

Development of Peach Gum Green Adhesive

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Abstract. A sodium hydroxide solution of peach gum with a pH of 13 was prepared and different quantities of borax and p-nitrophenol were added to achieve mass fractions of 0.025 wt%, 0.05 wt%, 0.075 wt%, 0.1 wt%, 0.125 wt%, 0.15 wt%, 0.175 wt%, 0.5 wt%, 1 wt%, 1.5 wt%, 2 wt%, 2.5 wt%, 3 wt%, and 3.5 wt%. Then, the solutions were subjected to heating and oscillation treatments, and each sample was observed under a microscope (200×). Photographs were taken to record the forms of the samples. The viscosity of the samples was determined over time and at different frequencies using an advanced rheological expansion system. The results were recorded, analyzed, and mapped to evaluate the viscosity and feasibility of the products for adhesive production. The results showed that the products exhibited a certain level of stickiness. Because they are economic and environmentally friendly materials, green adhesives have a promising future.

Peach gum (also known as peach tree gum) is a translucent gelatinous substance secreted by the trunks of Rosaceae plants such as peaches, wild peaches, and almonds after being mechanically damaged (such as insect bites, cuts, etc.) or infected with diseases (Yin and Shen 2006). The solid substance formed by air-drying on the tree trunk or using other dehydration methods is called raw peach gum. It is a semi-transparent solid block with a peach-red or light yellow to yellow-brown color and a smooth outer surface. Generally, it can only swell and does not easily dissolve. Peach gum is a viscous aqueous solution and a polysaccharide (Qi et al. 2009; Wang and Huang 2005). Relevant studies have confirmed that the main components of peach gum are polysaccharides and proteins; however, the contents of its other substances are extremely low. Its polysaccharides are composed of components such as galactose, rhamnose, and glucuronic acid (Huang 2015; Qian et al. 2011). Currently, there are few available reports of the properties

of peach gum. Traditional Chinese medicine books have reported the relevant properties of raw peach gum for medicinal use (Jiangsu New Medical College 1977), but there are no reports of its systematic physical and chemical properties. Most studies have reported the properties of commercial peach gum and focused on its solubility and solution rheological properties; however, its viscosity varies greatly depending on the manufacturer, acidity, and temperature (Huang 2015).

Peach gum has been used in fields such as food and medicine, and it is often used as a substitute for gum arabic. The thickening, emulsifying, and coagulating properties of peach gum can be used to produce candies, jelly-like foods, edible food preservative films, and beverages. Peach gum has good solubility, and some researchers have used it in microencapsulated foods (Liu and Xu 1998). Domestic research of peach gum includes the pharmacognostic identification of peach gum (Guo and Liu 1998), the harvesting and processing methods of peach gum, the extraction process of peach gum (He and Li 2001), and the properties of peach gum (Qian 2018). Nevertheless, current studies of the properties of peach gum only focused on the effects of the concentration, pH, and temperature on viscosity, and the sample concentrations were less than 10%. Therefore, we conducted a more in-depth study of the properties of peach gum and its mechanics. Different masses of boric acid and p-nitrophenol were added and the rheological property of the viscosity of its polymer at different times and frequencies were studied, thus providing a theoretical basis for peach gum to be used as a natural and green adhesive.

Novelty comparison between peach gum adhesives and other biopolymer adhesives

To accurately highlight the innovative value of peach gum in the field of natural adhesives, a comparison of peach gum (Fang et al. 2025;

Qian 2018; Wang et al. 2023) and three types of mainstream natural biopolymer adhesives, namely, gum arabic (Guo 2014; Zhang et al. 2009), guar gum (Hu and Zhai 2002; Sun et al. 2024), and karaya gum (Geng et al. 2015; Zhao et al. 2021), was conducted to evaluate the following four core dimensions: raw material sustainability, processing convenience, environmental adaptability, and industrial application compatibility (Table 1).

The results showed that the core advantage of peach gum is its high-efficiency conversion of agricultural and forestry by-products. It effectively addresses the pain points of existing natural adhesives, such as reliance on imported raw materials/specialized cultivation, high processing energy consumption, and weak industrial linkage. These findings indicate the potential for large-scale application of green adhesives because they combine economy and environmental friendliness.

Rationale for the selection of pH values and peach gum concentrations in the experiment

We adopted the 4% peach gum solution with a pH of 13 in this study based on the considerations of previous research and the practical application requirements of adhesives.

Basis for concentration selection. The optimal purification process of peach gum polysaccharides has been previously reported (Wang et al. 2010). A 4% peach gum concentration achieves the highest polysaccharide yield (54.89%) while preserving the cross-linking activity of polysaccharides. Specifically, when the concentration is lower than 4%, the spacing between polysaccharide molecules is too large, making it difficult to form the continuous network structure required for adhesives. Conversely, when the concentration exceeds 4%, the solution tends to agglomerate and form lumps, resulting in decreased dissolution uniformity and, in turn, poor viscosity stability.

Basis for pH value selection. The main chain of peach gum polysaccharides contains a large number of hydroxyl groups and carboxyl groups. From the perspective of crystal properties, studies (Wang et al. 2010) have shown that within the pH range of 11 to 13, peach gum undergoes a transformation from an amorphous structure to a crystalline structure, and the crystal structure is closely related to that of polysaccharides. This indicates that within this alkaline range, the internal structure of peach gum undergoes changes that are conducive to enhancing its performance.

The crystallinity of almond gum (a type of peach gum) hydrolysates under different pH conditions was determined using a RINT2000 vertical goniometer. It was found that as the pH value increased from 7, the crystallinity of almond gum showed an increasing trend of alkalinity, which is more favorable for the formation of a stable structure.

Comprehensive research findings of crystal properties, texture properties, solubility properties, and other aspects have indicated that an alkaline environment with a pH of 13 can result

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Table 1. Comparison of characteristics of peach gum and mainstream natural biopolymer adhesives.

Comparison dimension	Peach gum	Arabic gum	Guar gum	Karaya gum
Raw material sustainability	Secretion from the trunks of almond/peach trees with stable yield	Relies on imports and is greatly affected by the international supply chain	Requires specialized cultivation, competes with food crops for land, and relies on imports	Limited yield; collection is highly difficulty
Processing convenience	The processing technology is simple, and a stable colloid can be formed in a short time at a concentration of 4%	The processing technology is complex, with a long processing cycle; easy to stratify at low concentrations	The processing technology is complex, with high processing energy consumption; dissolution requires high-temperature stirring	Full swelling is difficult; multiple filtrations are needed to remove impurities
Environmental adaptability	Stable under alkaline conditions and can inhibit microbial growth	Performs stably under neutral conditions and is prone to degradation in alkaline environments	Poor acid resistance and weak salt resistance; prone to flocculation in the presence of electrolytes	Easy to decompose at high temperatures and solidify at low temperatures
Industrial application compatibility	Suitable for wood and paper substrates; similar to commercially available formaldehyde-free adhesives	Mainly used in the food and cosmetics fields; has low bonding strength	Mostly used in the textile and petroleum fields; poor wettability with wood substrates	Only used in traditional coatings and drug coating applications

in electrostatic repulsion between peach gum polysaccharide molecules and their water solubility, thus laying a solid foundation for the application of peach gum in the field of adhesives.

Compatibility with practical applications. Natural adhesives commonly used in fields such as woodworking and packaging (e.g., starch adhesives, soybean adhesives) are mostly weakly alkaline systems (pH = 8–14). The alkaline environment can inhibit microbial growth, extend the shelf-life of adhesives, and improve the wettability of wood substrates. The selection of a pH of 13 in this study is consistent with the industrial application scenarios of this type of adhesive.

Rheological properties of peach gum. Rheological properties are important physical and chemical properties of peach gum. The viscosity coefficient, rheological index, and flow energy are important parameters of rheological properties. The rheological properties of fluids vary with composition, temperature, shear rate,

time, and initial shear conditions. Peach gum is a fluid that does not follow Newton's law of viscosity and has non-Newtonian fluids, and its viscosity coefficient changes with time and frequency. The rheological properties of peach gum were measured using the 2-2000g-cm Advanced Rheological Expansion System (ARES; TA Instruments, New Castle, DE, USA) instrument to study its rheological characteristics. By analyzing the rheological properties of peach gum, the viscosity characteristics of its polymer were gradually understood, providing a theoretical basis for scientific research and real-life applications. At the same time, it also laid a foundation for adhesive development, food processing, food product development, and sensory evaluation to provide a theoretical basis for peach gum to be used as a natural, green adhesive.

