CHEMISTRY AND MATERIALS
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MAGICAL LIQUID UNVEILED! ELECTRIC AND MAGNETIC FIELDS FREEZE IT INSTANTLY

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YOUNG REVIEWERS:

BNS
HUGE FRESH
AGES: 13–14

INQUISITIVE PANDA (爱问熊猫)
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You surely know that the transition between the liquid and solid states of materials can be controlled by changing the temperature. But did you know that this transition can also be achieved using magnetic or electric fields? Some substances, called electrorheological fluids, can have their physical state changed by an electric field. Other substances, called magnetorheological fluids, can change states under the influence of a magnetic field. Under the influence of magnetic or electric fields, the particles in these fluids line up a certain way, forming structures that turn the fluids from a flowing liquid to a state similar to a solid. Electrorheological and magnetorheological fluids have many possible uses, such as controlling vibration in buildings or in certain kinds of robots.

SOLIDS AND LIQUIDS

Solids, liquids, and gases are the three states of matter that you are probably familiar with. The term "materials" might make you might think of stone, bronze, iron, and steel, for example, which could stem from the fact that eras are named after the materials humans used, such as the Stone Age, Bronze Age, Iron Age, and Steel Age. These materials share a common characteristic: they are all hard solids. Of course, you might also think that the paint you use for oil painting or painting walls, and even liquids like water should be considered materials too, but their state is significantly different from solids like steel. The most obvious difference is that these liquids flow.

Are substances like rubber, plastic, glass, pitch, starch paste, jelly, pudding, and toothpaste solid or liquid? You might say that they are solids, but the truth is not so simple. If you exert a constant force, even a minor one, upon these substances and observe for a sufficiently long period, you will discover that they flow like water! And when you withdraw the external force, they tend to return to their original form, yet this recovery also takes a relatively long time, and they do not recover completely as do common solids like steel.

Here are a few examples. When you apply a small and constant force to a rubber band, it gradually gets longer. And when you withdraw the force, it gradually contracts. When you step into a building with ancient glass windows, you might observe that the glass is thicker at the bottom and thinner at the top. This is because, under the continuous influence of gravity, the glass flows downward—yet the flow is much slower than the flow of water.

Here is a famous but rather boring experiment. In 1927, to demonstrate that pitch has the properties of a fluid, some scientists put a pitch sample into a funnel with a sealed opening. Three years later, the seal of the funnel was cut open. The scientists were convinced that, under the continuous effect of gravity, the pitch would flow. They wanted to know just how slow this flow would be. This is the longest-running experiment recorded in the Guinness World Records (Figure 1), and as of now, people have recorded 9 drops of pitch falling—the last drop falling on July 9, 2013 [1].

So, you can see that there is no clear boundary between solids and liquids. The vast majority of substances are actually in a state between completely solid and completely liquid, with the difference lying only in whether the substance has more properties similar to steel or water. These substances are called **viscoelastic materials**—they exhibit both the elasticity (means a material can change shape when pushed or pulled and then return to its old shape) of steel and the **viscosity** of water. In plain language, they are also called semi-solids or soft matter.

VISCOELASTIC MATERIALS

Materials that stretch like rubber (elastic) and flow like syrup (viscous), depending on the force and speed of stretching. They act between a solid and a liquid.

VISCOSITY

A measure of how thick or thin a fluid is. Thick fluids have high viscosity.

