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Optimization of Proportioning and Application of Shear Thickening Material from Corn Starch Aqueous Solution

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Abstract

Shear thickening materials are a class of materials whose viscosity increases with the increase of shear rate. This study takes the non-Newtonian fluid corn starch aqueous solution as an example, focuses on the research of the solvent system of shear thickening materials, selects solvents that can improve material performance, and optimizes the proportioning of shear thickening materials through orthogonal tests. The optimal proportioning scheme is determined as follows: corn starch: solvent = 45:55, where the solvent consists of ethyl oleate: butyl acetate: ethanol: amyl acetate = 45:15:15:25. Through impact resistance tests, the maximum impact energy per unit area that the shear thickening material can withstand is found to be 4.64×10^6 J/m^2. Through protection performance tests, it is determined that when the thickness of the shear thickening material is 3 mm, the effect of protecting glass bottles is optimal, and it can be applied in production and daily life.

Keywords

Non-Newtonian fluid; shear thickening material; proportioning optimization; orthogonal test; impact resistance test.

1. INTRODUCTION

Shear thickening materials, a special type of non-Newtonian fluid, exhibit a rapid increase in viscosity with increasing shear stress [1]. In their normal state, they show liquid-like softness and fluidity, but they instantly harden under high-speed impact or shear stress, demonstrating excellent impact resistance and energy absorption capabilities. Current research on shear thickening materials has made certain progress [5]. In terms of material composition, they are mostly composed of dispersed phase particles and a continuous phase medium, with performance optimized by adjusting particle concentration, particle size, and medium properties. Applications include protective equipment such as sports gear and military armor, which effectively reduce impact injuries, as well as industrial shock absorption for buffering mechanical vibrations and impacts [3]. However, limitations remain, such as significant room for improvement in material stability and composite performance with other materials.

Non-Newtonian fluids are highly diverse, including shear-thinning fluids and others. Currently, only a few types have found applications in specific fields, with numerous potential non-Newtonian fluid materials remaining undeveloped. Many theoretically superior non-Newtonian fluids have not achieved industrialization due to technical bottlenecks, high costs, or insufficient research. With technological advancements and evolving needs, there is a pressing demand in fields such as intelligent materials, biomedicine, and aerospace for developing new non-Newtonian fluid materials to meet special working conditions and functional requirements [6]. Therefore, this study focuses on the proportioning design of shear thickening materials, aiming to break through existing limitations, explore broader application potentials, provide insights for developing other non-Newtonian fluid materials, and promote their comprehensive application in production and daily life.

2. EXPERIMENTAL RAW MATERIALS AND PERFORMANCE TESTING

The raw materials involved in this study include tap water, glycerin, ethanol, corn starch, etc. Their physical properties are shown in Table 1.

Table 1. Comparison of Physical Properties of Raw Materials

Index/Solvent	Water	Glycerin	Ethanol	Silicone Oil	Propylene Glycol
Density	1 g/cm^3	1.26 g/cm^3	0.79 g/cm^3	1 g/cm^3	1.04 g/cm^3
Boiling Point	100℃	290℃	78.3℃	~250℃	~200℃
Solubility	—	Soluble in water and many organic solvents	Miscible with water, soluble in many organic solvents	Poorly soluble in water	Miscible with water, soluble in many organic solvents
Viscosity and Fluidity	Low viscosity, significantly affected by temperature; good fluidity	High viscosity, significantly affected by temperature; poor fluidity	Low viscosity, significantly affected by temperature; good fluidity	Wide viscosity range, little temperature effect; low-viscosity silicone oil has good fluidity; high-viscosity silicone oil has poor fluidity	Moderate viscosity, significantly affected by temperature; slightly worse fluidity than water
Volatility	Moderate	Poor	Strong	Low	Low
Stability	High	Good	General	Good	Good
Low-Temperature Test (-40℃ to low temperature)	Poor low-temperature resistance	Good low-temperature resistance	Good low-temperature resistance	Excellent low-temperature resistance	Good low-temperature resistance
High-Temperature Test (room temperature to 150℃)	Moderate high-temperature resistance	Moderate high-temperature resistance	Poor high-temperature resistance	Excellent high-temperature resistance	Good high-temperature resistance

As shown in Table 1, different solvents have dual characteristics, leading to the following challenges in solvent selection for shear thickening materials:

(1) Contradiction between viscosity and fluidity: Solvents need sufficient viscosity to prevent particle sedimentation (e.g., high-viscosity glycerin), but this can cause stirring difficulties. Excessively high viscosity may lead to over-thickening during impact, while too low viscosity may fail to trigger thickening.

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(2) Conflict between volatility and stability: Highly volatile solvents (e.g., ethanol) are prone to loss during storage or use, causing concentration changes and general stability; low-volatility solvents (e.g., silicone oil) may affect material curing or release performance, though they offer good stability.

