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Preparation of a high-solid-content paraffin emulsion for wood-based panels by a one-pot method

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High-solid-content paraffin emulsions are essential for waterproofing thick wood-based panels. To address this requirement, a one-pot preparation method was developed using glyceryl monostearate, Pingpingjia O-20, PEG-100 stearate, and sodium dodecylbenzenesulfonate as composite emulsifiers, with small-molecule alcohols and polyether-modified silicone oil introduced as additives. The effects of HLB value and additive composition on emulsion properties were systematically evaluated. The results indicate that at an HLB value of 10.5, and with a 2 : 1 mass ratio of ethylene glycol to polyether-modified silicone oil at 1% of the paraffin mass, the emulsion achieves a viscosity of 13 s, a solid content of 55.43%, no stratification under centrifugal testing, and grade 1 dispersibility. Reproducibility and scale-up experiments confirm that the prepared paraffin emulsion satisfies performance requirements and exhibits stable quality.

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Introduction

Hydrophobic substances are widely used as waterproofing agents in the production of fiberboard, particleboard, and other artificial boards to improve panel water resistance.[1] Waterproofing agents for sheet materials can be broadly classified into three categories: hydrocarbons, organosilicon compounds, and fluorocarbon compounds. Hydrocarbon-based agents, represented by paraffin and polyethylene wax, form hydrophobic films on surfaces and within the pores of sheet materials through their non-polar molecular structures. Organosilicon compounds, such as organosilanes and organosilicone emulsions, react with hydroxyl groups on the substrate to form stable siloxane hydrophobic layers, providing longer-lasting waterproofing. Fluorocarbon compounds, including fluorinated acrylic esters, exhibit excellent hydrophobic and oleophobic properties due to their extremely low surface energy. Each class of waterproofing agent presents distinct advantages and limitations. Organosilicon compounds provide excellent durability but involve high raw material costs and require strict compatibility control with certain sheet adhesives. Fluorocarbon compounds offer superior performance but suffer from complex production processes and high costs, limiting their suitability for large-scale industrial application. In contrast, paraffin is widely used as a waterproofing agent for sheet materials due to its balanced performance and cost advantages. This non-polar hydrocarbon, composed primarily of C20–C30 *n*-alkanes, exhibits strong hydrophobicity and chemical stability. Studies have shown that paraffin can uniformly adsorb onto fiber surfaces and pores, forming a physical barrier that inhibits moisture penetration and reduces panel thickness swelling.[2–4] Paraffin also offers advantages in cost and process compatibility. It is inexpensive and readily available, and compared with organosilicon and fluorocarbon waterproofing agents, significantly reduces raw material costs, making it suitable for large-scale production. Its application can be readily integrated into existing manufacturing processes through simple methods such as melt impregnation or spray addition, without requiring modification of production lines. In addition, paraffin interacts physically with the sheet substrate and adhesive, without adversely affecting key performance indicators such as bonding strength and mechanical properties, thereby enabling effective waterproofing through the formation of a continuous hydrophobic barrier.

Engineered wood panels are generally classified into three thickness categories: thin panels (3–9 mm), used for back panels, veneer panels, and partitions; medium panels (12–18 mm), with 18 mm being the most commonly used thickness for furniture, cabinet bodies, and flooring substrates; and thick panels (20–32 mm), which are primarily produced from particleboard.[5] Thick panels are mainly used for load-bearing components, countertops, and customized structural applications. For medium and thin panels, paraffin emulsions with a solid content of approximately 30% are sufficient to provide waterproofing and moisture resistance. However, this level is inadequate for thick panels. The core layer of thick panels

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requires paraffin emulsions with higher solid content and lower water content. During hot pressing, low-solid-content emulsions tend to demulsify, causing water to remain trapped in the core layer, which leads to defects such as cracking or bulging. To reduce production costs, manufacturers typically apply a 30% solid content emulsion to the surface layer and a paraffin emulsion with a solid content of 50% or higher to the core layer during thick panel production.

