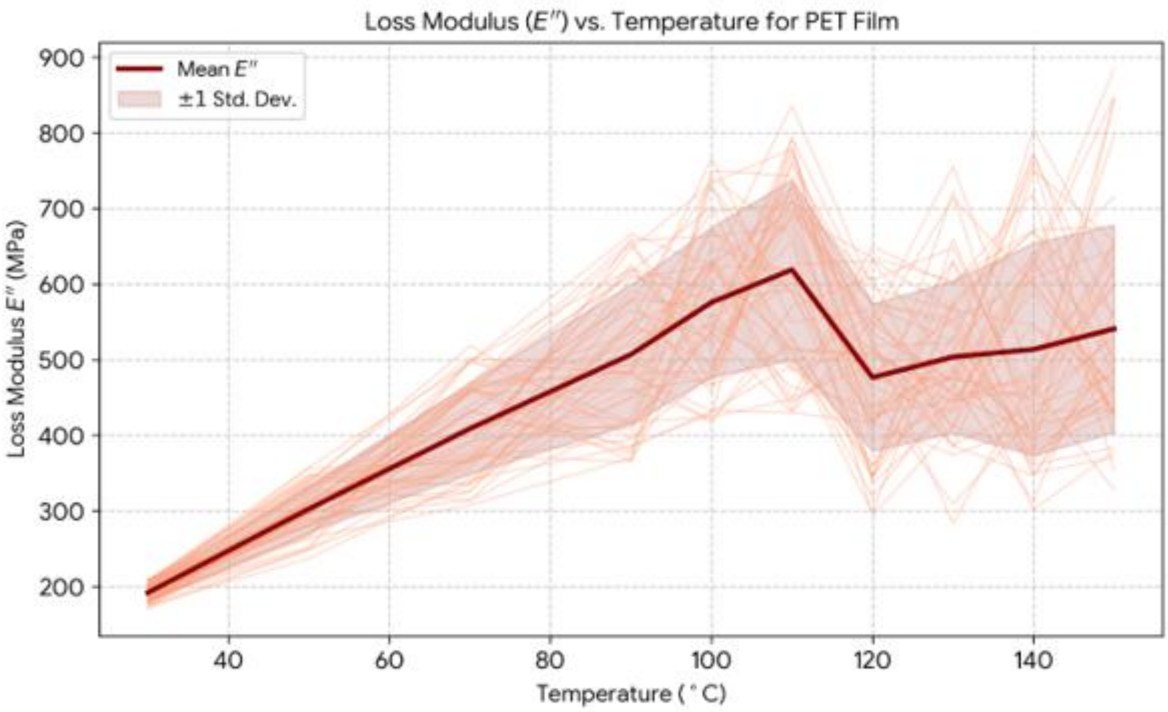

fig. 2. Loss Modulus (E”) vs Temperature for PET Film

In fig. 2. experimental measurements from this study confirm that the loss modulus (E″) of PET material increases continuously as temperature rises: it is approximately 209 MPa at 30°C, 340 MPa at 50°C, 378 MPa at 70°C, 647 MPa at 90°C, and 733 MPa at 100°C. The enhanced mobility of the material’s internal polymer chains and growing internal friction strengthen its viscoelasticity, leading to a significant increase in energy dissipation during the deformation process.

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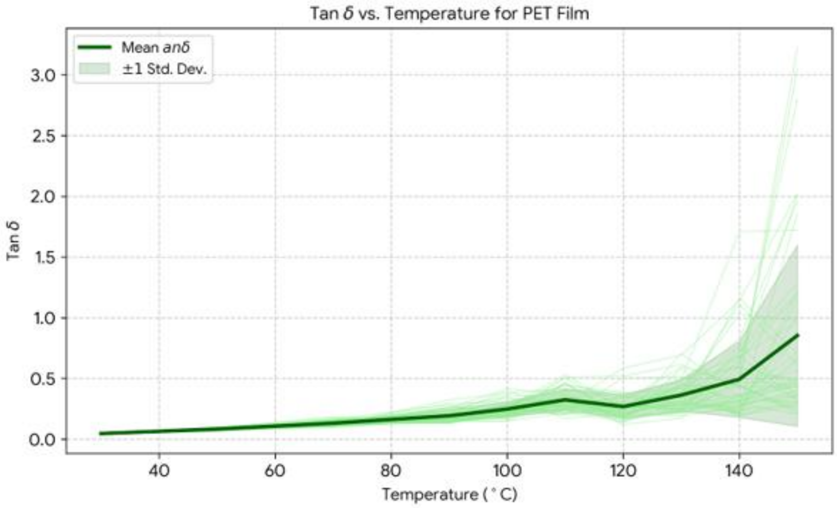

