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Study on real-time water absorption characteristics of syntactic foams

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A system for real-time monitoring of water absorption of floating materials based on underwater strain gauges, a deep-sea high-pressure simulation chamber and strain gauges has been created. Changes in the rate of water absorption of synthetic foams in a simulated high pressure environment were monitored in real time to achieve two critical hydrostatic pressures for safety and ultimate failure. The results show that a real-time water absorption monitoring using the system based on underwater deformation detection is a suitable detection method. It can truly reflect the real-time water absorption rate change of the material during a full cycle of hydrostatic pressure, which can greatly reduce the detection load and improve efficiency.

Keywords: syntactic foams, hydrostatic pressure, real-time water absorption rate.

Дослідження характеристик водопоглинання синтаксичних пінопластів у режимі реального часу. *Jian Guo, Binbin Pan, Weicheng Cui, Shengbing Hu, Zhiyang Han*

Створено систему моніторингу водопоглинання плавучих матеріалів у режимі реального часу на основі підводних тензометрів, глибоководної камери високого тиску моделювання та тензометрів. Зміни у швидкості водопоглинання синтаксичних пінопластів у симульованому середовищі високого тиску відстежувалися в режимі реального часу, прагнучи до двох критичних гідростатичних тисків для безпеки та остаточної відмови. Результати показують, що система моніторингу водопоглинання в режимі реального часу, заснована на підводному виявленні деформації, є відповідним методом виявлення. Він може справді відображати зміну швидкості водопоглинання матеріалу в режимі реального часу протягом повного циклу гідростатичного тиску, що може значно зменшити навантаження на виявлення та підвищити ефективність.

1. Introduction

Currently, one of the most promising and widely used in the marine, aerospace, construction and military fields are syntactic foams [1, 2]. As a new type of floating material for marine equipment with low density, low water absorption rate and high compressive strength, deep ocean syntactic foam not only has excellent corrosion resistance and impact resistance, but also can overcome the limitations of traditional syntactic foams in volume and form. This contributes to the miniaturization and aesthetics of marine structures [3]. The syntactic foam composed of hollow glass microspheres and an epoxy resin matrix can maintain sufficient strength under low density conditions and can be applied to deeper seas, so it has been widely concerned [4–6]. In view of the particularity of syntactic foams, a certain safety factor must be considered

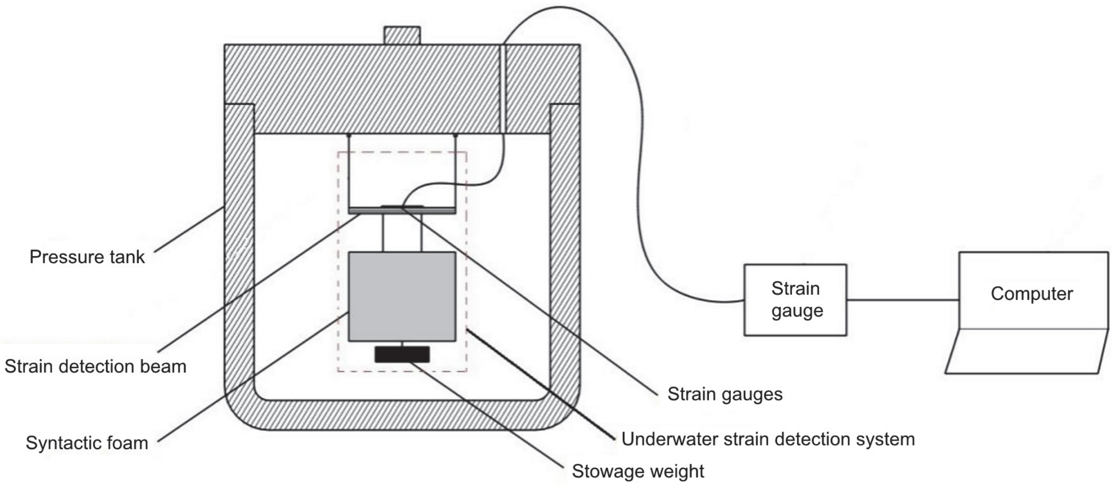

Fig. 1. Real-time water absorption test system for syntactic foams under full ocean depth.

when these are applied to marine engineering equipment; and the change of water absorption performance under high pressure environment is one of the main indicators to measure the safety performance of deep-sea syntactic foams [7, 8]. At present, we know only the water absorption rate of syntactic foams in initial and final states, and they are all performance parameters at atmospheric pressure [9], which does not meet the actual working environment of deep-sea equipment such as manned submersibles.