Materials and Methods

Experimental materials. The experimental materials were peach gum (collected from the

Italian No. 1 almond tree in Jiangshan Horticultural Farm, Luoyang, Henan) collected in Sep 2024, boric acid, p-nitrophenol, sodium hydroxide buffer solution, and distilled water.

Experimental instruments. The experimental instruments were the DKZ-2 Electric Thermostatic Oscillating Water Bath (Shanghai Jinghong Experimental Equipment Co., Ltd., Shanghai, China), ARES (2-2000g-cm ARES; TA Instruments); Model 80i Microscopic Image System (Nikon Corporation, Tokyo, Japan), SPX-250B-Z Biochemical Incubator (Boxun Industry Co., Ltd., Shanghai, China), and AR1140/C Analytical Balance (Ohaus, Parsippany, NJ, USA).

Experimental methods

Sample processing. The collected peach gum was soaked and impurities were removed. Then, it was rinsed, freeze-dried, and sieved after crushing. The peach gum with a mass fraction of 4 wt% was treated with a buffer

Table 2. Different mass fractions of the peach gum, boric acid, and sodium hydroxide buffer gel viscosity over time, and comparison of the relationships between frequencies.

No.	Content (wt%)	Equation for the relationship between time and viscosity (R^2)	Equation for the relationship between frequency and viscosity (R^2)	Viscosity under the conditions of $T = 215$ s and $f = 100$ Hz
1	0.025	$y = 26.225e^{0.0114x}$ (0.9809)	$y = 30.063x^{0.4757}$ (0.9831)	275.662 ± 10.32
2	0.050	$y = 15.385e^{0.0124x}$ (0.9815)	$y = 17.62x^{0.5169}$ (0.9877)	204.585 ± 9.17
3	0.075	$y = 14.536e^{0.0126x}$ (0.9865)	$y = 16.322x^{0.5249}$ (0.9923)	189.592 ± 7.84
4	0.100	$y = 5.5605e^{0.0142x}$ (0.9861)	$y = 6.5537x^{0.5753}$ (0.9881)	94.5844 ± 5.62
5	0.125	$y = 9.0924e^{0.0126x}$ (0.9867)	$y = 10.266x^{0.5344}$ (0.9925)	124.120 ± 6.38
6	0.150	$y = 11.722e^{0.0122x}$ (0.9897)	$y = 13.227x^{0.5011}$ (0.9932)	138.190 ± 7.15
7	0.175	$y = 9.522e^{0.0137x}$ (0.991)	$y = 11.202x^{0.542}$ (0.9938)	145.303 ± 8.01
8	Control group	$y = 10.368e^{0.013x}$ (0.9844)	$y = 12.263x^{0.5375}$ (0.9855)	152.786 ± 8.25

Table 3. Different mass fractions of the peach gum, p-nitrophenol, sodium hydroxide buffer gel viscosity with time and comparison of the relationships between frequencies.

No.	Content (wt%)	Equation for the relationship between time and viscosity (R^2)	Equation for the relationship between frequency and viscosity (R^2)	Viscosity under the conditions of $T = 215$ s and $f = 100$ Hz
1	0.5	$y = 3.4587e^{0.0162x}$ (0.9897)	$y = 4.1838x^{0.6387}$ (0.9939)	86.6684 ± 5.21
2	1.0	$y = 7.7926e^{0.0142x}$ (0.9913)	$y = 9.344x^{0.5552}$ (0.9933)	126.852 ± 6.74
3	1.5	$y = 23.962e^{0.0116x}$ (0.9809)	$y = 27.121x^{0.4817}$ (0.9841)	269.982 ± 9.86
4	2.0	$y = 10.759e^{0.0136x}$ (0.9887)	$y = 12.657x^{0.5461}$ (0.9914)	167.829 ± 7.53
5	2.5	$y = 4.6973e^{0.0153x}$ (0.9938)	$y = 5.6614x^{0.6084}$ (0.996)	100.158 ± 5.92
6	3.0	$y = 2.1706e^{0.0161x}$ (0.9977)	$y = 3.1322x^{0.6554}$ (0.9969)	69.4082 ± 4.37
7	3.5	$y = 7.0827e^{0.0143x}$ (0.9913)	$y = 8.3813x^{0.5703}$ (0.9942)	124.724 ± 6.18
8	Control group	$y = 10.368e^{0.013x}$ (0.9844)	$y = 12.263x^{0.5375}$ (0.9855)	152.786 ± 8.25

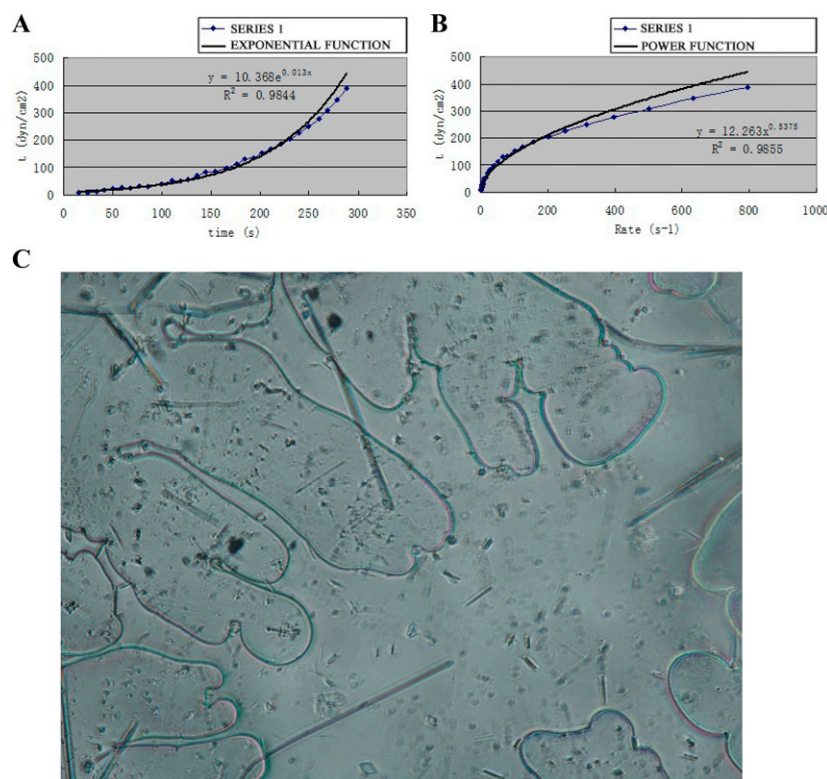


Fig. 1. (A) The relationship between shear stress at different times (control). (B) The relationship between shear stress at different frequencies (control). (C) Micrograph of almond gel (control).

solution with a pH of 13. It was stirred thoroughly until the gel dispersed. Then, it was sealed in plastic film, placed in a water bath

at 95 °C, gently shaken, and heated for 24 h. Next, shaking was stopped and heating continued for 30 min. Finally, it was removed

from the water bath, filtered, and placed in an incubator at 20 °C for 24 h for later use.

Experimental design. A spare sample was divided evenly into 15 parts. One part was used as a control. Different masses of boric acid and p-nitrophenol were added to the other parts so that their mass fractions in the 4% peach gum hydrolysate (pH = 13) were 0.025 wt%, 0.05 wt%, 0.075 wt%, 0.1 wt%, 0.125 wt%, 0.15 wt%, 0.175 wt%; 0.5 wt%, 1 wt%, 1.5 wt%, 2 wt%, 2.5 wt%, 3 wt%, and 3.5 wt%. After sealing, the sample was shaken for another 24 h. Microscopic slide specimens were made and morphology was observed using a 200 × 80i microscopic imaging system. Photos were taken to record the images.