High-solid-content paraffin emulsions have attracted increasing attention in recent years. However, studies on paraffin emulsions with solid contents exceeding 50% remain limited. Increasing the solid content of paraffin emulsions for sheet material processing primarily depends on optimization of the emulsification system and preparation process, among which emulsifier selection is the key factor. Nonionic emulsifiers, such as Span-80/Tween-80 mixed systems and AEO series surfactants, achieve emulsification by adjusting the HLB value to match the characteristics of paraffin. This reduces oil–water interfacial tension, and enables paraffin to form uniform and stable fine particles dispersed in the aqueous phase. These emulsifiers also exhibit good compatibility with sheet substrates and adhesives, without adversely affecting key properties such as panel bonding strength. Cationic emulsifiers, including alkyl quaternary ammonium salts, mainly play auxiliary roles by enhancing emulsion stability. Their positively charged groups adsorb onto paraffin particles surfaces, preventing agglomeration through electrostatic repulsion. They also improve interfacial interaction between the emulsion and negatively charged wood fibers or other sheet materials, thereby enhancing the integrity of the waterproof film. Previous studies have shown that paraffin emulsions can be effectively prepared using combinations of nonionic emulsifiers such as Span-80/Tween-80 or AEO/OP systems, with HLB values typically adjusted within the range of 8–12. In some cases, a small amount of auxiliary emulsifier, such as sodium dodecylbenzenesulfonate, is introduced, and the total emulsifier dosage is typically controlled at 5–10% of the paraffin mass. Such systems exhibit strong compatibility with paraffin, effectively reduce interfacial tension, and promote the formation of uniformly dispersed fine paraffin particles in the aqueous phase, while maintaining compatibility with substrates and adhesives. Several studies have reported progress in high-solid-content paraffin emulsions. Wang Ke *et al.*[6] prepared a liquid paraffin nanoemulsion with a solid content of 51.13%, an average particle size of 0.261 μm, and a viscosity of 160 mPa s, using Tween-60 and Span-60 as composite emulsifiers. However, the low melting point of liquid paraffin limits its applicability in engineered wood panels. Cheng Zhenfeng *et al.*[7] prepared a paraffin nanoemulsion with a solid content of 51.46% using 58# paraffin and a composite emulsifier system consisting of Span-60, Tween-60, potassium oleate and Tween-80. This method required separate preparation and subsequent mixing of the oil and aqueous phases, resulting in a relatively complex process. Huang Jingming *et al.*[8] prepared a paraffin emulsion with a solid content of 50% for particleboard production. Chen Hui *et al.*[9] obtained paraffin emulsions with solid contents of 50–54% and particle sizes of 500–800 nm using a combination of emulsifiers, including oleyl alcohol polyoxyethylene ether-25, lauryl alcohol polyoxyethylene ether-20, stearic acid, and glycerol monostearate. The resulting panels exhibited a 24 h thickness swelling of 6.72%, meeting waterproofing the requirements, although the emulsion particle size remained relatively large.

Based on the market requirements proposed by Anyang Linwei Adjuvant Co., Ltd, this study addressed key challenges related to the shear resistance of paraffin emulsions and the safety and environmental performance of compounded emulsifiers. The target paraffin emulsion was required to achieve a solid content of approximately 55%, a viscosity not exceeding 15 s, no stratification under centrifugal stability testing, and grade 1 dispersibility. In addition, the preparation process was required to be simple and suitable for implementation using a one-pot method. The one-pot method enables the simultaneous addition of paraffin, emulsifiers, water, and other components into a single reaction vessel, eliminating the need for separate preparation of oil and aqueous phases. This approach reduces process complexity, minimizes equipment transfer, shortens the production cycle, and lowers energy labor, and material handing costs. It also improves raw material utilization by reducing transfer losses. During processing, all components are heated, stirred, and emulsified within the same system, which promotes more uniform mixing and avoids issues such as localized emulsification and broad particle size distributions associated with stepwise addition. As a result, emulsions with more uniform particle size distribution and improved stability can be obtained. The simplicity and controllability of this method also facilitate large-scale continuous production. Building upon previous studies,[10–12] the HLB value of a mixed emulsifier system composed of glycerol monostearate, Pingpingjia O-20, PEG-100 stearate, and sodium dodecylbenzenesulfonate was systematically adjusted. Sodium dodecylbenzenesulfonate, a typical anionic emulsifier with high surface activity, effectively reduces oil–water interfacial tension and promotes the formation and stabilization of fine paraffin droplets. It also exhibits good resistance to hard water and strong dispersibility, which suppress particle aggregation and phase separation. When combined with nonionic emulsifiers such as Pingpingjia O-20 and glycerol monostearate, a synergistic effect enhances emulsion uniformity and storage stability. The effects of different additives and their dosages on emulsion performance were systematically investigated, and the optimal emulsifier composition and mixing ratio for paraffin emulsion preparation were determined.

Materials and methods

Experimental reagents and instruments

Laboratory reagents. Monoglyceride (industrial grade), Suzhou Xiongrun Chemical Co., Ltd; Span-60 (industrial grade), Shenzhen Hengsheng Biotechnology Co., Ltd; PEG-100 (industrial grade), Shanghai Kaiyin Chemical Co., Ltd; Pingpingjia O-20 (industrial grade), Nantong Jienuo Chemical Co., Ltd; sodium dodecylbenzenesulfonate (industrial grade), Jinan Jiasheng Chemical Co., Ltd; 58# paraffin (industrial grade), Henan

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Yuyang Wax Industry Co., Ltd; ethylene glycol, propylene glycol, *n*-butanol, and isopentanol (analytical grade), Sinopharm Chemical Reagents Co., Ltd; polyether-modified silicone oil (industrial grade), Zhuhai Xiande New Materials Technology Co., Ltd.

Experimental equipment. JJ-1 electric stirrer (Changzhou Guohua Electric Co., Ltd); LCD-A1000 electronic balance (Huazhi (Fujian) Electronic Technology Co., Ltd); HDM-250 temperature-controlled electric heating jacket (Changzhou Guohua Electric Co., Ltd); MD-400 benchtop low-speed centrifuge (Zhangjiagang Antian Machinery Manufacturing Co., Ltd); LND-1 coating viscometer (Shanghai Jingxi Instrument Manufacturing Co., Ltd). Each experiment was conducted in triplicate, and the results are presented as mean ± standard deviation.