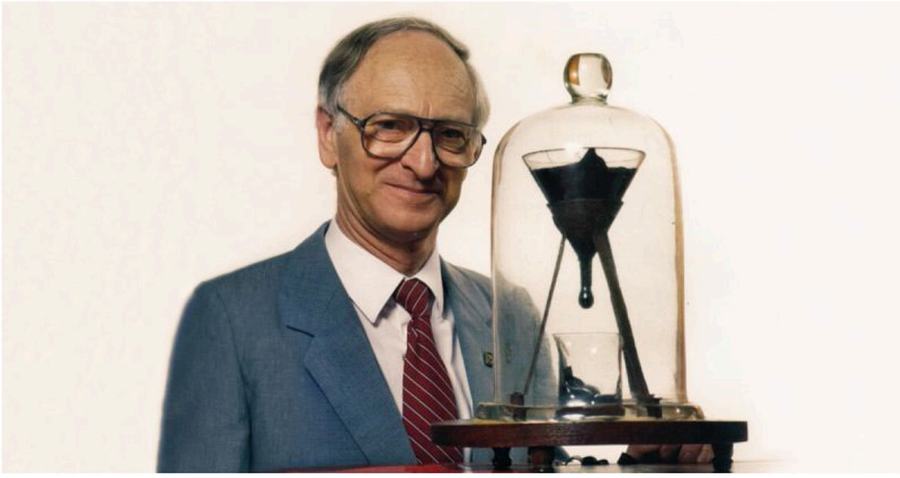

Figure 1

Figure 1

The-pitch-drop-experiment is the longest-running experiment recorded in the Guinness World Records [1]. Since the experiment began in 1927, nine drops of pitch have fallen. This proves that pitch has some of the properties of a liquid.

TEMPERATURE CHANGES THE STATE OF MATERIALS

You probably already know that we can control the state of matter through temperature. The most typical example is water. When we heat ice, it turns into water at temperatures above 0°C, and when the temperature rises above 100°C, it evaporates into steam.

Similarly, when we heat plastic, it gradually becomes soft; when we cool rubber, it gradually becomes hard and even brittle. The main reason for the Challenger space shuttle disaster in 1986 was the loss of elasticity of the rubber seals at low temperatures, leading to fuel leakage. At that time, the famous physicist Richard Feynman helped investigate the accident, and he demonstrated the cause of the disaster using an experiment with ice water and rubber (see this video) [2].

In fact, rubber and plastic are just different states of substances called polymers that exist at different temperatures. Polymers are like long chains of tiny pieces all joined together. At lower temperatures, polymers cannot be deformed (change shape) very easily, but as the temperature rises, the ability of polymer materials to deform gradually increases. Within a certain temperature range, polymers are easy to deform, with properties similar to rubber. When we continue to raise the temperature, polymers eventually change into a fluid state, which is thicker than water.

MATERIALS WHOSE STATE CAN BE CONTROLLED BY MAGNETIC OR ELECTRIC FIELDS

Besides temperature, are there other ways to change the physical state of matter?

In 1948, a scientist named Jacob Rabinow mixed magnetic particles with oil to form a **suspension** [3]. When a magnetic field is applied to this suspension, the magnetic particles align in chains along the direction of the magnetic field. When the magnetic field is increased, these particles even form the shape of columns. At this point, the liquid completely loses its fluidity and behaves more like a solid than a liquid. When the magnetic field is removed, it returns to the original fluid state (Figure 2). Yes, Rabinow changed the state of matter using a magnetic field!

SUSPENSION

A mixture where solid particles are spread in a liquid without dissolving.