The blend of peach gum, boric acid, and p-nitrophenol at a constant temperature of 25 °C was tested using the ARES (TA Instruments) instrument. Changes in the rheological properties of the viscosity of the blend with time and frequency were analyzed to further study the viscosity properties of peach gum and determine the feasibility of using it to make green adhesives.

Data analysis. Each experimental group (including the control group) was subjected to three parallel experiments to avoid random errors. The average value of the results was used for analysis. Errors represent the standard deviation (SD) of the three replicate experiments (Tables 2 and 3). SPSS 26.0 software (SPSS Inc., IBM, Armonk, NY, USA) was used to perform a one-way analysis of variance (ANOVA) to verify the reliability of differences between groups.

Results and discussion

Rheological properties of a sodium hydroxide solution of peach gum. The data from the experiment were analyzed and curve-fitted to obtain the characteristic curve of peach gum in an alkaline environment with a pH of 13. The viscosity of peach gum (Fig. 1A) exponentially increased over time. The equation describing the effect of time on the viscosity of peach gum is $y = 10.368e^{0.013x}$ ($R^2 = 0.9844$). The viscosity of peach gum (Fig. 1B) also showed a power law increase with the increase in frequency. The equation describing the effect of frequency on the viscosity of peach gum is $y = 12.263x^{0.5375}$ ($R^2 = 0.9855$). In the the micrograph (Fig. 1C), the hydrolysate of peach gum presents a natural flaky and branched shape under extrusion.

Boric acid additions

Rheological properties of peach gum after adding 0.025 wt% boric acid. The data from this experiment were analyzed and curve-fitted to obtain the X-Y scatter characteristic curve of peach gum in an alkaline environment. The viscosity of peach gum (Fig. 2A) showed an upward trend of the exponential function over time. The equation for the influence of time on the viscosity of peach gum is $y = 26.225e^{0.0114x}$ ($R^2 = 0.9809$). The viscosity of peach gum (Fig. 2B) also showed an upward trend of the power function with the change in

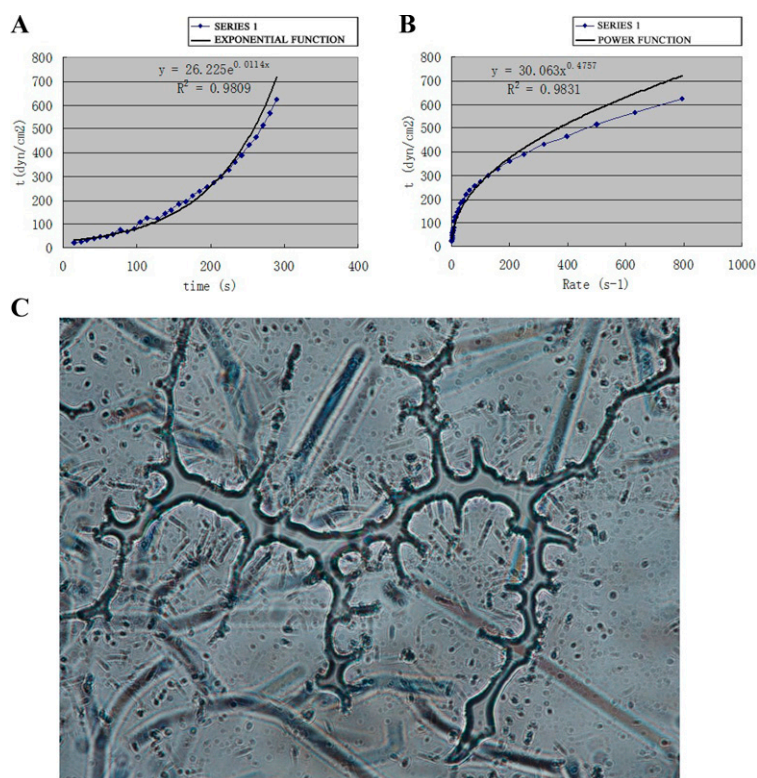


Fig. 2. (A) The relationship between shear stress at different times (peach gum + 0.025 wt% boric acid). (B) The relationship between shear stress at different frequencies (peach gum + 0.025 wt% boric acid). (C) Micrograph of peach gum + 0.025 wt% boric acid.

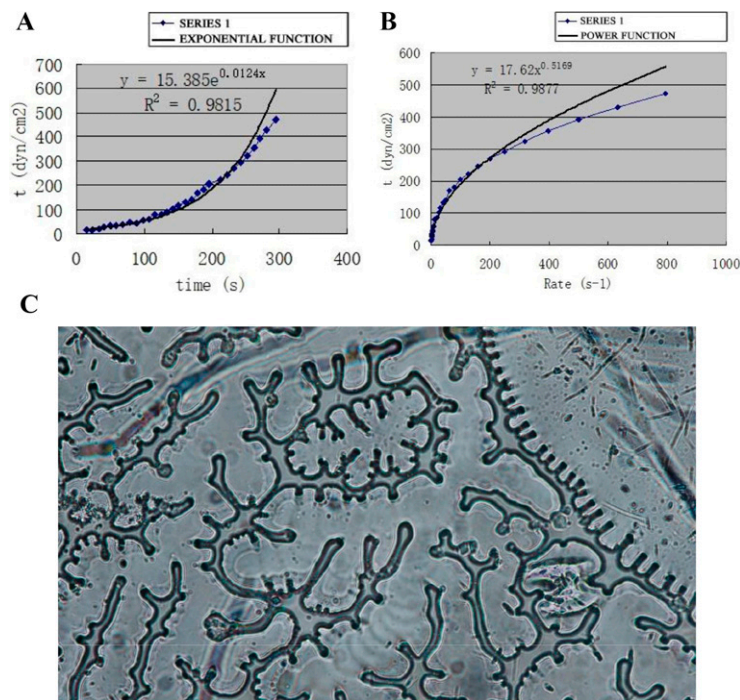


Fig. 3. (A) The relationship between shear stress at different times (peach gum + 0.05 wt% boric acid). (B) The relationship between shear stress at different frequencies (peach gum + 0.05 wt% boric acid). (C) Micrograph of peach gum + 0.05 wt% boric acid.

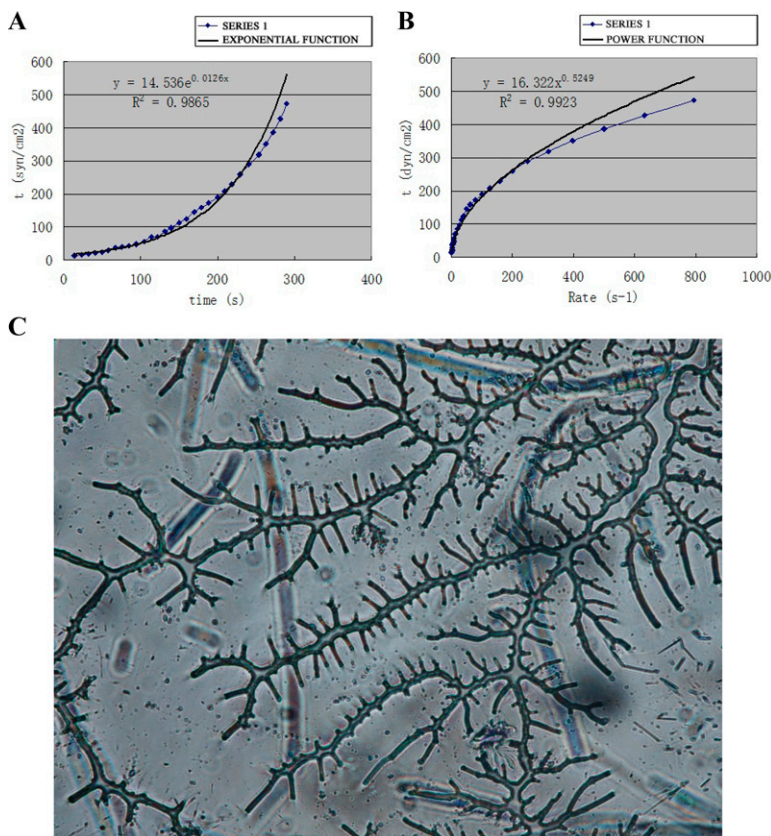


Fig. 4. (A) The relationship between shear stress at different times (peach gum + 0.075 wt% boric acid). (B) The relationship between shear stress at different frequencies (peach gum + 0.075 wt% boric acid). (C) Micrograph of peach gum + 0.075 wt% boric acid.

frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 30.063x^{0.4757}$ ($R^2 = 0.9831$). In the micrograph (Fig. 2C), the peach gum polymer with 0.025 wt% boric acid is branched.