Preparation process of mineral paraffin

58# paraffin wax and deionized water were weighed according to the required proportions and transferred into a 250 mL three-neck flask. The mixture was heated until the paraffin was completely melted, after which the emulsifier, additives, and stabilizer were added sequentially. The electric stirrer was then operated at 1000 rpm. After complete dissolution of the emulsifier, emulsification was maintained at 75 ± 2 °C for 30 min. Heating was then stopped, and the emulsion was allowed to cool to 35 °C before stirring was terminated. The resulting paraffin emulsion was subsequently subjected to performance evaluation.

Performance testing of mineral paraffin

(1) Solid content: approximately 2 g of emulsion was weighed into a porcelain dish and placed in a constant-temperature drying oven at (105 ± 5) °C for 2 h. The sample was dried to constant mass, and the solid content was calculated using eqn (1).

$$\text{Solid content} = \frac{\text{the mass of the sample after drying}}{\text{the mass of the sample before drying}} \times 100\% \quad (1)$$

(2) Viscosity: the viscosity of the paraffin emulsion was measured using the cup no. 4 method in accordance with GB/T 1723-93.

(3) Centrifugal stability: a 45 mL sample of paraffin emulsion was placed in a centrifuge tube and centrifuged at 4500 rpm for 15 min. Phase separation was visually observed. Greater bottom-layer separation indicates poorer stability, whereas less separation indicates better stability. The water output rate was calculated using eqn (2).

$$\text{Water output rate} = \frac{\text{water phase volume}}{\text{total volume of lotion}} \times 100\% \quad (2)$$

(4) Dispersibility: the dispersibility of the paraffin emulsion was evaluated, with reference to the method for agricultural emulsifiable concentrates.[9] Dispersibility was classified into five grades, where grade 1 represents the best performance and grade 5 the worst.

(5) Particle size and zeta potential analysis: particle size distribution was measured using a Nano ZS90 laser particle size analyzer (Malvern Instruments, UK). The zeta potential was determined using a Zetasizer Nano ZS90 (Malvern Instruments, UK).

(6) Rheological properties: rheological measurements were performed using a TA Discovery HR-1 rheometer at 25 °C under steady-state shear conditions. The shear rate ranged from 0.01 to 1000 s^{-1}, and the rheological behavior of the paraffin emulsion was recorded.

Results and discussion

Effect of HLB value on emulsification

The HLB value characterizes the hydrophilic–lipophilic balance of an emulsifier and directly influences emulsification performance. Selecting an HLB value close to that of paraffin (9–11) favors the formation of a stable emulsion.[13–15] Based on the additive principle of HLB values,[15] a composite emulsifier system was designed. Four surfactants, namely sodium dodecylbenzenesulfonate, Span-60, monoglyceride, and PEG-100, were combined to prepare composite emulsifiers with HLB values of 9.6, 9.9, 10.2, 10.5, and 10.8.

A total of 70 g of 58# paraffin wax and 70 mL of deionized water were transferred into a three-neck flask. The composite emulsifier dosage was fixed at 15% of the paraffin mass. Without the addition of additives, the effect of HLB value on paraffin emulsion performance was investigated. Emulsification was conducted at 75 °C for 30 min under a stirring speed of 1000 rpm. The results are presented in Table 1.

As the HLB value increases, the viscosity of the emulsion gradually decreases. This is because an increase in the HLB value leads to an increase in the hydrophilicity of the composite

Table 1 Experimental design for paraffin emulsion preparation at different HLB values

Test number	HLB price	Viscosity/s	Solid content/%	Centrifugal stability (effluent rate)	Dispersibility
1	9.6	—	—	—	Grade 5
2	9.9	>60	53.23 ± 0.21	(45 ± 2)%	Grade 4
3	10.2	30 ± 0.5	53.45 ± 0.18	(20 ± 1)%	Grade 3
4	10.5	16 ± 0.5	54.78 ± 0.16	Non-layered	Grade 2
5	10.8	14 ± 0.5	52.18 ± 0.15	Non-layered	Grade 1