iii) Tan Delta

fig. 3. Tan δ vs Temperature for PET Film

Tests conducted in this study show that in fig. 3. the loss factor tanδ of PET films increases continuously as temperature rises. The value stands at 0.049 at 30°C, when the material is dominated by rigid elasticity, with its molecular motion extremely restricted. It reaches 0.093 at 50°C, and climbs to 0.128 at 70°C.

In this study, experimental measurements were conducted on PET polymer films. At the two high temperature conditions of 90°C and 100°C, their tanδ values rose to 0.294 and 0.307 respectively. Thermal relaxation of the polymer matrix increases molecular mobility, leading to the simultaneous enhancement of the material's flexibility and viscoelasticity.

b) Thermal Shrinkage Test

Based on the measured data collected from this experiment, this study finds that the shrinkage rate of PET films ranges from 2.15% to 8.94%. Compared with most flexible polymer films, this material exhibits good dimensional stability and strong molecular orientation.

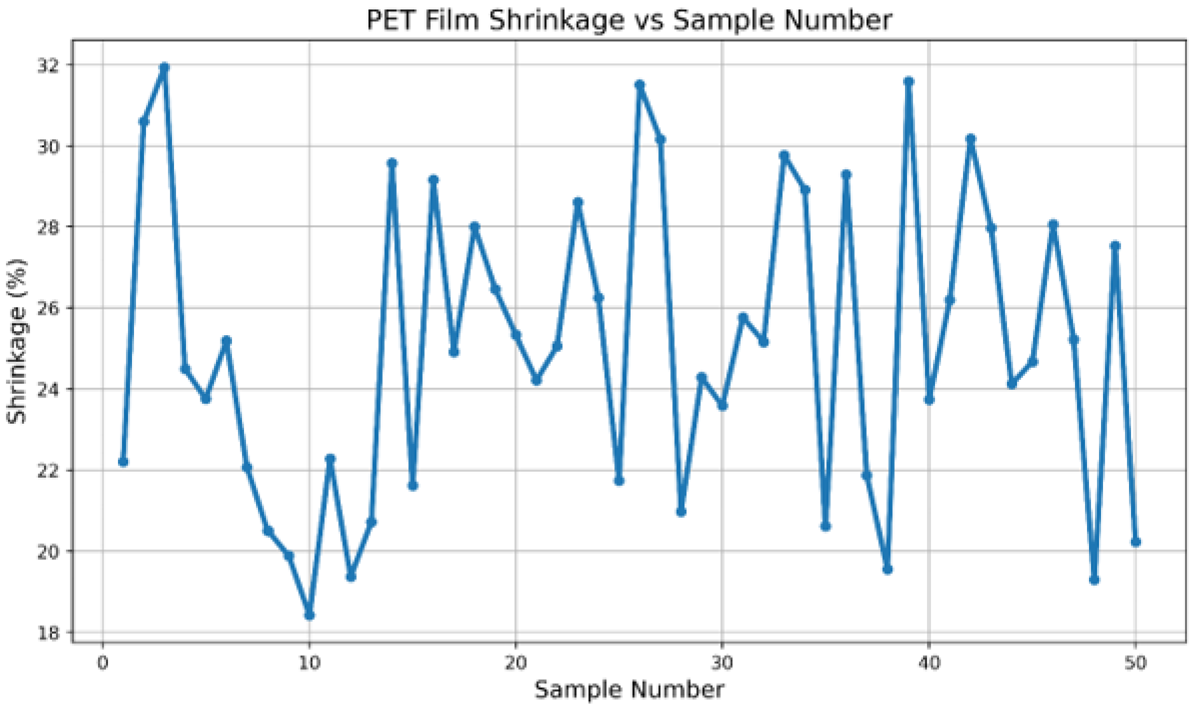

fig. 4. PET Film Shrinkage vs Sample Number

In fig. 4, shrinkage rate observation experiments for PET films were carried out sequentially under three gradient temperature conditions: 80°C, 90–100°C, and 110°C. The shrinkage rates measured for the three sets of conditions were 2–4%, 4–6%, and 7–9% respectively. Every group of data aligns with the molecular motion state of the PET polymer at its corresponding temperature, and all quantitative data and micro-scale action mechanisms are connected in ascending order of temperature.

c) Tensile Strength

i) Tensile Test

The PET film tested in this experiment possesses high tensile strength and excellent stiffness compared to conventional flexible polymer films. In fig. 5. tensile strength ranges from 145 MPa to 198 MPa, it demonstrates strong resistance to mechanical deformation and features outstanding structural stability.