Rheological properties of peach gum after adding 0.05 wt% boric acid. The viscosity of peach gum (Fig. 3A) showed an exponential upward trend over time. The equation for the influence of time on the viscosity of peach gum is $y = 15.385e^{0.0124x}$ ($R^2 = 0.9815$). The viscosity of peach gum (Fig. 3B) also showed an upward trend in the power function with the change in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 17.62x^{0.5169}$ ($R^2 = 0.9877$). In the micrograph (Fig. 3C), the peach gum polymer with a boric acid mass fraction of 0.050% is lichen-like.

Rheological properties of peach gum after adding 0.075 wt% boric acid. The viscosity of peach gum (Fig. 4A) showed an exponential upward trend over time. The equation for the influence of time on the viscosity of peach gum is $y = 14.536e^{0.0126x}$ ($R^2 = 0.9865$). The viscosity of peach gum (Fig. 4B) also showed an upward trend in the power function with the increase in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 16.322x^{0.5249}$ ($R^2 = 0.9923$). In the micrograph (Fig. 4C), the peach gum polymer with a boric acid mass fraction of 0.075% has a dense branched shape.

Rheological properties of peach gum after adding 0.1 wt% boric acid. The viscosity of peach gum (Fig. 5A) showed an exponential upward trend over time. The equation for the influence of time on the viscosity of peach gum is $y = 5.5605e^{0.0142x}$ ($R^2 = 0.9861$). The viscosity of peach gum (Fig. 5B) also showed an upward trend in the power function with the change in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 6.5537x^{0.5753}$ ($R^2 = 0.9881$). In the micrograph (Fig. 5C), the peach gum polymer with 0.1 wt% boric acid has a fern leaf shape.

Rheological properties of peach gum after adding 0.125 wt% boric acid. The viscosity of peach gum (Fig. 6A) showed an exponential upward trend over time. The equation for the influence of time on the viscosity of peach gum is $y = 9.0924e^{0.0126x}$ ($R^2 = 0.9867$). The viscosity of peach gum (Fig. 6B) also showed an upward trend in the power function with the change in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 10.266x^{0.5344}$ ($R^2 = 0.9925$). In the micrograph (Fig. 6C), the peach gum polymer with a boric acid mass fraction of 0.125% is jellyfish-like.

Rheological properties of peach gum after adding 0.15 wt% boric acid. The viscosity of peach gum (Fig. 7A) showed an exponential upward trend over time. The equation for the influence of time on the viscosity of peach gum is $y = 11.722e^{0.0122x}$ ($R^2 = 0.9897$). The viscosity of peach gum (Fig. 7B) also showed an upward power function trend with the change in frequency. The equation for the

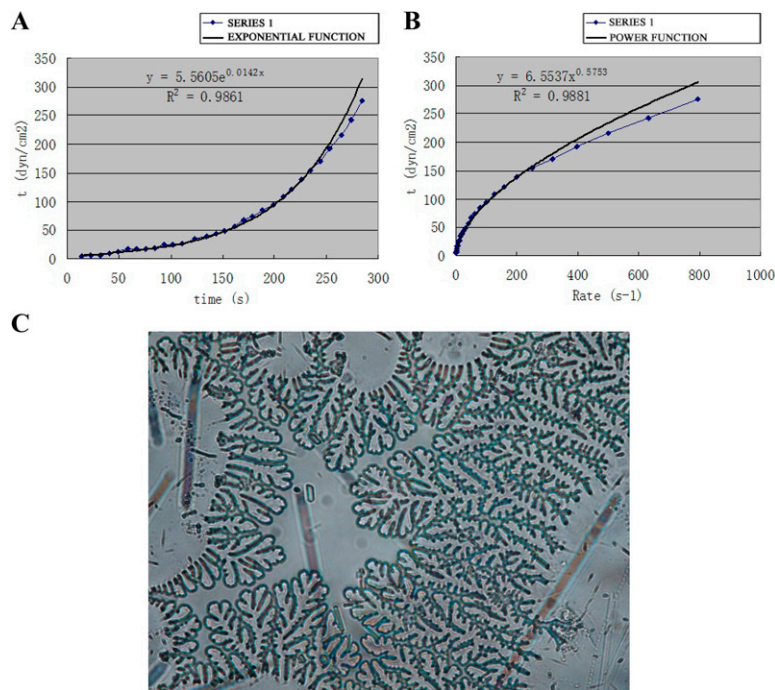


Fig. 5. (A) The relationship between shear stress at different times (peach gum + 0.100 wt% boric acid). (B) The relationship between shear stress at different frequencies (peach gum + 0.100 wt% boric acid). (C) Micrograph of peach gum + 0.100 wt% boric acid.

influence of frequency on the viscosity of peach gum is $y = 13.227x^{0.5011}$ ($R^2 = 0.9932$). In the micrograph (Fig. 7C), the peach gum polymer with 0.15 wt% boric acid has a vein-like shape.

Rheological properties of peach gum after adding 0.175 wt% boric acid. The viscosity of peach gum (Fig. 8A) showed an exponential upward trend over time. The equation for the influence of time on the viscosity of peach

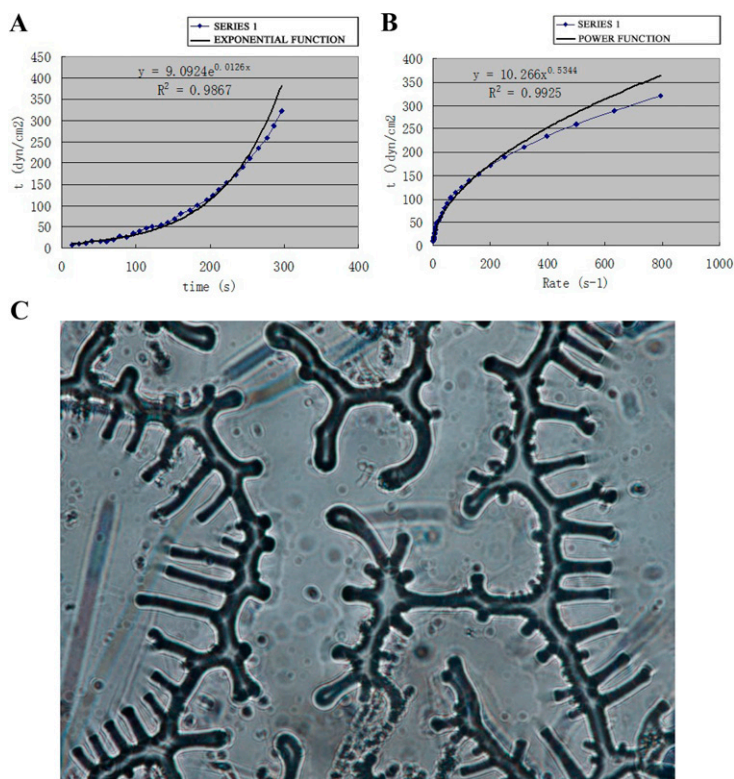


Fig. 6. (A) The relationship between shear stress at different times (peach gum + 0.125 wt% boric acid). (B) The relationship between shear stress at different frequencies (peach gum + 0.125 wt% boric acid). (C) Micrograph of peach gum + 0.125 wt% boric acid.

gum is $y = 9.522e^{0.0137x}$ ($R^2 = 0.991$). The viscosity of peach gum (Fig. 8B) also showed an upward power function trend with the change in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 11.202x^{0.542}$ ($R^2 = 0.9938$). In the micrograph (Fig. 8C), the peach gum polymer with a boric acid mass fraction of 0.175% shows a thorned shape.