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emulsifier, and the paraffin particles are more uniformly dispersed in water, resulting in enhanced fluidity of the emulsion. Initially, the solid content increases. This is because as the HLB value increases, the paraffin particles become more uniformly dispersed, and the amount of dispersion increases. It reaches 54.78% at 10.5, and then the solid content decreases as the HLB increases, possibly because the enhanced hydrophilicity leads to a decrease in the solubility of paraffin in the surfactant micelles. Centrifugal stability improves significantly, and dispersibility is enhanced. At an HLB value of 10.5, the paraffin emulsion exhibits a viscosity of 16 s, a solid content of 54.78%, no phase separation under centrifugal testing, and grade 2 dispersibility. This behavior is attributed to the increased hydrophilicity of the composite emulsifier at higher HLB values, which reduces oil–water interfacial tension and promotes uniform dispersion of paraffin droplets in the aqueous phase.[16] When the HLB value is further increased to 10.8, the hydrophilicity of the emulsifier is further enhanced, the interfacial tension decreases, and the paraffin becomes smaller and more uniform droplets. The overall fluidity of the emulsion improves, and the overall flow resistance of the emulsion decreases, resulting in a decrease in viscosity. In addition, the ability to encapsulate the paraffin begins to decline. Excessive paraffin cannot be effectively emulsified and encapsulated, leading to precipitation and stratification, causing a decrease in its solid content. In this state, the emulsifier forms a dense and highly mechanically strong interface film at the oil–water interface, which can prevent the stratification and demulsification of paraffin droplets, and the electrostatic repulsion of the double layer can also counteract the influence of centrifugal force, thus maintaining the centrifugal stability unaffected. The surface energy of the emulsion diffusion remains unchanged, the uniformity of dispersion does not undergo a sudden change, and thus the diffusivity also remains basically unchanged.

Effects of additives on emulsification

To reduce viscosity and improve the flowability of high-solid-content paraffin emulsions, three types of additives were investigated: small-molecule alcohols (ethylene glycol, propylene glycol, *n*-butanol, and isopentanol), polyether-modified silicone oil, and their mixtures. Each experiment used 70 g of 58# paraffin wax and 70 mL of deionized water. The composite emulsifier dosage was 15% of the paraffin mass, with the HLB value fixed at 10.5. Emulsification was conducted at 75 °C for 30 min under a stirring speed of 1000 rpm, and the total additive dosage was 1% of the paraffin mass. The results are summarized in Table 2.

As shown in Table 2, increasing the dosage of ethylene glycol has little effect on solid content and centrifugal stability, except at 1.5%. Dispersibility improves from grade 2 to grade 1, while viscosity initially increases and then decreases. At a dosage of 1.5%, phase separation and agglomeration occur after cooling, indicating emulsion failure. This behavior is attributed to the polar nature of ethylene glycol. Ethylene glycol contains two hydroxyl groups, which have extremely strong polarity and can completely dissolve in water. The hydroxyl groups of ethylene glycol form hydrogen bonds with the hydrophilic chains of the emulsifier and seize the water molecules of the emulsifier, resulting in a decrease in the strength of the interface film, a thinning of the hydration layer at the hydrophilic end, and a significant reduction in the spatial hindrance between the liquid droplets. Eventually, the wax droplets undergo irreversible coalescence and phase separation.[17] At low dosage (0.2%), the effect is minimal. As the dosage increases, the viscosity of the aqueous phase increases and intermolecular interactions are strengthened, reduce the surface activity of the surfactant, weaken the emulsifying effect and result in higher emulsion viscosity. At 1.0%, ethylene glycol acts as an interfacial mediator between surfactant ions within micelles, reducing electrostatic repulsion between terminal groups and improving stability.[18] Further increases in dosage disrupt the hydrophilic–lipophilic balance, leading to aggregation and phase separation after cooling.

As shown in Table 3, the effect of propylene glycol on emulsion viscosity follows a similar trend, with viscosity increasing and then decreasing as dosage increases. At 0.8%, phase separation occurs, with a water effluent rate of 3%. Further increases in dosage lead to increased water separation, and excessive addition results in demulsification. This is because propylene glycol is a polar molecule. It has two hydroxyl groups and a slightly longer carbon chain, and its molecular polarity is slightly weaker than that of ethylene glycol. Its presence leads to an increase in the critical micelle concentration of the surfactant and a decrease in surface activity. Comparison of Tables 2 and 3 shows that, at the same dosage, emulsions prepared with propylene glycol exhibit higher viscosity than those prepared with ethylene glycol, indicating

Table 2 Effects of ethylene glycol dosage on paraffin emulsion properties

Test number	Alcohols	Dosage[a]	Viscosity/s	Solid content/%	Centrifugal stability (effluent rate)	Dispersibility
6	Ethylene glycol	0.2%	16.76 ± 0.13	54.86 ± 0.15	Non-layered	Grade 2
7	Ethylene glycol	0.5%	19.12 ± 0.16	54.79 ± 0.16	Non-layered	Grade 2
8	Ethylene glycol	0.8%	20.43 ± 0.18	54.45 ± 0.10	Non-layered	Grade 2
9	Ethylene glycol	1%	18.04 ± 0.19	54.36 ± 0.12	Non-layered	Grade 1
10	Ethylene glycol	1.5%	After cooling, it separates into layers, forms lumps, and breaks down the emulsion			

[a] The dosage of alcohol-based additives is expressed as a percentage of the solid paraffin mass. The same definition applies to the dosages in Tables 3–8.