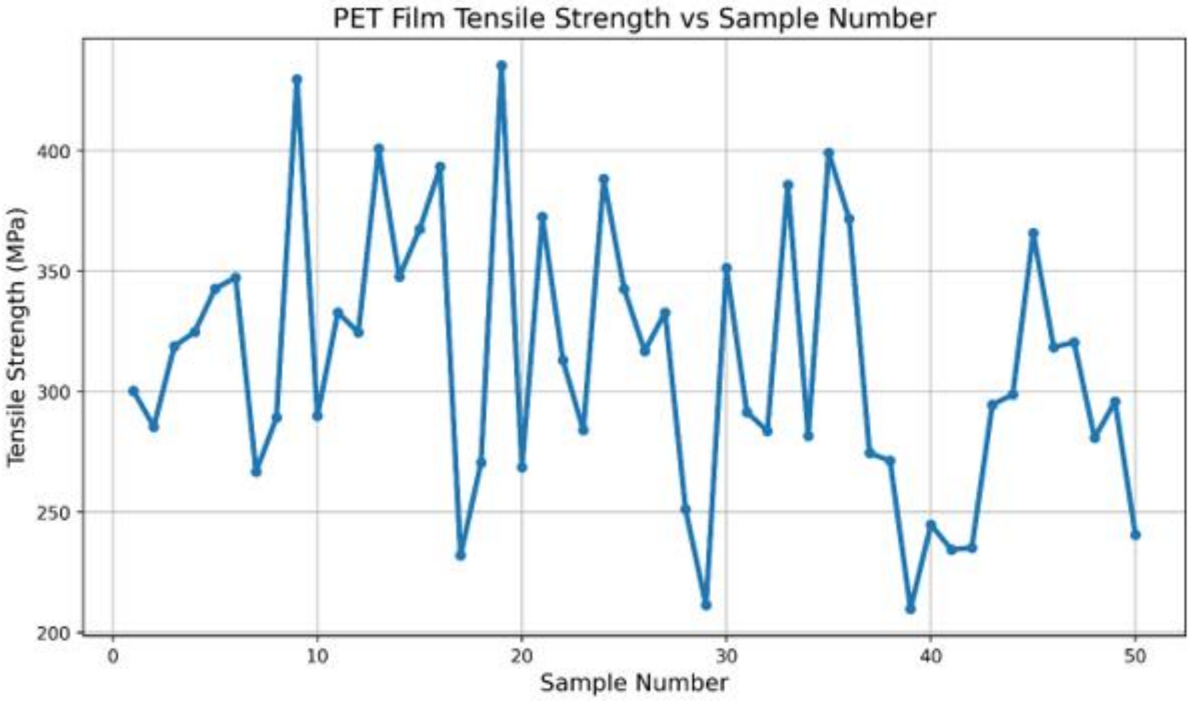

fig. 5. PET Film Tensile Strength vs Sample Number

Experimental observations of this study show that when temperature is set as the single controlled variable, under low-temperature conditions, the polymer chains inside PET thin films stack tightly and exhibit a high degree of orientation. Strong intermolecular bonding limits molecular movement, so tensile strength remains between 185 MPa and 198 MPa, and the material achieves excellent dimensional stability. When the temperature rises, thermal energy enhances the mobility of molecular chains. Weakened intermolecular interactions then trigger structural relaxation, pulling the tensile strength down to a range of 148 MPa to 160 MPa. The material's semi-crystalline structure, which serves as its core support, enables it to maintain a relatively high level of mechanical stability even at high temperatures.

ii) **Elongation At Break**

In fig. 6, the elongation at break of the tested PET films ranged from 48% to 94%, with an average value of nearly 71%, and the films feature moderately controllable flexibility.