Under certain times and frequencies (Table 2), the rheological viscosities of the blends of peach gum and boric acid differed. Plotting (Fig. 9) for analyses and comparisons showed that the trend line went from high to low, indicating a trough state, possibly because the concentrations of the test samples were not scientific, resulting in the absence of peak points. However, the highest point appeared when the boric acid concentration was 0.025 wt%, which may be a peak. That is, the shear stress of peach gum may reach the maximum value at that time, and its viscosity may be the highest.

The concentration-viscosity curve of the boric acid group showed a high-low-high valley state (Fig. 9).

With low concentrations (0.025 wt%–0.075 wt%), boric acid dissociates into borate ions, which form borate ester bonds with the hydroxyl groups of peach gum polysaccharides, promoting cross-linking and leading to an increase in viscosity.

With a medium concentration (0.1 wt%), excessive borate ions occupy the hydroxyl binding sites, destroying the cross-linked network and causing the viscosity to drop to the valley value.

With high concentrations (0.125 wt%–0.175 wt%), unreacted borate ions form hydrogen bonds with water molecules, resulting in a slight recovery of viscosity; however, this effect is weaker than the cross-linking effect at low concentrations.

Considering both viscosity and structural integrity, the optimal concentration of boric acid is 0.025 wt%. At this concentration, the viscosity reaches the highest value (275.662 mPa·s), and the micromorphology has a dense branched structure, which balances fluidity and bonding strength.

Additions of p-nitrophenol

Rheological properties of peach gum after adding 0.5 wt% p-nitrophenol. Data from this experiment were analyzed and curve-fitted to obtain the X-Y scatter characteristic curve of peach gum in an alkaline environment with a pH of 13. The viscosity of peach gum (Fig. 10A) showed an exponential upward trend over time. The equation for the influence of time on the viscosity of peach gum is $y = 3.4587e^{0.0162x}$ ($R^2 = 0.9897$). The viscosity of peach gum (Fig. 10B) also showed an upward power function trend with the increase in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 4.1838x^{0.6387}$ ($R^2 = 0.9939$). In the micrograph (Fig. 10C),

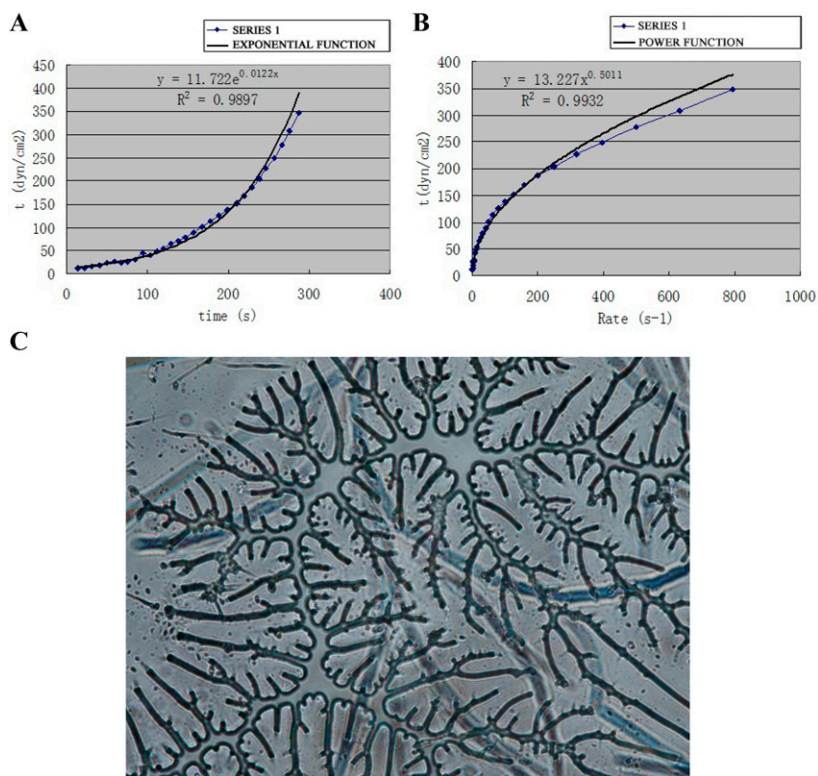


Fig. 7. (A) The relationship between shear stress at different times (peach gum + 0.150 wt% boric acid). (B) The relationship between shear stress at different frequencies (peach gum + 0.150 wt% boric acid). (C) Micrograph of peach gum + 0.150 wt% boric acid.

the peach gum polymer with a p-nitrophenol mass fraction of 0.5% has a vine-branch shape.

Rheological properties of peach gum after adding 1 wt% p-nitrophenol. The viscosity of peach gum (Fig. 11A) showed an exponential

upward trend over time. The equation for the influence of time on the viscosity of peach gum is $y = 7.7926e^{0.0142x}$ ($R^2 = 0.9913$). The viscosity of peach gum (Fig. 11B) also showed an upward power function trend with the increase in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 9.344x^{0.5552}$ ($R^2 = 0.9933$). In the micrograph (Fig. 11C), the peach gum polymer with 1.0 wt% p-nitrophenol is branched.

Rheological properties of peach gum after adding 1.5 wt% p-nitrophenol. The viscosity of peach gum (Fig. 12A) showed an exponential upward trend over time. The equation for the influence of time on the viscosity of peach gum is $y = 23.962e^{0.0116x}$ ($R^2 = 0.9809$). The viscosity of peach gum (Fig. 12B) also showed an upward power function trend with the increase in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 27.121x^{0.4817}$ ($R^2 = 0.9841$). In the micrograph (Fig. 12C), the peach gum polymer with 1.5 wt% p-nitrophenol has an irregular chain shape.

Rheological properties of peach gum after adding 2 wt% p-nitrophenol. The viscosity of peach gum (Fig. 13A) showed an exponential increase over time. The equation for the influence of time on the viscosity of peach gum is $y = 10.759e^{0.0136x}$ ($R^2 = 0.9887$). The viscosity of peach gum (Fig. 13B) also showed an increase in the power function with the increase in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 12.657x^{0.5461}$ ($R^2 = 0.9914$). In the micrograph (Fig. 13C), the peach gum polymer with 2.0 wt% p-nitrophenol has a dendritic shape in the extrusion environment.

Rheological properties of peach gum after adding 2.5 wt% p-nitrophenol. The viscosity of peach gum (Fig. 14A) showed an exponential upward trend over time. The equation for the influence of time on the viscosity of peach gum is $y = 4.6973e^{0.0153x}$ ($R^2 = 0.9938$). The viscosity of peach gum (Fig. 14B) also showed an upward power function trend with the increase in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 5.6614x^{0.6084}$ ($R^2 = 0.996$). In the micrograph (Fig. 14C), the peach gum polymer with a p-nitrophenol mass fraction of 2.5% has leaf-like branches.

Rheological properties of peach gum after adding 3 wt% p-nitrophenol. The viscosity of peach gum (Fig. 15A) showed an exponential upward trend over time. The equation for the influence of time on the viscosity of peach gum is $y = 2.1706e^{0.0161x}$ ($R^2 = 0.9977$). The viscosity of peach gum (Fig. 15B) also showed an upward power function trend with the increase in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 3.1322x^{0.6554}$ ($R^2 = 0.9969$). In the micrograph (Fig. 15C), the peach gum polymer with a p-nitrophenol mass fraction of 3.0% has a winding chain shape.