According to the corresponding relationship between the water absorption rate of the syntactic foam and the real-time strain, the real-time change of the full cycle water absorption rate of the syntactic foam in a simulated deep-sea environment was monitored by the water absorption rate using a real-time monitoring system. This provides reliable performance parameters for the comprehensive evaluation of the performance of syntactic foams and provides some theoretical justification for the integrated safety factor of manned submersibles and many other deep-sea engineering structures.

2. Experimental

2.1 Materials

The real-time water absorption test sample of the syntactic foam used for full ocean depth is the HZ-42 model produced by Engineered Syntactic Systems, and its specific physical characteristic parameters are shown in Table 1.

Table 1. Physical characteristics of HZ-42 syntactic foams [10]

Physical characteristics	
Sizes, mm	610×305×100
Density, kg·m^{-3}	667.04
Service pressure, MPa	113
Compressive Modulus, GPa	3.5
Crush Pressure, MPa	169
Water Absorption, %	<1

2.2 Experimental setup and method

The deep-sea pressure environment simulation chamber (≤180 MPa) is provided by the Shanghai Engineering Research Center of Hadal Science and Technology; the strain detection equipment is obtained from the Japanese KYOWA strain gauge (UCAM-60B). The experimental setup is shown in Fig. 1.

2.3 Test method

(1) Preliminary preparation: The test sample is weighed after drying, and the volume and density of the sample are measured under normal pressure;

(2) Pre-compression test: The syntactic foam is subjected to a pre-pressure testing under 20 MPa, and the pressure increases or decreases un iformly at a rate of 2 MPa/min. After the pre-compression, the material is sequentially dried, weighed and density measured. The weight and density at this time are used as the initial values of the material.

(3) Safety pressure test: pressure is increased evenly to 143.8 MPa at a rate of 2 MPa/min, held for 2 h, and then the pressure is released to 0 MPa at a rate of 2–3 MPa/min. After taking out the sample, the surface state is observed and quickly cleaned and dried. It is required to complete the physical parameter measurement of the sample within 15 minutes.

(4) Ultimate failure pressure test: the pressure is increased evenly to 165 MPa at

a rate of 2 MPa/min, held until the material breaks down, and then released to 0 MPa at a rate of 2 3 MPa/min. After taking out the sample, the surface state is observed and quickly cleaned and dried. It is required to complete the physical parameter measurement of the sample within 15 minutes.

2.4 Research method of real-time water absorption

Water absorption is defined as the degree of absorption of water molecules by materials immersed in water [11]. The loss of buoyancy of syntactic foams under hydrostatic pressure conditions can be fully detected using a real-time subsea strain detection system.

2.4.1 Total buoyancy loss of syntactic foams

The total buoyancy loss of syntactic foams under hydrostatic pressure is mainly caused by the volume shrinkage of the material and water absorption [12].

$$F = F_e + F_a, \qquad (1)$$

where F is the total buoyancy loss under hydrostatic pressure; F_e is the buoyancy loss caused by volume contraction; F_a is the buoyancy loss caused by water absorption.

2.4.2 Underwater strain detection system

The material of the underwater strain detection beam is 316L stainless steel. The length of the beam is 400 mm, the width is 10 mm, and the thickness is 2 mm. The schematic diagram of the specific detection system is shown in Fig. 2, and the cross section of the detection beam is shown in Fig. 3.

The moment of inertia of the beam section is

$$I_x = \frac{ab^3}{12}, \qquad (2)$$

where I_x is the moment of inertia of the beam section; a is the width of the section (m); b is the height of the section (m).

The bending moment of the slat beam is

$$M_c = \frac{1}{2} \cdot F_x \cdot \frac{L}{3}, \qquad (3)$$

where M_c is the bending moment of the beam; F_x is the concentrated force on the beam; L is the length of the slat beam.