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Table 3 Effects of propylene glycol dosage on paraffin emulsion properties

Test number	Alcohols	Dosage[a]	Viscosity/s	Solid content/%	Centrifugal stability (effluent rate)	Dispersibility
11	Propylene glycol	0.2%	17.86 ± 0.11	55.23 ± 0.13	Non-layered	Grade 2
12	Propylene glycol	0.5%	20.83 ± 0.12	55.78 ± 0.15	Non-layered	Grade 2
13	Propylene glycol	0.8%	22.43 ± 0.13	55.67 ± 0.14	(3 ± 0.10)%	Grade 2
14	Propylene glycol	1%	20.12 ± 0.12	55.42 ± 0.13	(5 ± 0.14)%	Grade 2
15	Propylene glycol	1.5%	After cooling, it separates into layers and forms lumps, and the emulsions break			

[a] Based on these results, an HLB value of 10.5 was selected for subsequent experiments, and additives were introduced to further reduce emulsion viscosity.

Table 4 Effects of *n*-butanol dosage on paraffin emulsion properties

Test number	Alcohols	Dosage[a]	Viscosity/s	Solid content/%	Centrifugal stability (effluent rate)	Dispersibility
16	*n*-Butanol	0.2%	18.57 ± 0.11	54.12 ± 0.15	Non-layered	Grade 2
17	*n*-Butanol	0.5%	20.34 ± 0.15	54.08 ± 0.14	Non-layered	Grade 2
18	*n*-Butanol	0.8%	22.79 ± 0.14	54.32 ± 0.11	Non-layered	Grade 2
19	*n*-Butanol	1%	23.22 ± 0.11	53.76 ± 0.10	Non-layered	Grade 2
20	*n*-Butanol	1.5%	23.34 ± 0.14	53.47 ± 0.12	(10 ± 0.35)%	Grade 3

[a] The dosage of alcohol-based additives is expressed as a percentage of the solid paraffin mass. The same definition applies to the dosages in Tables 3–8.

a stronger thickening effect of propylene glycol on the emulsion system.[19]

As shown in Table 4, increasing the dosage of *n*-butanol results in a gradual increase in paraffin emulsion viscosity to approximately 23 s, with limitedl variation. The solid content remains around 54%. At a dosage of 1.5%, centrifugal stability decreases, with an effluent rate of 10%, and dispersibility declines from grade 2 to grade 3. By comparing Tables 3 and 4, it can be seen that the promoting effect of *n*-butanol on emulsification is stronger than that of propylene glycol. This is because *n*-butanol is also a polar molecule, which leads to a decrease in surface activity. However, it has only one hydroxyl group, and the alkyl carbon chain is further extended compared to propylene glycol, resulting in a lower molecular polarity than propylene glycol.

As shown in Table 5, increasing the dosage of isopentanol causes the emulsion viscosity to decrease initially and then increases. This is because at low addition levels, isopentanol can achieve synergistic emulsification, refine droplets, and reduce internal friction. However, at high addition levels, isopentanol will dissolve in the aqueous phase, forming "alcohol-emulsifier mixed micelles". The large aggregation of these micelles causes an increase in the viscosity of the aqueous phase. The solid content exhibits a slight upward trend, while centrifugal stability and dispersibility remain stable across the tested range. This behavior is attributed to the adsorption of isopentanol at the oil–water interface, where it fills intermolecular gaps within the emulsifier film, enhances interfacial film strength and elasticity, and improves emulsion fluidity and stability.[20]

As shown in Table 6, increasing the dosage of polyether-modified silicone oil reduces emulsion viscosity to below 15 s, while the solid content remains approximately 54.5%. However, centrifugal stability and dispersibility deteriorate significantly with increasing dosage. This effect arises from the amphiphilic structure of the additive: hydrophobic siloxane chains adsorb onto paraffin surface, while hydrophilic polyether chains extend into the aqueous phase.[21] This configuration reduces oil–water

Table 5 Effects of isopentanol dosage on paraffin emulsion properties

Test number	Alcohols	Dosage[a]	Viscosity/s	Solid content/%	Centrifugal stability (effluent rate)	Dispersibility
21	Isopentanol	0.2%	16.21 ± 0.12	55.15 ± 0.08	Non-layered	Grade 2
22	Isopentanol	0.5%	15.19 ± 0.11	55.63 ± 0.10	Non-layered	Grade 2
23	Isopentanol	0.8%	13.02 ± 0.13	55.23 ± 0.13	Non-layered	Grade 2
24	Isopentanol	1%	22.15 ± 0.15	56.32 ± 0.12	Non-layered	Grade 2
25	Isopentanol	1.5%	22.42 ± 0.12	56.09 ± 0.14	Non-layered	Grade 2

[a] The dosage of alcohol-based additives is expressed as a percentage of the solid paraffin mass. The same definition applies to the dosages in Tables 3–8.

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Table 6 Effects of polyether-modified silicone oil dosage on paraffin emulsion properties

Test number	Alcohols	Dosage[a]	Viscosity/s	Solid content/%	Centrifugal stability (effluent rate)	Dispersibility
26	Polyether-modified silicone oil	0.2%	15.89 ± 0.11	54.78 ± 0.11	Non-layered	Grade 2
27	Polyether-modified silicone oil	0.5%	13.12 ± 0.09	54.67 ± 0.10	(10 ± 1)%	Grade 3
28	Polyether-modified silicone oil	0.8%	12.37 ± 0.10	54.69 ± 0.10	(25 ± 1.4)%	Grade 4
29	Polyether-modified silicone oil	1%	12.45 ± 0.10	54.45 ± 0.11	(40 ± 1.8)%	Grade 5
30	Polyether-modified silicone oil	1.5%	After cooling, it separates into layers and forms lumps, and the emulsions break			

[a] The dosage of alcohol-based additives is expressed as a percentage of the solid paraffin mass. The same definition applies to the dosages in Tables 3–8.