Rheological properties of peach gum after adding 3.5 wt% p-nitrophenol. The viscosity of peach gum (Fig. 16A) showed an exponential

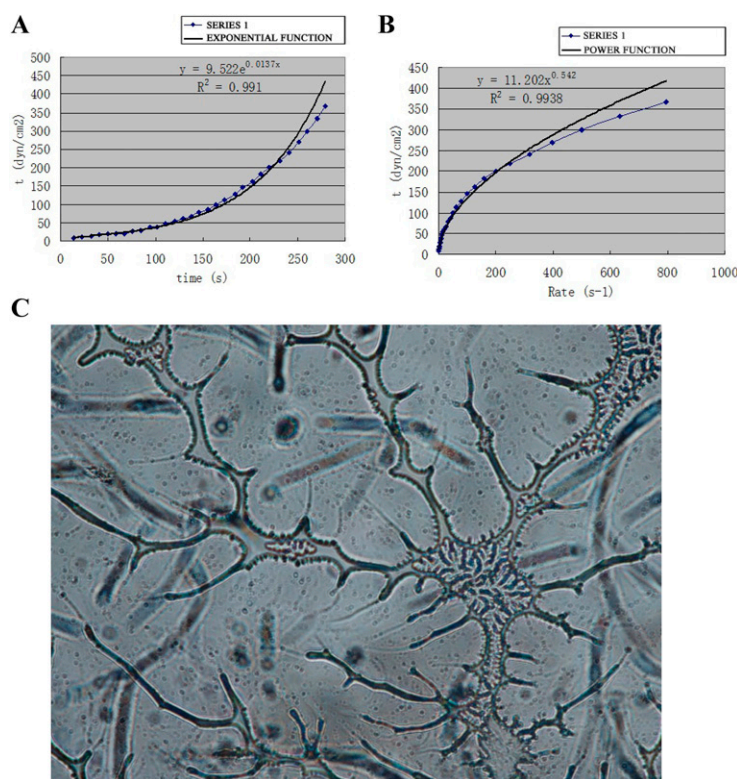


Fig. 8. (A) The relationship between shear stress at different times (peach gum + 0.175 wt% boric acid). (B) The relationship between shear stress at different frequencies (peach gum + 0.175 wt% boric acid). (C) Micrograph of peach gum + 0.175 wt% boric acid.

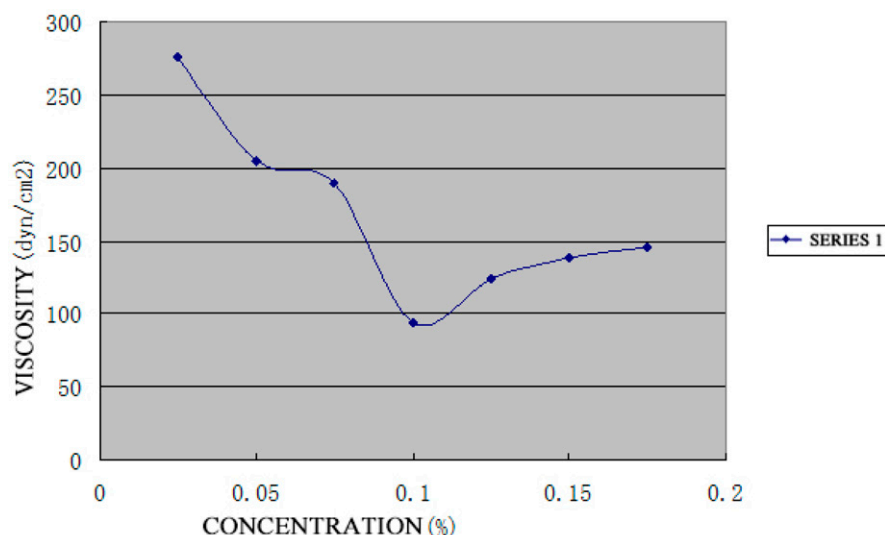


Fig. 9. The relationship between viscosity and concentration at certain times and frequencies.

increase with time. The equation for the influence of time on the viscosity of peach gum is $y = 7.0827e^{0.0143x}$ ($R^2 = 0.9913$). The viscosity of peach gum (Fig. 16B) also showed an increased power function with the increase in frequency. The equation for the influence of frequency on the viscosity of peach gum is $y = 8.3813x^{0.5703}$ ($R^2 = 0.9942$). In the micrograph (Fig. 16C), the peach gum polymer with 3.5 wt% p-nitrophenol has unconnected small branches.

Under different times and frequencies (Table 3), the rheological viscosities of the

blends of peach gum and p-nitrophenol differ. Through plotting and analyses (Fig. 17), the trend line rose from low to high and showed a peak point in the middle. That is, when the mass fraction of p-nitrophenol is 1.5 wt%, the shear stress of peach gum reaches the highest value and its viscosity is largest.

The concentration-viscosity curve of the p-nitrophenol group exhibited a low-high-low peak state (Fig. 17), and its mechanism was directly related to the molecular structure of p-nitrophenol and the interaction of characteristics of peach gum polysaccharides.

With low concentrations (0.5 wt%–1.0 wt%), the nitro group and hydroxyl group in p-nitrophenol molecules form polar groups, which can form weak interactions with the hydroxyl groups on peach gum polysaccharide chains through hydrogen bonds. However, the number of molecules is small at this stage, resulting in only local promotion of the aggregation of polysaccharide molecules without formation of a complete cross-linked network. Thus, the viscosity increases slowly.

With a medium concentration (1.5 wt%), the p-nitrophenol molecules reach a saturated binding state. A large number of nitro groups form stable hydrogen bonds with polysaccharide hydroxyl groups; at the same time, hydrophobic association occurs between hydrophobic groups (benzene rings) among molecules. These two effects jointly promote the formation of a dense three-dimensional cross-linked network by polysaccharide molecules. The viscosity reached a peak value (269.982 mPa·s) and the stability of the cross-linked structure significantly improved.

With high concentrations (2.0 wt%–3.5 wt%), after excessive p-nitrophenol molecules occupy the binding sites of polysaccharide hydroxyl groups, the remaining molecules aggregate with each other through van der Waals forces to form “molecular clusters,” which destroy the continuity of the original three-dimensional cross-linked network. This leads to enhanced fluidity of polysaccharide chain segments, a continuous decrease in viscosity, and the occurrence of “chain breakage” in the micromorphology.

Considering both the viscosity data and the integrity of the microstructure, the optimal concentration of p-nitrophenol is 1.5%. At this concentration, the viscosity is close to the peak value (269.982 mPa·s) and microscopic observations indicate that the peach gum system presents an “irregular dense chain structure.”

Conclusions

Through a series of chart analyses, under the conditions of different added amounts of boric acid and p-nitrophenol to peach gum, the R^2 value is almost equal to 1, indicating that peach gum has good viscosity. Under the conditions of boric acid added at a concentration of 0.025 wt% and p-nitrophenol added at a concentration of 1.5 wt%, the viscosity of the peach gum blend reached its maximum and was basically the same. Under these conditions, the amount of boric acid added is less than that of p-nitrophenol. Moreover, boric acid is nontoxic, pollution-free, and inexpensive; however, p-nitrophenol is slightly toxic. Additionally, p-nitrophenol is irritating to the skin and respiratory tract, and long-term exposure may damage the liver and kidney. Furthermore, degradation of p-nitrophenol in the environment is difficult, and it tends to cause water pollution. In contrast, boric acid can be used as a food additive; therefore, it is more compatible with the industrial demands for green adhesives. Peach gum also has good

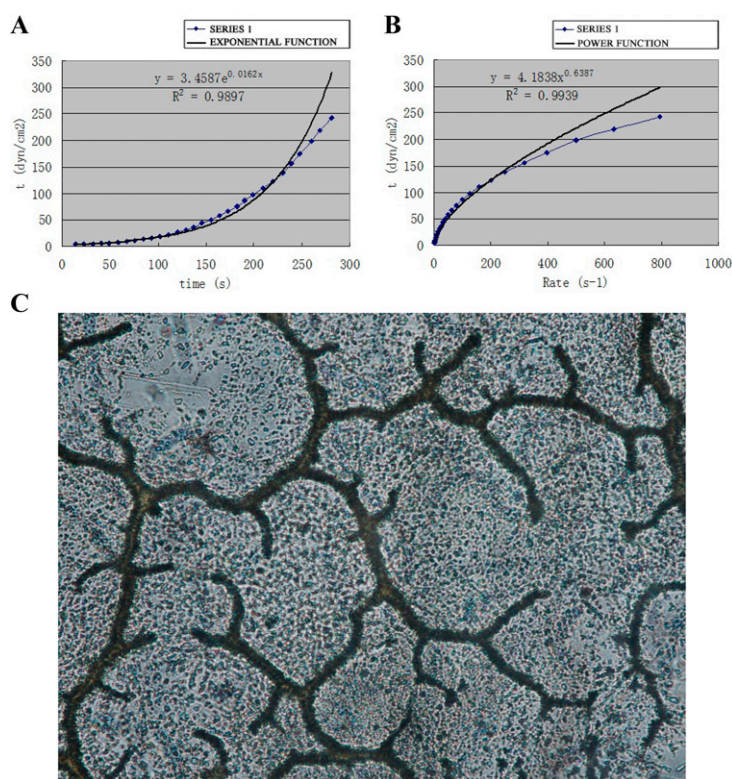


Fig. 10. (A) The relationship between shear stress at different times (peach gum + 0.5 wt% p-nitrophenol). (B) The relationship between shear stress at different frequencies (peach gum + 0.5 wt% p-nitrophenol). (C) Micrograph of peach gum + 0.5 wt% p-nitrophenol.