The normal stress of the slat beam in pure bending is

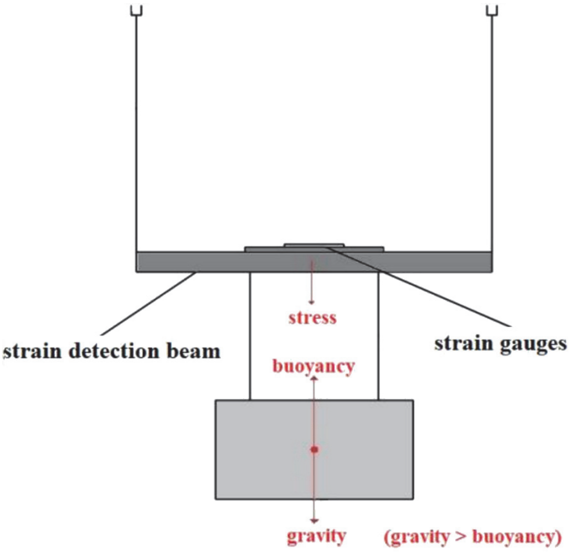

Fig. 2. Underwater strain detection system for syntactic foams.

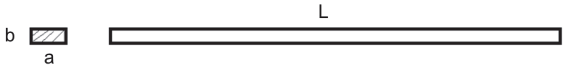

Fig. 3. Cross section of beam for underwater strain detection.

$$\left.\begin{array}{l} \sigma = \dfrac{M_c \cdot y}{I_x} \\ I_x = \dfrac{a \cdot b^3}{12} \\ y = \dfrac{b}{2} \\ \sigma = E \cdot \varepsilon \end{array}\right\} \Rightarrow M_c = \frac{E \cdot \varepsilon \cdot a \cdot b^2}{6}. \qquad (4)$$

Here σ is the normal stress at any point on the cross-section of the beam; I_x is the inertial distance of the cross-section facing the neutral axis; y is the distance from the normal stress point to the neutral axis.

The concentrated force on the beam is

$$F_x = \frac{E \cdot \varepsilon \cdot a \cdot b^2}{L}, \qquad (5)$$

where E is the Young's modulus of the syntactic foam (Pa); ε is the strain value at the strain gauge on the beam when the pressure is P MPa.

In summary, the total buoyancy loss of syntactic foams after P (MPa) pressure is

$$F = F_x = \frac{E \cdot \Delta\varepsilon \cdot a \cdot b^2}{L}, \qquad (6)$$

where F is the total buoyancy loss under hydrostatic pressure; Δε is the change value of the axial strain of the cross section under the pressure of 0 to P (MPa).

2.4.3 Buoyancy loss due to volume shrinkage

The volumetric shrinkage of syntactic foams under hydrostatic pressure is related to hydrostatic pressure and volumetric elastic modulus, but not to the shape and volume of the material [12].

In view of the fact that the syntactic foam belongs to a uniform brittle solid material, which is isotropic, the main direction of stress coincides with the main direction of strain [13]. Under the action of hydrostatic pressure, any unit body inside the syntactic foam (Fig. 4) is subjected to compressive stress in three directions, and the principal stress and corresponding principal strain in the three directions are equal.

$$\begin{cases} \sigma_1 = \sigma_2 = \sigma_3 = \sigma = -P \\ \varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon \end{cases}, \quad (7)$$

where P is the hydrostatic pressure of the syntactic foam, $-P$ means, that the material is compressed; σ_1, σ_{21} and σ_3 are the principal stress values in the three compressive stress directions of the unit body under the pressure of P (MPa); ε_1, ε_2 and ε_3 are corresponding principal strains in the principal stress direction.

According to the generalized Hooke's law of isotropic materials, the principal stress in each direction is determined from the following formulas:

$$\begin{cases} \varepsilon_1 = \frac{1}{E}[\sigma_1 - \mu(\sigma_2 + \sigma_3)] \\ \varepsilon_2 = \frac{1}{E}[\sigma_2 - \mu(\sigma_1 + \sigma_3)], \\ \varepsilon_3 = \frac{1}{E}[\sigma_3 - \mu(\sigma_1 + \sigma_3)] \end{cases} \quad (8)$$

where μ is the Poisson's ratio of the syntactic foam; E is the elastic modulus value.