Table 7 Effects of mixture (ethylene glycol/isopentanol) on paraffin emulsion properties

Test number	Recombinant ratio (ethylene glycol : isopentanol)	Viscosity/s	Solid content/%	Centrifugal stability (effluent rate)	Dispersibility
31	3 : 1	18.89 ± 0.12	54.71 ± 0.10	Non-layered	Grade 2
32	2 : 1	18.67 ± 0.10	55.02 ± 0.11	Non-layered	Grade 2
33	1 : 1	18.43 ± 0.13	55.21 ± 0.14	Non-layered	Grade 2
34	1 : 2	16.62 ± 0.11	55.61 ± 0.10	Non-layered	Grade 2
35	1 : 3	16.38 ± 0.12	55.64 ± 0.12	Non-layered	Grade 2

interfacial tension and decreases droplet cohesion and flow resistance, thereby improving fluidity.[22] At the same time, steric hindrance from the polyether chains suppresses droplet aggregation. However, excessive addition alters the effective HLB value of the emulsifier system, disrupting the hydrophilic-lipophilic balance and leading to reduced stability and dispersibility.[23]

Under identical dosage conditions, paraffin emulsions prepared with ethylene glycol exhibit lower viscosity and better centrifugal stability and dispersibility than those prepared with propylene glycol. Similarly, emulsions prepared with isopentanol outperform those prepared with *n*-butanol.[24] Although polyether-modified silicone oil effectively reduces viscosity, it compromises stability and dispersibility at higher dosages. Therefore, two binary additive systems, namely ethylene glycol/isopentanol and ethylene glycol/polyether-modified silicone oil were further evaluated at different mass ratios, with the total additive dosage fixed at 1% of the paraffin mass. The results are presented in Tables 7 and 8.

As shown in Table 7, decreasing the ethylene glycol-to-isopentanol ratio (*i.e.*, increasing the isopentanol content) leads to a gradual decrease in emulsion viscosity. When the ratio reaches 1 : 2, the viscosity falls below 17 s, after which further changes are minimal. The solid content remains approximately 55%, and both centrifugal stability and dispersibility remain stable across all ratios.[25]

As shown in Table 8, decreasing the ethylene glycol-to-polyether-modified silicone oil ratio results in a continuous decrease in viscosity, while the solid content remains near 55%. In contrast, centrifugal stability progressively deteriorates, as indicated by the increasing effluent rate. Dispersibility initially improves from grade 2 to grade 1 and then declines with further increases in silicone oil content. At a mass ratio of 2 : 1, the emulsion achieves a viscosity of 13.89 s, a solid content of 55.43%, no stratification under centrifugal testing, and grade 1 dispersibility, meeting the target performance requirements.[26]

Polyether-modified silicone oil is a structurally controllable polymer-based interface regulator, possessing moderate hydrophobicity and hydrophilicity, only enhancing the interface and moderately reducing viscosity; while isopentanol is a small molecule amphiphilic alcohol, which competes with the interface and disrupts the hydration layer. Comparison of Tables 7 and 8 indicates that the ethylene glycol/polyether-modified silicone oil system provides a more favorable balance between viscosity reduction and emulsion stability than the ethylene

Table 8 Effects of ethylene glycol/polyether-modified silicone oil mixtures on paraffin emulsion properties

Test number	Recombinant ratio (ethylene glycol : polyether-modified silicone oil)	Viscosity/s	Solid content/%	Centrifugal stability (effluent rate)	Dispersibility
36	3 : 1	14.37 ± 0.15	54.84 ± 0.10	Non-layered	Grade 2
37	2 : 1	13.89 ± 0.13	55.43 ± 0.12	Non-layered	Grade 1
38	1 : 1	13.34 ± 0.14	55.12 ± 0.15	(2 ± 0.1)%	Grade 2
39	1 : 2	12.65 ± 0.10	54.37 ± 0.14	(5 ± 0.1)%	Grade 3
40	1 : 3	12.72 ± 0.11	54.14 ± 0.12	(10 ± 0.15)%	Grade 4

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Table 9 Reproducibility of paraffin emulsion preparation

Test number	Viscosity/s	Solid content/%	Centrifugal stability (effluent rate)	Dispersibility
41	13 ± 0.13	55.45 ± 0.08	Non-layered	Grade 1
42	14 ± 0.23	56.12 ± 0.05	Non-layered	Grade 1
43	13 ± 0.08	55.89 ± 0.04	Non-layered	Grade 1
44	13 ± 0.10	55.78 ± 0.08	Non-layered	Grade 1
45	13 ± 0.12	56.42 ± 0.10	Non-layered	Grade 1