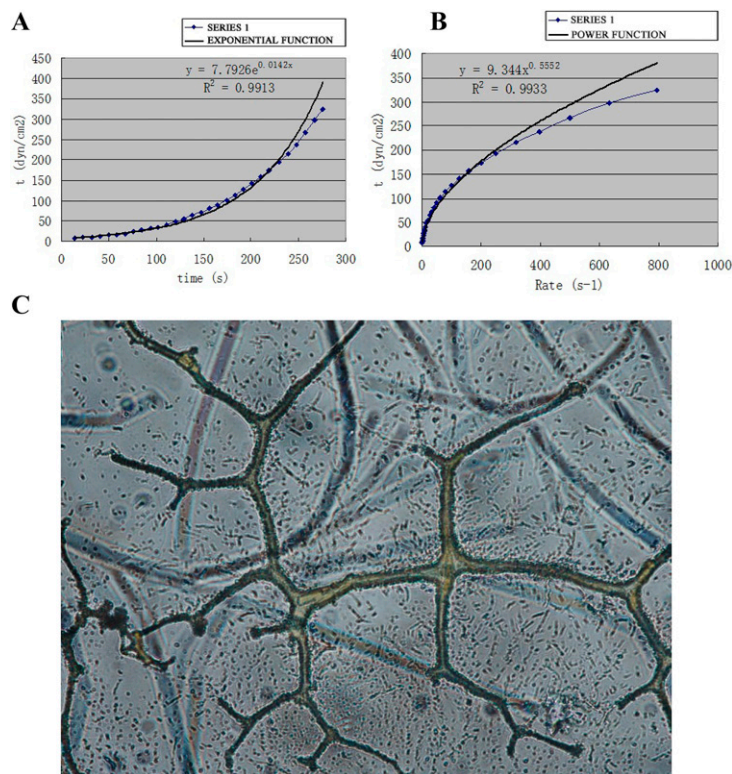


Fig. 11. (A) The relationship between shear stress at different times (peach gum + 1.0 wt% p-nitrophenol). (B) The relationship between shear stress at different frequencies (peach gum + 1.0 wt% p-nitrophenol). (C) Micrograph of peach gum + 1.0 wt% p-nitrophenol.

adhesion and film-forming properties, and it is a natural adhesive with great development potential. With the introduction of environmental

protection regulations and the enhancement of health awareness, the state has become increasingly strict in restricting the volatile amount of

free formaldehyde in acetal adhesives. According to the principle of efficiency, in the green adhesive manufacturing industry, choosing a

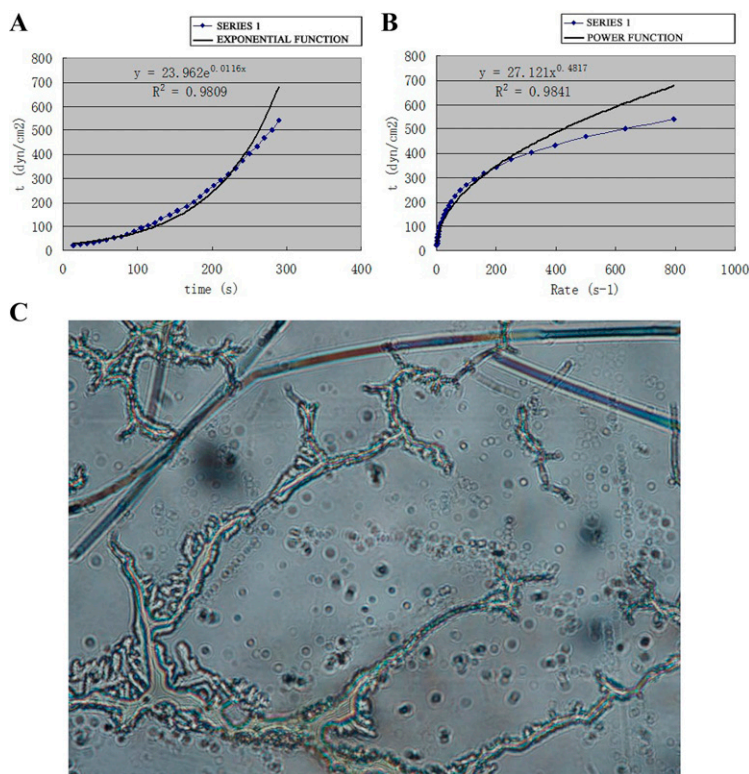


Fig. 12. (A) The relationship between shear stress at different times (peach gum + 1.5 wt% p-nitrophenol). (B) The relationship between shear stress at different frequencies (peach gum + 1.5 wt% p-nitrophenol). (C) Micrograph of peach gum + 1.5 wt% p-nitrophenol.

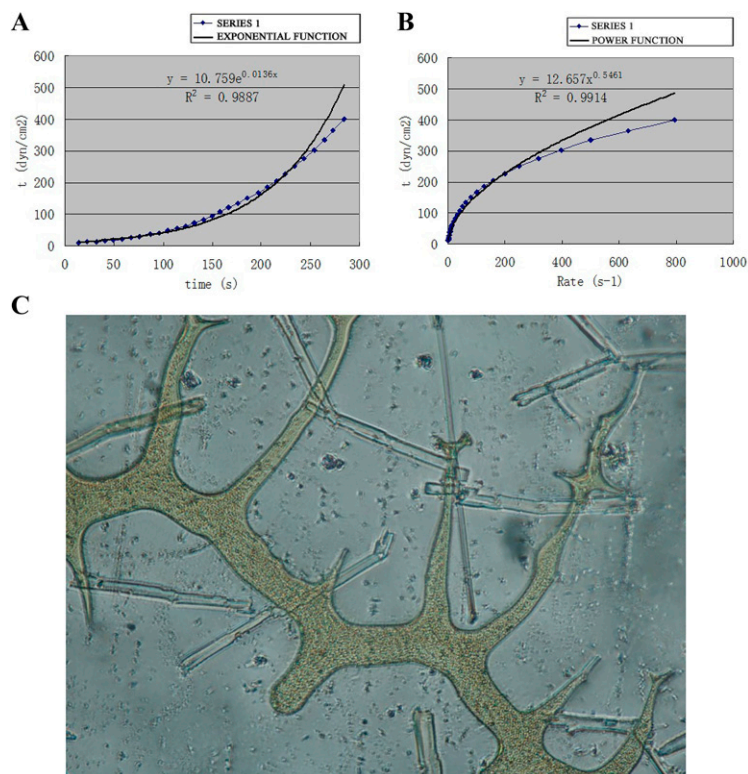


Fig. 13. (A) The relationship between shear stress at different times (peach gum + 2.0 wt% p-nitrophenol). (B) The relationship between shear stress at different frequencies (peach gum + 2.0 wt% p-nitrophenol). (C) Micrograph of peach gum + 2.0 wt% p-nitrophenol.