Combining equations (7) and (8):

$$\varepsilon = \frac{-P(1-2\mu)}{E}. \quad (9)$$

The volume shrinkage rate of the unit body when the hydrostatic pressure is P *(MPa)*:

$$e = \frac{V_p - V_0}{V_0} \times 100\% = \quad (10)$$

$$= \frac{[(1+\varepsilon_1)dx \cdot (1+\varepsilon_2)dy(1+\varepsilon_3)dz] - dxdydz}{dxdydz} \cdot 100\%$$

$$\approx (\varepsilon_1 + \varepsilon_2 + \varepsilon_3) \cdot 100\% = 3\varepsilon \cdot 100\%,$$

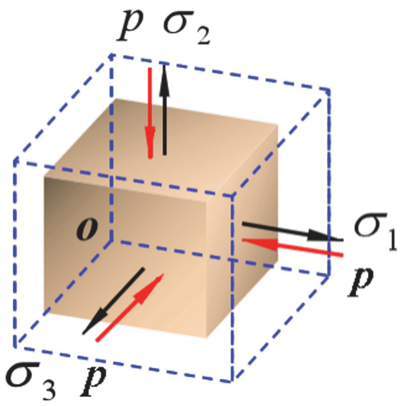

Fig. 4. Unit body of syntactic foams.

Here e is the volumetric shrinkage of the syntactic foam under hydrostatic pressure; V_0 is the initial volume of the syntactic foam; V_p is the volume of the syntactic foam at P (MPa) pressure.

In summary, the buoyancy loss caused by the volume contraction of the syntactic foam is

$$F_e = (V_p - V_0) \cdot \rho \cdot g = \quad (11)$$

$$= V_0 \cdot e \cdot \rho \cdot g = 3 \cdot V_0 \cdot \varepsilon \cdot \rho \cdot g =$$

$$= \frac{3V_0 \cdot \rho \cdot g \cdot P(1-2\mu)}{E},$$

where ρ is the density of the liquid medium, $\rho = 997.6\ \mathrm{kg/m^3}$; $g = 9.8\ \mathrm{m/s^2}$ is the acceleration of gravity.

2.4.4 Buoyancy loss due to water absorption

As the pressure value and duration change, the water absorption behavior of the syntactic foam will change accordingly, so that the buoyancy of the syntactic foam will be lost. Based on the above formulas (1), (6) and (11):

$$F_a = F - F_e =.$$

$$= \frac{E \cdot \Delta\varepsilon \cdot a \cdot b^2}{L} - \frac{3V_0 \cdot \rho \cdot g \cdot P(1-2\mu)}{E}, \quad (12)$$

2.4.5 Real-time water absorption of syntactic foams

According to the principle of conservation of energy, the buoyancy loss caused by the water absorption of the syntactic foam can also be expressed as:

$$F_a = \Delta M \cdot g = (M_0 \cdot \eta) \cdot g = V_0 \cdot \rho_0\, \eta\, g, \quad (13)$$

where η is the water absorption rate of the syntactic foam at pressure of P (MPa); ρ_0 is the initial density of the syntactic foam.

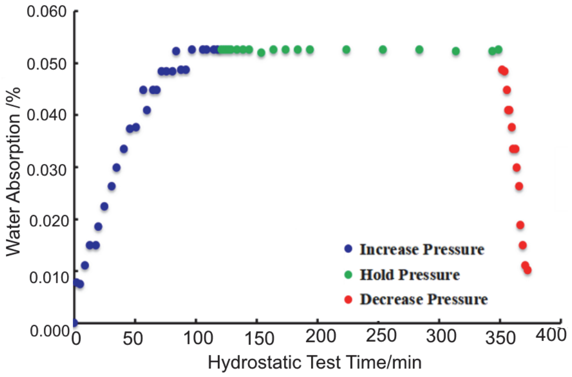

Fig. 5. Time of each stage of hydrostatic pressure test (≤143.8 MPa) and water absorption of corresponding syntactic foams.

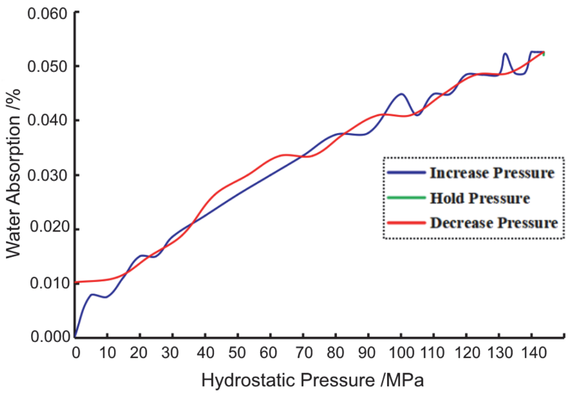

Fig. 6. Effect of hydrostatic pressure (≤143.8 MPa) on the water absorption of syntactic foams.