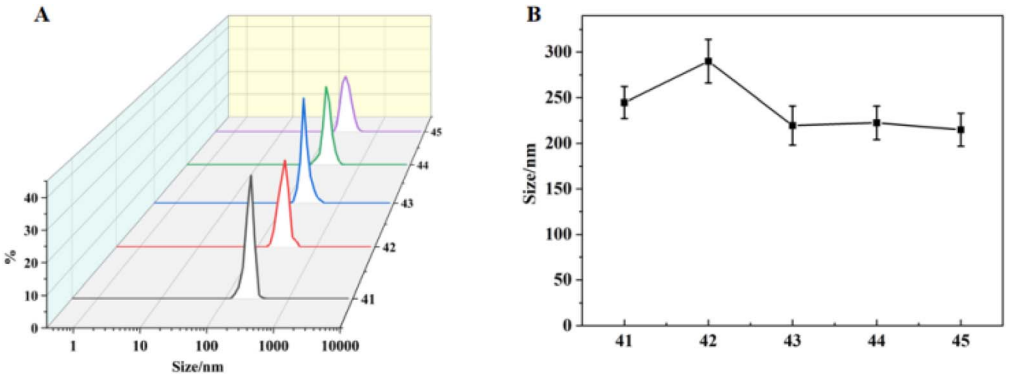

Fig. 1 Particle size distribution (A) and corresponding error bar (B) of paraffin emulsions obtained from repeated experiments.

glycol/isopentanol system and is therefore more suitable for practical application.

Repetitive trials and scale-up trials

Reproducible experiment. A total of 70 g of 58# paraffin wax and 70 mL of deionized water were added to a 250 mL three-neck flask equipped with a reflux condenser. After complete melting of the paraffin, 10.5 g of composite emulsifier (HLB value 10.5), 0.7 g of additive (ethylene glycol to polyether-modified silicone oil mass ratio of 2 : 1), and 0.7 g of stabilizer were added sequentially. Emulsification was conducted at 75 °C for 30 min under a stirring speed of 1000 rpm. After cooling to below 35 °C, the emulsion properties were evaluated.[27] The experiment was repeated five times (tests 41–45). The results are shown in Table 9, with particle size distributions presented in Fig. 1 and zeta potential in Fig. 2.

As shown in Fig. 1 and 2, the particle size of the paraffin emulsions obtained from repeated experiments is mainly distributed in the range of 100–300 nm, and the zeta potential is concentrated between 36 and 41 mV. Emulsions with zeta potential values close to 40 mV generally exhibit good stability.

Scale-up experiment (50-fold). A total of 3500 g of 58# paraffin wax and 3500 mL of deionized water were transferred into a 5 L reactor. After complete melting, 525 g of composite emulsifier (HLB value 10.5), 35 g of additive (ethylene glycol to polyether-modified silicone oil mass ratio of 2 : 1), and 35 g of stabilizer were added. Emulsification was conducted at 75 °C for 30 min under a stirring speed of 1000 rpm. After cooling to below 35 °C, emulsion properties were evaluated. The results are presented in Table 4, with particle size distribution shown in Fig. 3, zeta potential in Fig. 4, and rheological behavior in Fig. 5.

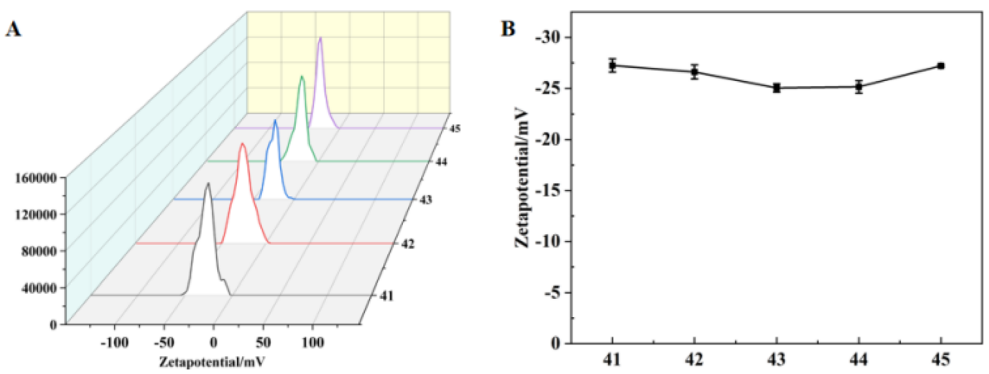

Fig. 2 Zeta potential (A) and corresponding error bar (B) of paraffin emulsions obtained from repeated experiments.

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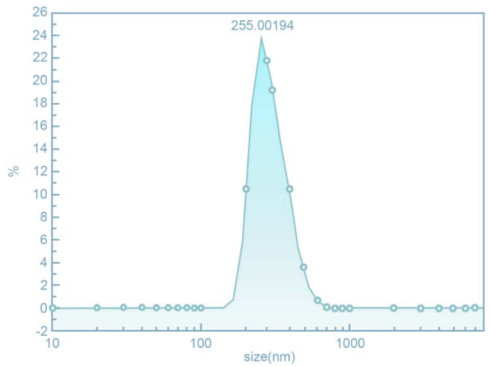

Fig. 3 Particle size distribution of the scaled-up paraffin emulsion.