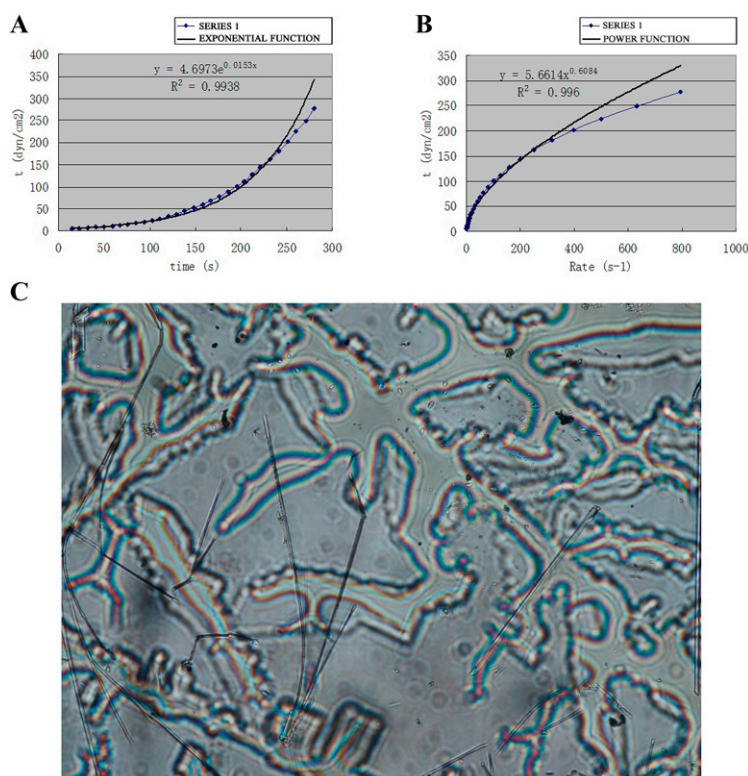


Fig. 14. (A) The relationship between shear stress at different times (peach gum + 2.5 wt% p-nitrophenol). (B) The relationship between shear stress at different frequencies (peach gum + 2.5 wt% p-nitrophenol). (C) Micrograph of peach gum + 2.5 wt% p-nitrophenol.

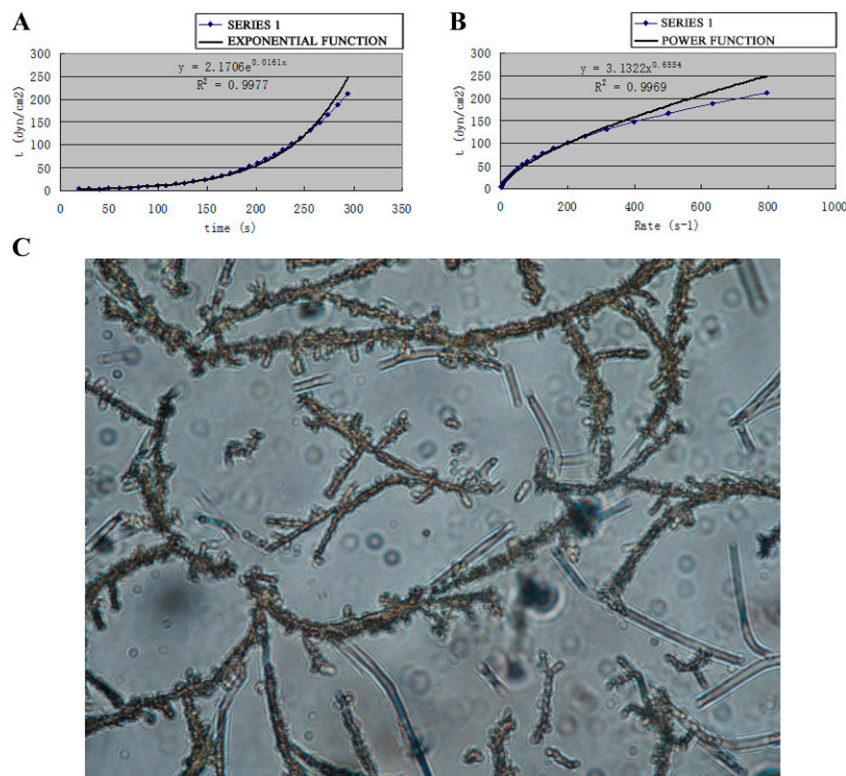


Fig. 15. (A) The relationship between shear stress at different times (peach gum + 3.0 wt% p-nitrophenol). (B) The relationship between shear stress at different frequencies (peach gum + 3.0% wt p-nitrophenol). (C) Micrograph of peach gum + 3.0 wt% p-nitrophenol.

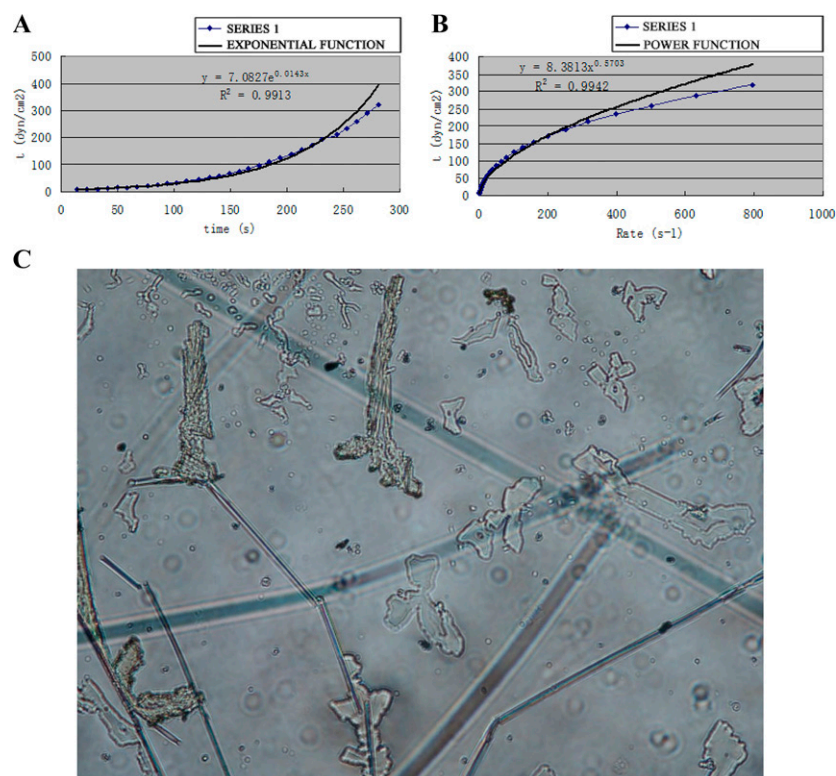


Fig. 16. (A) The relationship between shear stress at different times (peach gum + 3.5 wt% p-nitrophenol). (B) The relationship between shear stress at different frequencies (peach gum + 3.5 wt% p-nitrophenol). (C) Micrograph of peach gum + 3.5 wt% p-nitrophenol.

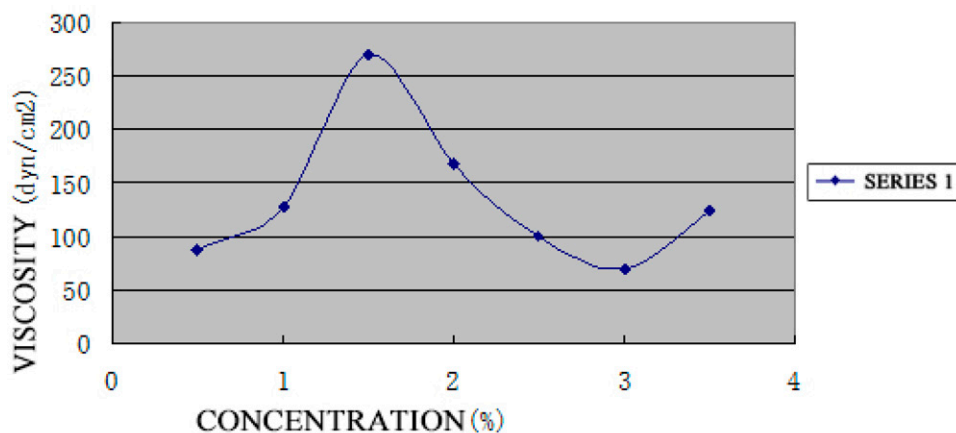


Fig. 17. The relationship between rheological viscosities under certain times and frequencies.

blend of boric acid and peach gum to develop green adhesives has broad prospects.

Subsequent research should focus on conducting durability tests under different temperatures and on various substrates, optimizing plasticizers and compound modifications, and validating 100-kg batches to further enhance industrial applicability.

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