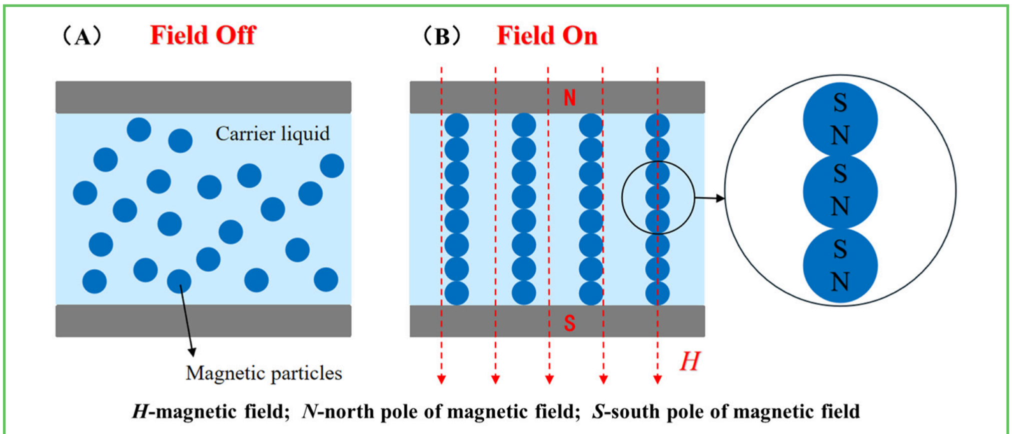

Figure 2

Figure 2

Scientists created a suspension of magnetic particles in oil, called a magnetorheological fluid. **(A)** In the absence of a magnetic field, the particles were unorganized and behaved like a fluid. **(B)** In the presence of a magnetic field, the particles became organized in columns, and the material behaved like a solid.

Scientists do not simply describe the state of matter as solid or liquid. They also use another concept called **shear yield strength**, which is the critical value of shear stress below which the fluid behaves like a solid and does not flow. To understand this concept, think of toothpaste. When you do not squeeze the toothpaste, it acts like a solid; but when you squeeze the toothpaste with a certain force, it has properties similar to a fluid. The difference between states of matter lies only in the magnitude of the shear yield strength. From this perspective, the shear yield strength of water is approximately zero, while that of steel is very large. The shear yield strength of the material Rabinow discovered can be quickly and reversibly controlled by a magnetic field. At high magnetic field strengths, its shear yield strength is very high. Rabinow named this fascinating substance a **magnetorheological fluid**. To help people understand the high shear yield strength of magnetorheological fluids under a magnetic field, he made a demonstration device, proving that the magnetorheological fluid could support the weight of a 117-pound girl (Figure 3). For a more vivid and detailed introduction to magnetorheological fluid, please refer to **Video 1**.

SHEAR YIELD STRENGTH

The smallest force needed to permanently change a material’s shape under sliding stress. Below this force, the material bends but bounces back; above it, changes are permanent.

MAGNETORHEOLOGICAL FLUIDS

Liquids with tiny magnetic particles that can quickly turn thicker or solid-like when a magnetic field is applied, making them useful for things like shock absorbers or brakes.

VIDEO 1

The magical magnetorheological fluid.

Could we also invent a liquid that can have its shear yield strength controlled by an electric field?

A year before Rabinow invented magnetorheological fluids, American scholar W. M. Winslow applied for a patent for **electrorheological**

Figure 3

Rabinow made a demonstration device with a magnetorheological fluid, proving that it could support the weight of a 117-pound girl [3].

ELECTRORHEOLOGICAL FLUIDS

Liquids that become thicker or more solid-like when an electric field is applied. They contain tiny particles that react to electricity, making them useful in devices like clutches or vibrational dampers.