The above formulas (12) and (13) show that:

$$\eta = \frac{E \cdot \Delta\varepsilon \cdot a \cdot b^2}{V_0 \cdot \rho_0 \cdot g \cdot L} - \frac{3 \cdot \rho \cdot P(1 - 2\mu)}{\rho_0 \cdot E}. \quad (14)$$

3. Results and discussions

The characteristics of water absorption and crushing strength under the action of hydrostatic pressure are the two most important characteristics of buoyant materials. The water absorption of buoyant materials is mainly due to three factors: hollow glass beads, epoxy resin matrix, interface defects of epoxy resin and glass beads [14, 15]. Hollow glass beads are an inorganic material, and their water absorption under safe pressure is basically negligible [16]; thus, the water absorption of the epoxy resin matrix and the defect of the two-phase interface are the dominant factors in the water absorption of syntactic foams.

3.1 Real-time change of water absorption under safe hydrostatic pressure

The rate of water absorption of syntactic foams will change significantly only in the moment when the hydrostatic pressure exceeds a certain critical value of the material [4]. After being maintained at a pressure of 143.8 MPa for 2 hours, the overall test performance of the syntactic foam is good, the appearance is complete, and there is no obvious cracking, shedding and depression. The time of each stage of the hydrostatic pressure test and the corresponding water absorption rate of syntactic foams are shown in Fig. 5. After the hydrostatic pressure test, the weight of the syntactic foam increased by about 2.0 g, the density reached 668.50 kg/m^3, and the water absorption rate was 0.01 %.

The whole process of water absorption of syntactic foams under the action of hydrostatic pressure was monitored by the real-time water absorption monitoring system. The results showed that the water absorption rate had a uniform positive correlation with an increase or decrease of hydrostatic pressure. During the pressure holding period, the monitored water absorption rate of the material remains basically unchanged, and no obvious change point appears, as shown in Fig. 6. It can be seen that the water absorption rate of the buoyant material reaches its maximum at the hydrostatic pressure of 143.8 MPa; and the peak value is 0.05 %. After a hydrostatic pressure cycle, the water absorption degree of the material at 0 MPa is 0.01 %, which is an increase of 108.2 % compared to the initial value. In summary, within the safe pressure range, the water absorption rate of the buoyant material shows a uniform positive correlation with the change in the static water pressure. There is a clear difference between the water absorption rate of buoyancy materials under static water pressure and normal pressure. Within the safe pressure range, the hydrostatic pressure has a significant promotion effect on the water absorption rate of the material, but the effect of this promotion on the overall water absorption rate of the material is slight.

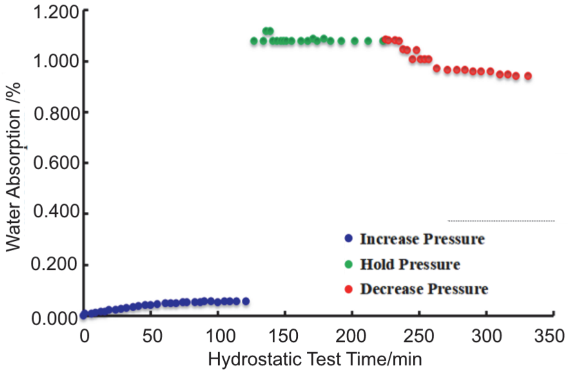

Fig. 7. Time of each stage of hydrostatic pressure test (≤165 MPa) and water absorption rate of corresponding syntactic foams.