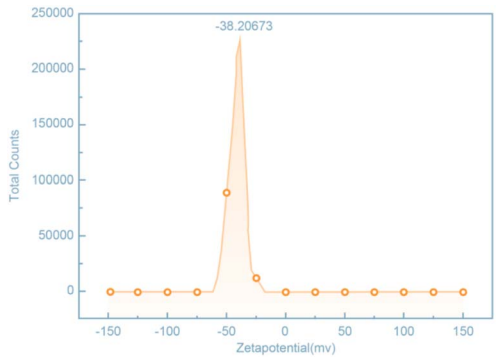

Fig. 4 Zeta potential of the expanded paraffin emulsion.

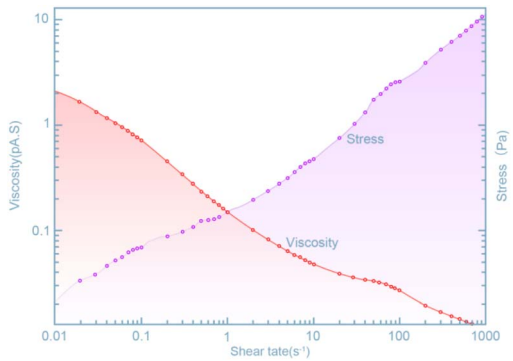

Fig. 5 Rheological properties of the scaled-up paraffin emulsion.

As shown in Fig. 3, increasing the production scale by 50 times yields a paraffin emulsion with a relatively narrow particle size distribution centered at approximately 255 nm. Fig. 4 shows that the zeta potential of the scaled-up emulsion is 38 mV, indicating good stability.[28] Fig. 5 shows that the apparent viscosity decreases with increasing shear rate, while shear stress increases correspondingly, demonstrating typical pseudoplastic fluid behavior.[29,30]

Waterproof performance of the emulsion

To evaluate the waterproof performance of the paraffin emulsion on wood-based substrates, contact angle, linear swelling rate, and volumetric swelling rate were measured. The contact angle of the emulsion was first determined. As shown in Fig. 6, the contact angle exceeds 90°, indicating good hydrophobicity and effective water repellency. For linear swelling measurement, both treated and untreated wood samples were prepared as regular rectangular specimens. The initial length was measured using a vernier caliper. The samples were then immersed in deionized water until saturation. After removal, surface water was wiped off, and the length was measured again. The calculated linear swelling rate was 2%, indicating that the paraffin emulsion significantly improves the dimensional stability of the wood. The volumetric swelling rate was determined by measuring the volume change before and after water immersion. The volumetric swelling rate was 3%, indicating effective pore sealing and strong resistance to water-induced expansion. These results demonstrate that the paraffin emulsion provides effective waterproofing and anti-swelling performance when applied to wood-based substrates.

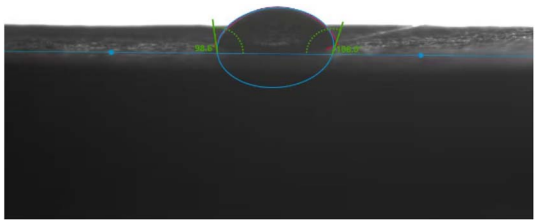

Fig. 6 Contact angle the emulsion.

Conclusions

A one-pot preparation method for high-solid-content paraffin emulsions was developed using glycerol monostearate, Pingpingjia O-20, PEG-100 stearate, and sodium dodecylbenzenesulfonate as composite emulsifiers, with small-molecule alcohols and polyether-modified silicone oil introduced as additives. The effects of HLB value and additive composition on emulsion performance were systematically investigated. At an HLB value of 10.5, the paraffin emulsion exhibited a solid content of 54.78%, a viscosity of 16 s, no phase separation under centrifugal testing, and grade 2 dispersibility. Under optimized additive conditions, the emulsion achieved a viscosity of 13 s, a solid content of 55.43%, no stratification under centrifugal testing, and grade 1 dispersibility. Reproducibility and scale-up experiments confirmed that the prepared paraffin emulsion exhibited stable quality and reliable performance. Application tests on wood substrates demonstrated good hydrophobicity, low swelling rates, and effective waterproofing performance, indicating suitability for practical use in wood-based panel production. This study has certain limitations. The investigation focused on a single preparation route and a limited range of application conditions. The effects of different wood substrates, environmental temperature and humidity, and long-term aging on emulsion stability and waterproof durability were not systematically evaluated. Further work is required to clarify process parameters and underlying mechanisms. Future research should focus on optimizing the one-pot preparation

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process to achieve high stability and cost-effective large-scale production. In addition, extending functionality to multifunctional wood composites, such as flame-retardant and anti-corrosion systems, and applying advanced characterization techniques to elucidate paraffin–wood interfacial interactions will support the development of high-performance waterproof wood-based materials.

Author contributions

Yanwei Zhang: conceptualization, funding acquisition. Xinrui Meng: methodology. Haoran Wang: supervision. Yuchen Zhao: resources. Guangqing Chai: writing-original draft.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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