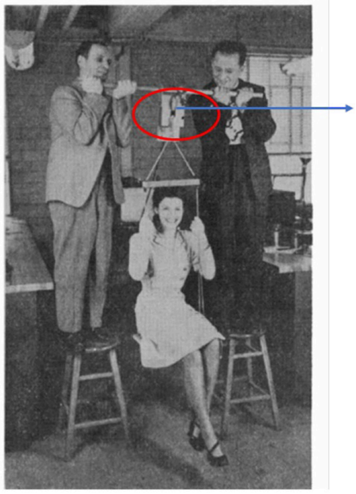

Figure 3

fluids [4]. He mixed some starch, silica, and oil together to make a kind of suspension. Then, when he put this suspension in an electric field, he found that it had a really strong resistance to being pushed or pulled sideways. This resistance is called shear yield strength, and it was very high in this case. In 1949, Winslow conducted more in-depth research with limestone, flour, and other substances, and proved that this material could quickly return to a fluid-like state after the electric field was removed [5]. This effect of a liquid state control by an electric field is called the electrorheological effect, or Winslow effect. Electrorheological fluids behave similarly to magnetorheological fluids: under an electric field, the surfaces of the particles generate positive and negative charges, causing oppositely charged particles to attract each other, forming chain-like or columnar structures along the direction of the electric field. This gives the suspension a higher shear yield strength, so it has properties similar to solids. It's like when you make a thick slime. The slime can hold its shape and doesn't just run all over like water. That's because it has a kind of strength that makes it act more like a solid, just like the suspension with higher shear yield strength. Unfortunately, the shear yield strength of early electrorheological fluids was usually rather low, and other technical problems made these fluids less useful than magnetorheological fluids. However, in the past 20 years, researchers have developed new electrorheological fluids with higher shear yield strength, increasing the potential uses of electrorheological fluids.

STRUCTURAL VIBRATION DAMPING

The process of reducing building shakes using special materials or devices.

USES OF MAGNETORHEOLOGICAL AND ELECTRORHEOLOGICAL FLUIDS

The main use of magnetorheological and electrorheological fluids is **structural vibration damping**. You probably know that strong vibrations can damage or destroy structures like buildings. For example, tens of thousands of buildings collapse due to earthquakes every year, and many people lose their lives due to such disasters. Even if you have not experienced an earthquake, you have probably felt the bumps on uneven roads when riding in a car. Controlling the vibrations of buildings and vehicles is very important. Engineers have found that including devices that specifically decrease vibrational energy can reduce the vibration of a structure, avoiding damage. Such devices are called dampers. Some dampers, called **viscous dampers**, contain a liquid that provides resistance due to the viscosity of the liquid, which is essentially similar to the principle of you gradually stopping when swinging on a swing due to wind resistance [6]. However, the viscosity and shear yield strength of the liquid in ordinary viscous dampers cannot be adjusted, so they are only effective for certain vibration conditions. If the liquid in the viscous damper is replaced with magnetorheological fluid or electrorheological fluid, and a device for applying a magnetic or electric field is set up, more effective vibration damping can be achieved. These dampers are called magnetorheological dampers or electrorheological dampers [7]. Building structures with magnetorheological or electrorheological dampers can provide better vibration damping effects. For example, using these two types of dampers in car suspension systems can make the vehicle's driving smoother, more comfortable, and safer (see this video). Magnetorheological and electrorheological fluids can also be used to make artificial limbs (called prosthetics), joints of intelligent robots, and more [8].

VISCOUS DAMPERS

Devices that reduce vibrations by using a fluid to absorb and slow down movement. They turn vibration energy into heat, helping protect structures and machines from shaking too much.

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CONFLICT OF INTEREST: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

BNS HUGE FRESH, AGES: 13–14

Hello! We are seventh-grade students from a school in China. We have a strong passion for exploring science. During a science class, we were amazed by the wonders of the "Giant Vegetable Valley", which inspired us to name our group **Huge Fresh**. The word "Fresh" also represents our curiosity and enthusiasm for experiencing the world. Our group avatar was even created using AI technology we recently learned!

INQUISITIVE PANDA (爱问熊猫), AGES: 11–14

The group Inquisitive Panda consists of four members aged 11 to 14, spanning grades from fifth to ninth (junior high). Among them are a future astronomer, a math and physics enthusiast who also loves soccer, an avid reader of science and literature books, and an imaginative thinker who constantly asks "why" and documents their questions in a curiosity diary.

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Xufeng Dong is a Professor, Ph.D. Supervisor, and Associate Dean at the School of Materials Science and Engineering, Dalian University of Technology. He serves as the Editor-in-Chief of *Progress in Chinese Materials Science*, a super cool journal—like its "captain" steering the ship. He also leads Dalian University of Technology's "High-Performance Smart Composite Materials Preparation and Engineering Applications" Young Scientists Team, acting as the "super captain" of this fantastic group. On one hand, his research focuses on making materials as smart as humans (the "smart materials" discussed in this article); on the other hand, he cares deeply about human health, developing materials to repair the human body (biomedical materials). *dongxf@dlut.edu.cn