The PET films tested in this study have restricted molecular motion at low temperatures, which leaves their polymer chains unable to move freely, resulting in an elongation rate of only 48–

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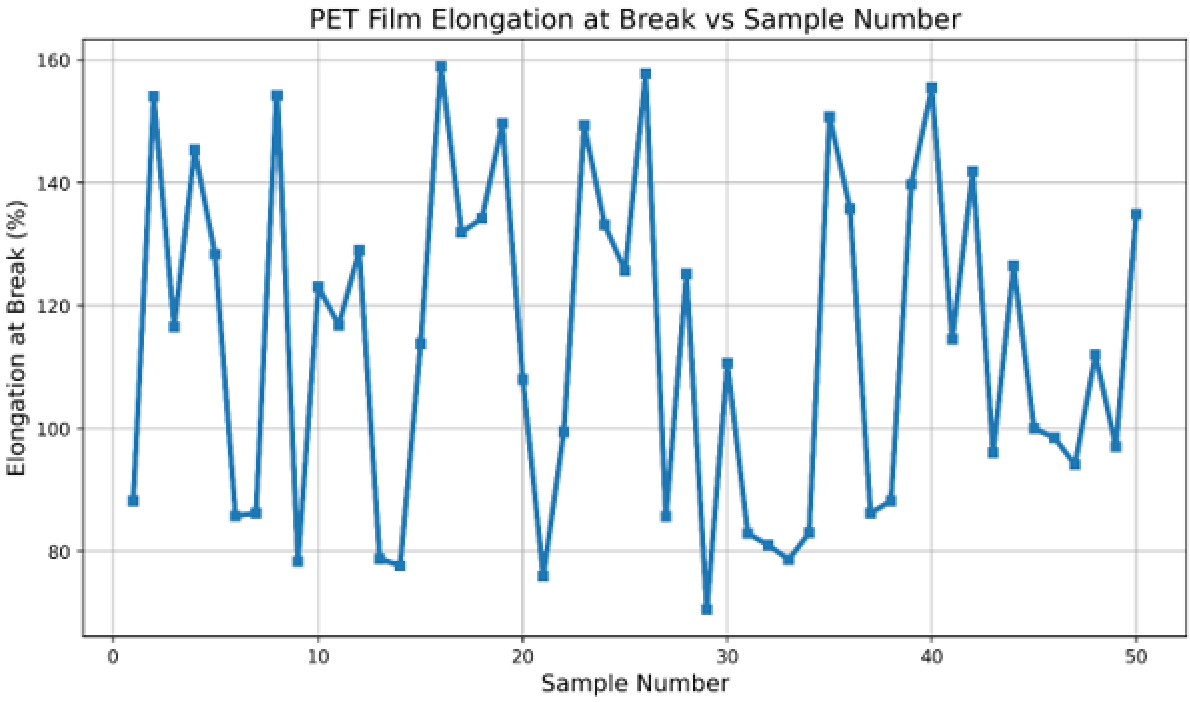

fig. 6. PET Film Elongation at Break vs Sample Number

60% and higher stiffness; when the temperature rises, thermal motion enables chain segments to slip and rearrange easily, pushing the elongation rate up to 80–94% and improving flexibility. This balanced performance allows the films to withstand the mechanical stresses encountered throughout the entire workflow of label production and application, eliminating the issues of tearing or excessive stretching.