(3) Temperature sensitivity: Solvent viscosity varies significantly with temperature (e.g., silicone oil viscosity surges at low temperatures), leading to unstable material performance.

To address these issues, this study proposes using a composite of oil-polar solvents to complement dissolution capabilities and adjust volatility.

3. OPTIMIZATION OF SHEAR THICKENING MATERIAL PROPORTIONING

To optimize the mix ratio of shear thickening materials, orthogonal test design was employed. The factors considered were: corn starch (Component A), ethyl oleate (Component B), bio-based butyl acetate (Component C), ethanol (Component D), and amyl acetate (Component E). Based on existing literature and relevant principles [4-7], the mass ratios of each component in the shear thickening material were estimated as follows: Component A accounts for 45%-55%, Component B accounts for 35%-45% of the total solvent, Component C accounts for 15%-25% of the total solvent, Component D accounts for 10%-20% of the total solvent, and Component E is calculated as E = 100% - B - C - D. Three different levels were set for each component within the estimated range for orthogonal test design, as shown in Tables 2 and 3.

Table 2. Factor-Level Table

Level	A/%	B/%	C/%	D/%	Blank Column
1	45	35	15	10	1
2	50	40	20	15	2
3	55	45	25	20	3

Note: General tests require a blank column; repeated tests are needed if omitted.

Table 3. Orthogonal Test Design Table

Test No.	A/%	B/%	C/%	D/%	STATUS_	CARD_
1	45	35	15	10	0	1
2	45	40	20	15	0	2
3	45	45	25	20	0	3
4	50	35	20	20	0	4
5	50	40	25	10	0	5
6	50	45	15	15	0	6
7	55	35	25	15	0	7
8	55	40	15	20	0	8
9	55	45	20	10	0	9

E (amyl acetate %) = 100 - B - C - D, with values: 40, 25, 10, 25, 25, 25, 25, 25, 25.

The actual components of each solvent calculated from Table 3 are shown in Table 4.

Table 4. Actual Solvent Component Table

Test No.	B/%	C/%	D/%	E/%
1	19.25	8.25	5.5	22
2	22	11	8.25	13.75
3	24.75	13.75	11	5.5
4	17.5	10	10	12.5
5	20	12.5	5	12.5
6	22.5	7.5	7.5	12.5
7	15.75	11.25	6.75	11.25
8	18	6.75	9	11.25
9	20.25	9	4.5	11.25

The key performance indicators of the shear thickening material in this study include: Index 1: Shear thickening strength (Y1); Index 2: Dispersion stability (Y2); Index 3: Low-shear fluidity (Y3) [2]. The test data and calculations are shown in Table 5.

Table 5. Orthogonal Test Performance Index Analysis Table

Test No.	Y1 (Pa·s)	Y2 (%)	Y3 (Pa·s)	Comprehensive Score
1	80	5	2.5	82
2	75	3	3.0	80
3	90	4	4.0	85
4	60	8	2.0	68
5	70	6	3.5	72
6	85	2	2.8	86
7	50	10	1.5	58
8	65	7	2.2	69
9	78	3	3.8	80

The average comprehensive scores and range (RA) of each factor calculated from Table 5 are shown in Table 6.

Table 6. Average Scores and Range of Each Factor Level

Level	Mean Score	Range (RA)
A (45%)	82.33	13.33
A (50%)	75.33	—
A (55%)	69.00	—
B (35%)	69.33	14.34
B (40%)	73.67	—
B (45%)	83.67	—
C (15%)	79.00	7.33
C (20%)	76.00	—
C (25%)	71.67	—
D (10%)	78.00	8.00
D (15%)	78.33	—
D (20%)	70.33	—

Based on the calculations, the optimal proportioning scheme is determined as: corn starch: solvent = 45:55, with the solvent composition being ethyl oleate: butyl acetate: ethanol: amyl acetate = 45:15:15:25.

4. RESEARCH ON IMPACT RESISTANCE OF SHEAR THICKENING MATERIAL

4.1. Impact Resistance Test

This study aims to compare the maximum impact energy per unit area that shear thickening materials can withstand under different impact energies.

(1) Test Equipment and Materials

Custom-made adjustable-height support crossbar (a), 3.7 g test needle (b), 50 g cylindrical weight (c), 100 g cubic counterweight (d), and shear thickening material prepared according to the proportion (e), as shown in Figure 1.

(a) Support crossbar; (b) Test needle; (c) Weight;

(d) Counterweight; (e) Shear thickening material

Figure 1. Impact Test Apparatus and Materials

(2) Test Design

A variable-controlled method was used, with the independent variables being the drop height and mass of the object, and the dependent variable being the impact energy per unit area of the shear thickening material. The test design is shown in Table 7.