3.2 Real-time change of water absorption under crushing hydrostatic pressure

The deep-sea syntactic foam is a lightweight, high-strength inorganic brittle composite material, and the crushing pressure is the main indicator to measure the safety factor of the material [17]. When the hydrostatic pressure reaches the ultimate damage value, the material will fail instantaneously and the water absorption rate will increase abruptly. After being maintained at 165 MPa for 1.7 hours, the overall test effect of the syntactic foam was obvious. The water absorption rate began to show abrupt growth when the pressure was held for 3 minutes. The material showed obvious cracks and reached the critical value of the ultimate failure pressure. The time of each stage of the hydrostatic pressure test and the corresponding water absorption rate of syntactic foam are shown in Fig. 7. After the hydrostatic pressure test, the weight increased by about 200 g, the density reached 681.2 kg/m^3, and the water absorption degree was 0.94 %. Compared with 143.8 MPa, a large change occurred, and the water absorption degree was close to 1 %.

The whole process of water absorption of syntactic foams under the action of hydrostatic pressure was monitored by the real-time water absorption monitoring system, as shown in Fig. 8. The results show that before the hydrostatic pressure reaches the critical limit, the water absorption degree of the syntactic foam exhibits a uniformly positive and slowly changing trend with an increase in the hydrostatic pressure. The water absorption degree begins to exhibit a sudden increase when the pressure is maintained at 165 MPa for 3 minutes. As the pressure is maintained, the water absorption degree of the material increases sharply to the maximum value of 1.12 % within 7 minutes, and then the change tends to be stable. Finally, the water absorption degree slowly decreases with a decrease in the pressure, and the water absorption degree at 0 MPa is 0.94 %. This is a 92-fold increase from the initial value. In summary, before reaching the critical value of crushing pressure, the water absorption degree of syntactic foams showed a uniform and slowly changing trend with an increase in the hydrostatic pressure. When the critical value of breaking the limit is broken, the water absorption degree increases sharply in a short time, and it is stabilized after a period of time. Then, as the pressure decreases, the water absorption degree decreases only slightly. The resulting failure damage is irreversible.

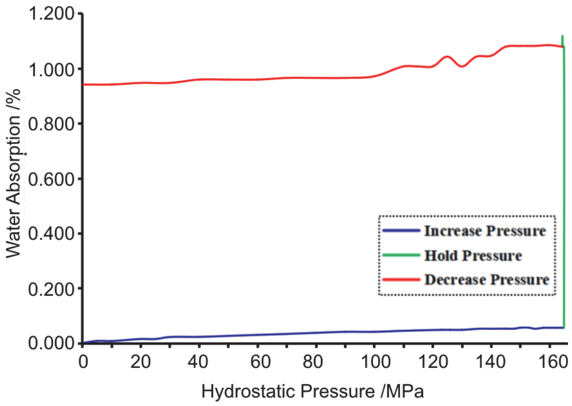

Fig. 8. Effect of hydrostatic pressure (≤165 MPa) on the water absorption of syntactic foams.

4. Conclusions

A system for real-time monitoring of water absorption of floating materials based on underwater strain gauges, a deep-sea high-pressure simulation chamber and strain gauges has been created. The real-time water absorption rate changes of syntactic foams under simulated high pressure environment were monitored at the two critical values of hydrostatic pressure in the safe range and under ultimate failure. This provides reliable data support for the comprehensive performance evaluation and safety factor of syntactic foams. The results show that a real-time water absorption monitoring system based on underwater strain detection is a feasible detection method. It can truly reflect the real-time water absorption change of the material during the full cycle of hydrostatic pressure, which can greatly reduce the workload of detection and improve efficiency.

Within the range of safe pressure, the water absorption degree of the syntactic foam shows a uniform positive correlation with the increase or decrease of the hydrostatic pressure. The short-term pressure maintenance has a little effect on the water absorption of the material, and it remains almost unchanged. For the syntactic foam whose performance parameters are determined, the continuous change in the water absorption degree within the safe pressure range is very small, and almost does not affect the normal use of the material.

When the pressure reaches the ultimate failure value, the syntactic foam will fail instantaneously and the water absorption rate will increase rapidly in a short time. Under the premise that the pressure does not increase, the water absorption rate maintains a short period of stability after a sharp increase, and then it shows a downward trend with a decrease in the hydrostatic pressure, but the magnitude and amount of the decrease are very small. The ultimate failure of syntactic foams and the increase in water absorption rate are irreversible.

There is a clear difference between the water absorption of syntactic foams under hydrostatic pressure and normal pressure. Hydrostatic pressure can accelerate the diffusion of water molecules and significantly affects the water absorption of the material. But within the safe pressure range, the effect of this promotion on the water absorption of the entire material is small and reversible.

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