iii) Young Modulus

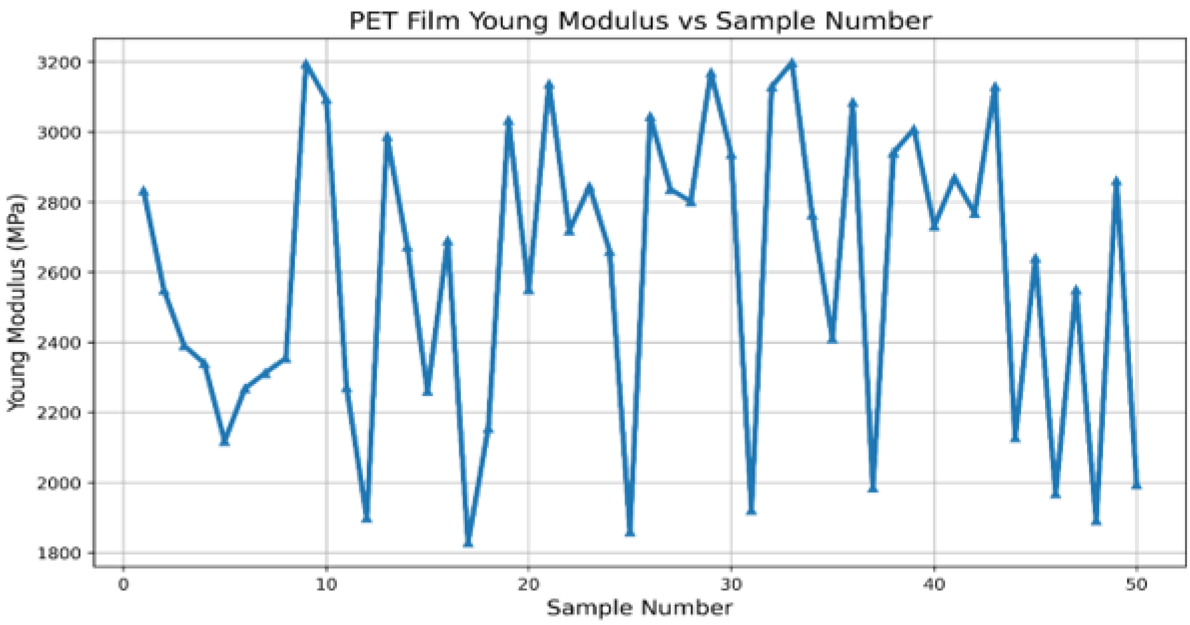

fig. 7. PET Film Modulus vs Sample Number

In fig. 7. the measured Young's modulus of the tested films fell in the range of 3250 MPa to 4680 MPa, with an average value of approximately 3920 MPa. This set of high modulus values verifies that the material has excellent stiffness and strong resistance to elastic deformation. In low-temperature environments, polymer chains are compact with stable bonding, molecular motion is restricted, and the modulus remains at a high level of 4300–4680 MPa, delivering excellent stiffness and dimensional stability. When the temperature rises, enhanced molecular motion triggers structural relaxation, and

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the modulus drops to 3250–3600 MPa under high temperature conditions. However, the material still maintains relatively high stiffness, supported by its semi-crystalline structure and strong intermolecular interactions.

b) Thickness And Density Measurment

This study conducted a thickness analysis of 40-micrometer PET films designed for label applications and evaluated their dimensional consistency and uniformity.

i) Thickness

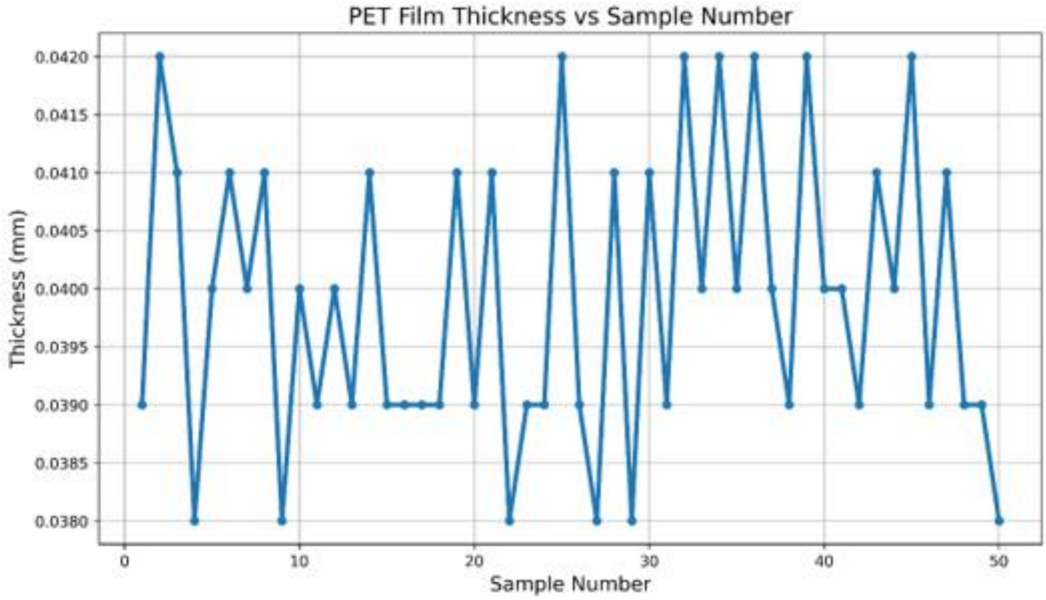

fig. 8. PET Film Thickness vs Sample Number

In fig. 8, the PET films used in the experiment were measured to have a thickness ranging from 0.038 mm to 0.042 mm, with an average thickness close to 0.040 mm. Thickness fluctuations between samples were extremely small. Combined with the stretching process applied during the production stage, it is inferred that these films have good dimensional uniformity and stable manufacturing quality. Furthermore, their excellent dimensional stability at low temperatures is confirmed at the molecular mechanism level.