Table 7. Impact Test Design Table

Test No.	Height h (m)	Mass m (g)
1	1	3.7
2	2	3.7
3	3	3.7
4	1	50
5	2	50
6	3	50
7	1	100
8	2	100
9	3	100

(3) Test Procedure

Place the prepared shear thickening material on the ground, adjust the support crossbar to 1 m height, use hooks and rubber bands on the crossbar to hang the three test objects, determine the object position using vertical alignment, cut the rubber bands to let the objects fall vertically, and observe changes in the shear thickening material. Repeat the steps by increasing the support crossbar height to 2 m and 3 m, as shown in Figure 2.

Figure 2. Test diagram of the weight at 1.5 meters

(4) Test Results

The impact energy (E) was calculated using formula (1): E=mgh

Where E= impact energy, g= gravitational acceleration (9.8 m/s^2), m = mass of the falling object (g), h = free-fall height (m).

The impact energy per unit area (Er) was calculated using formula (2) based on the contact area (A): Er=E/A

where Er = impact energy per unit area (J/m^2), E — impact energy(J), A= contact area (m^2).

Results are shown in Table 8.

Table 8. Impact Energy per Unit Area

Test No.	Impact Energy E (J)	Contact Area (cm^2)	Impact Energy per Unit Area (J/m^2)
1	0.0363	7.85×10^{-5}	4.64×10^{6}
2	0.0725	7.85×10^{-5}	9.24×10^{6}
3	0.1088	7.85×10^{-5}	1.386×10^{7}
4	0.49	3.14	1560.51
5	0.98	3.14	3121
6	1.47	3.14	4681.53
7	0.98	16	612.5
8	1.96	16	1225
9	2.94	16	1837.5

During the test, when the height of the bracket crossbar was 1 meter and the falling object was the test needle, a clear sound of hitting the bottom of the container was heard, which did not occur when the other two objects fell. It can be seen that the maximum impact energy per unit area that the shear thickening material can withstand is 4.64×106J/m2. As shown in Figure 3.

Figure 3. Diagram of the state after the test needle falls

4.2. Protection Performance Test of Shear Thickening Materials

This test aims to compare the protection performance of shear thickening materials with different thicknesses under varying impact energies.

(1) Test Equipment and Materials

Glass bottle (a), shear thickening material prepared according to the proportion (b), and 10-micron-thick aluminum foil paper (c). As shown in Figure 4.

Glass bottle (a) shear thickening material (b) aluminum foil paper (c)

Figure 4. Equipment and materials for the protection performance test

(2) Test Design Scheme

A variable-defined test method was adopted, where the independent variables were the dropping height of the glass bottle and the thickness of the wrapped shear thickening material, and the dependent variable was the intactness of the glass bottle. The test design is shown in Table 9.

Table 9. Protection Performance Test Design

Test No.	Height h (m)	Material Thickness t (mm)
1	1	1
2	1.5	1
3	2	1
4	1	3
5	1.5	3
6	2	3
7	1	5
8	1.5	5
9	2	5

(3) Test Procedure

Wrap a 1-mm-thick shear thickening material around the exterior of the glass bottle with 10-micron-thick aluminum foil paper. Manually place the glass bottle at a height of 1 meter above the ground, release it to let it fall to the ground under its own gravity, and observe whether the glass bottle remains intact. Continue to increase the dropping height to 1.5 meters and 2 meters, and change the material thickness, then observe the intactness of the glass bottle.

(4) Test Results

When the glass bottle was placed at a height of 2 meters from the ground and wrapped with a 1-mm-thick material, the glass bottle broke. The results are shown in Table 10.

Table 10. Intactness of Glass Bottle

Test No.	Intactness of Glass Bottle
1	Intact
2	Intact
3	Not intact
4	Intact
5	Intact
6	Intact
7	Intact
8	Intact
9	Intact

It can be seen from Table 10 that when the thickness of the shear thickening material is 3 mm, the protection effect is good, the consumption of the shear thickening material is small, and the cost is the lowest.

5. CONCLUSIONS

To prepare a shear thickening material with excellent impact resistance, this study optimized the existing mix proportion, carried out impact resistance tests on the optimized shear thickening material, and tested its protection performance. The conclusions are as follows:

(1) Through orthogonal tests, the optimal mix proportion scheme was determined: corn starch: solvent = 45:55, where the composition of the solvent is ethyl oleate: butyl acetate: ethanol: amyl acetate = 45:15:15:25.

(2) Through impact resistance tests, the maximum impact energy that the shear thickening material can withstand per unit area is 4.64×106J/m2.

(3) Through the protection performance test of the shear thickening material, the drop resistance results of the glass bottle show that when the thickness of the shear thickening material is 3 mm, the protection effect is good, the consumption of the shear thickening material is small, and the cost is the lowest, which can be applied to the production of glass bottle protective covers.

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