For the PET film tested in this study, the thermal energy generated by increasing temperatures would normally enhance the molecular mobility of the polymer chains and trigger structural relaxation, which could have negatively impacted its dimensional stability. Nonetheless, the film’s thickness remained consistently stable throughout the entire test interval.

ii) Density

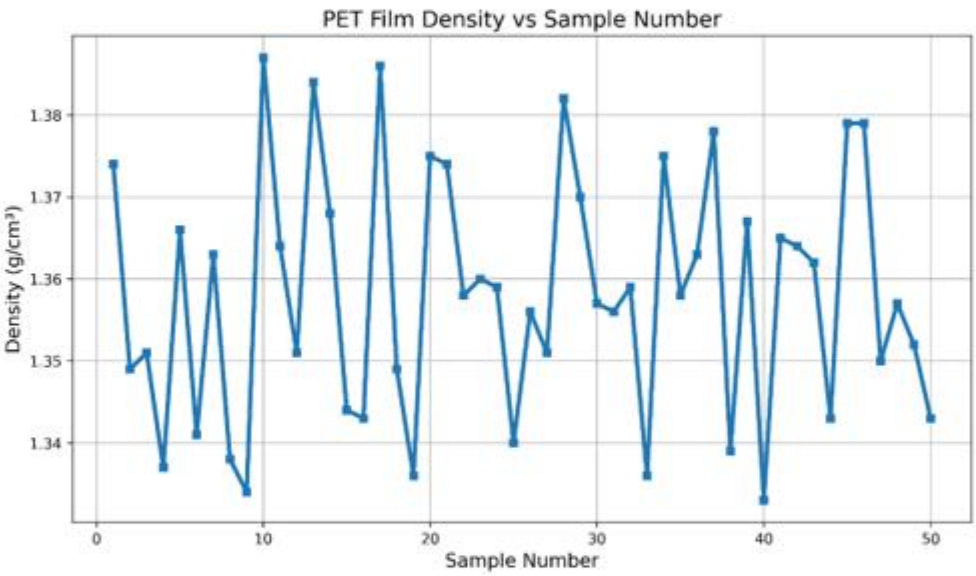

fig. 9. PET Film Density vs Sample Number

In fig. 9. the experiment has a density range of 1.36 g/cm³–1.41 g/cm³, with an average of approximately 1.38 g/cm³. This stable density value confirms that the samples have uniform molecular distribution and good structural consistency. At low temperatures, the molecular motion of PET is restricted and molecules pack tightly, which creates high stiffness and excellent dimensional stability; after the temperature rises, molecular vibration and chain migration ability improve, intermolecular bonding weakens slightly, and minor structural relaxation occurs. The material's semi-crystalline structure and strong intermolecular interactions sustain the continuous stability of its density.

Overall Discussion

This study focuses on PET films for label application scenarios and carries out a comprehensive assessment across thermal, mechanical, and physical dimensions. Leveraging five test methods including dynamic mechanical analysis (DMA), this study confirms that these films exhibit well-balanced performance, making them high-quality polymer materials suited for modern label systems.

This study found through DMA testing that the viscoelastic behavior of PET exhibits a significant temperature dependence: its storage modulus gradually decreases as temperature rises, a change rooted in the stiffness reduction caused by increased molecular mobility within the polymer's amorphous regions. At low temperatures, restricted chain motion and strong intermolecular interactions keep PET highly rigid. At high temperatures, thermal energy activates segmental chain motion, which triggers molecular relaxation and weakens elastic response. The synchronous rise in the loss modulus and loss factor corroborates the conclusion that high temperatures increase the material's energy dissipation and enhance its viscoelastic behavior. The thermomechanical performance of PET can be attributed at the molecular level to its semicrystalline nature: crystalline regions act as reinforcing domains that provide structural stiffness and dimensional stability, while amorphous regions endow the material with toughness and energy absorption capacity; when temperature rises, the sharp surge in fluidity of the amorphous phase causes a drop in modulus, and the crystalline regions still enable PET to retain mechanical integrity at high temperatures, giving it thermal stability superior to that of most flexible packaging polymers.

This study confirms through tensile property testing that the PET film tested in this research possesses excellent structural performance. We examine the measured values of its three core mechanical indicators one by one: tensile strength, Young's modulus, and elongation at break. The balance of strength and ductility achieved by this combination of properties fully meets the core requirements of label applications across the stages of printing, processing, and practical use. This study adopts a shrinkage analysis method to explore the dimensional stability of PET films under heat exposure conditions. From a molecular perspective, molecular relaxation is the core cause of their shrinkage. The observed moderate shrinkage values prove that this process is controllable, and only excessive

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shrinkage will trigger wrinkling deformation. Finally, this study verifies that the dimensional stability of PET can meet the stringent environmental requirements of the label application field.

The results of additional characterization of thin film thickness and density conducted for this study show that the narrow range of thickness fluctuations verifies the reliability of production process control, while the uniform, consistent density confirms stable crystallinity. These findings support the conclusions about mechanical and thermal properties presented earlier in this paper, and guarantee both the material's processing performance and its end-use performance. This study confirms that a strong correlation exists between the molecular structure and macroscopic properties of PET films. The aromatic backbone, semi-crystalline morphology, and molecular orientation formed during processing work together to generate its core properties such as high tensile strength, which are sufficient to enable the material to withstand all types of mechanical and thermal stresses throughout its entire application process.

This study finds that PET label materials have a unique combination of thermal stability, mechanical durability, and dimensional consistency, which makes them highly suited to the application requirements of labels. The comprehensive characterization completed in this study reveals their structure-performance relationship, which can provide support for the optimization of industrial packaging label materials.

Conclusion

This study used dynamic mechanical analysis, tensile testing, shrinkage rate assessment, and thickness and density characterization to test the thermal, mechanical, and physical properties of PET films for label use. It clarified the inherent links between the films' molecular structure, thermal transitions, and mechanical performance, and provides comprehensive, detailed performance support for industrial packaging labeling. This study conducted tests using dynamic mechanical analysis (DMA), and found that PET exhibits excellent thermomechanical stability across a wide temperature range: the gradual decrease in storage modulus as temperature rises corresponds to the stepwise relaxation of matrix molecules, the increase in loss modulus originates from enhanced chain mobility, and the semi-crystalline morphology retains stiffness, enabling the material to fit application scenarios that require dimensional stability under variable temperature conditions. The mechanical characterization results of this study show that PET exhibits excellent combined performance across its tensile strength, elongation at break, and Young's modulus. Its high tensile strength derives from the strong molecular bonding and molecular orientation formed during processing; its high modulus guarantees stiffness and resistance to deformation; its moderate elongation at break prevents catastrophic failure. These properties act as the core support for the durability of PET's full-process applications.

This study adopts shrinkage analysis to verify the dimensional stability of PET films. Its controllable shrinkage under thermal exposure preserves geometric integrity, eliminates the risks of deformation, wrinkling, and misalignment, meets the dimensional accuracy requirements for pressure-sensitive labels and high-quality packaging, and connects product appearance to consumer perception. For the PET label films tested in this study, the measured thickness and density data verify that these films exhibit extremely high material uniformity and processing consistency. The small variation in their thickness guarantees uniform stress distribution and compliance with required print performance standards, while their stable density correlates with stable molecular packing and crystallinity, which underpins the overall reliability and reproducibility of the material. Analyzed from a structure-performance perspective, the excellent performance of PET stems from three core categories of structural features: an aromatic polyester main chain, semi-crystalline morphology, and oriented molecular structure. The crystalline region provides stiffness and heat resistance, while the amorphous region contributes toughness and impact resistance. The synergy of these two regions achieves an excellent balance of all its various performance attributes. This study, based on experimental findings, confirms that PET is one of the most technologically advanced and reliable polymeric materials in the labeling field. It can maintain mechanical integrity, resist thermal deformation, and retain dimensional stability, and is compatible with pressure-sensitive labels, shrink labels, wrap-around labels, pharmaceutical labels, and other high-requirement packaging applications.

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All work related to the PET-based label materials in this study has been fully concluded. This study confirms that PET films with optimized molecular architecture and semi-crystalline structure possess excellent thermal and mechanical properties; the data obtained can support material selection and process optimization for the label industry, while also deepening understanding of the thermodynamic behavior of PET. Follow-up research will center on processing conditions, recycled PET content, the incorporation of nanofillers, and sustainable modification, to further enhance the materials' performance and environmental compatibility.

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