Physical properties of the inside ligament of the scallop shell

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Many investigations on the structure and mechanical properties of seashells have been carried out [1–3]. However little attention has been paid to the ligament joining the shell halves. Bivalve shells are connected with an inside and an outside ligament, which work like a hinge and also allow the animal to open its shell [4]. This paper describes our investigations into the physical properties of the inside ligament of the scallop.

The shells of a scallop are connected by inside and outside ligaments at the backside. The inside ligament contains calcium carbonate and the outside ligament does not. Both ligaments work together to support and open the shell. In general, the inside ligament consists of special epithelial cells. These cells are composed of juicy organic matter and fine particulate aragonite (about 40% by weight). The aragonite crystals are hexagonal prisms of diameter about 0.2 μm, and they are generally oriented in the radial direction, as shown in Fig. 2 [5]. There are also some scallop shell ligaments that do not contain this crystal structure. The outside ligament consists of the same kind of epithelial cells as the inside ligament, but the structure is more subtle. Under the microscope it is possible to make out only some faint layers. When the animal wishes to open its shell, the outside ligament sustains tensile stress and the inside ligament compression. It is thought that the crystal structures of the inside ligament assist with the transmission of compressive stress.

In the rest of this article ligament will be used to refer to the inside ligament only. Fig. 2 shows a schematic diagram of the structure and defines a useful coordinate system, and shows what is meant by radius. The dimensions of the ligament for a scallop shell with a diameter of 100 mm are 5 mm radius, 5 mm thickness and 60 degrees fan angle. Fig. 1 shows an SEM image of a scallop shell ligament that has been cleaved along the direction of the X-axis. Micro-fibers about 5 μm in diameter, and oriented parallel to the shell growth direction, can be seen. Note that the shell and ligament both grow in the x direction.

In seawater the ligament is soft and rubbery. To examine the diffusion of water into the ligament, some cubic specimens 3 mm on each side were cut from the ligaments, rubbed on fine sand paper, and then dried in air for about 3 days. They were then immersed in saline solutions of various concentrations and allowed to swell. The weight of the specimens was plotted with time. This type of experiment was performed at several ambient temperatures to build up the family of curves shown in Fig. 3. In Fig. 3 the units of the horizontal axis are square root seconds. The vertical axis is the weight gain per unit ligament unswollen volume. Fig. 4 shows similar curves, but this time for various saline concentrations and always at 20 °C.

From Figs 3 and 4 we can argue that (1) Fick's law of diffusion [6] is a good model for the early stage of diffusion and (2) the observed rate of diffusion seems to increase with either increased temperature or decreased saline concentration. We think that higher temperatures may open water passages in the ligament material, allowing water transport but not necessarily salt transport.

We wished to know if the observed diffusion behavior was anisotropic, that is, if it was greater along the x direction than the y direction. To investigate this we coated some of our cubic ligament specimens with glue to seal four of the six faces. Interestingly, we could not measure any difference between the diffusion behavior along the x direction, the y direction or z direction. It seems that the diffusion mechanism is equally effective in every direction through the material.

We performed compression tests on our cubic ligament specimens. The fibers in our specimens were aligned with the x-axis, so we expected that there would be little difference in stiffness in the y direction as compared to the z direction and lower stiffness for compression along the x-axis. These guesses were confirmed by experiment, see Fig. 5. The horizontal axis of Figs 5 and 6 is the draw ratio, meaning the length of the compressed specimen over its initial length (L/L_0). The vertical axis is nominal stress. We then proceeded to test a series of specimens having different water contents. The results of these tests, for z-axis only, are shown in Fig. 6. We defined 100% water content as the condition of a fully saturated specimen at 20 °C.
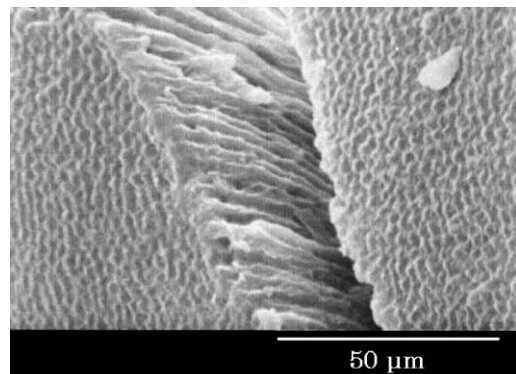

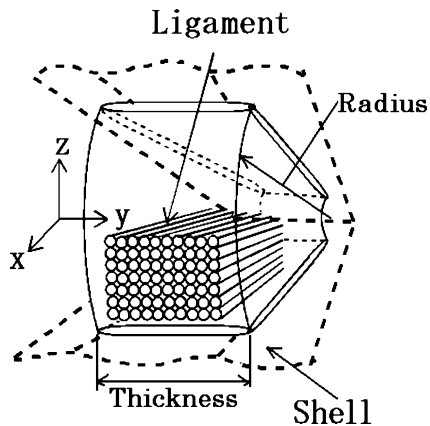*Figure 1* SEM observation of inside ligament of scallop shell.

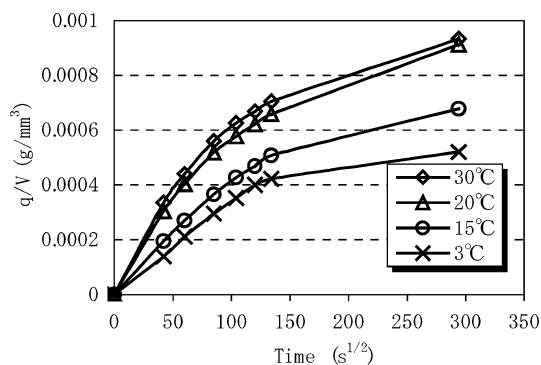*Figure 2* Schematic illustration of inside ligament of scallop shell.

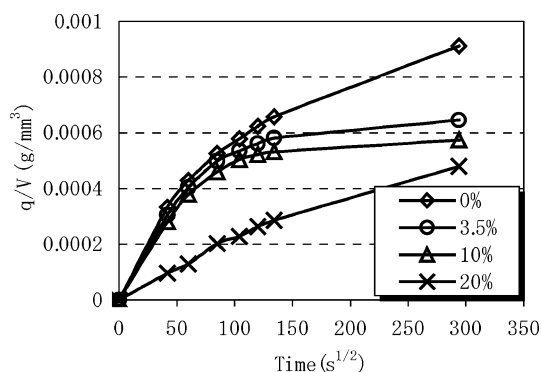*Figure 3* Diffusion of water into ligament at different temperatures.

Figure 4 Diffusion of saline solution into ligament with different concentrations.

Fig. 6 suggests that for completely dried ligament, stress is proportional to the draw ratio (curve 6). However as the water content increases, the curves tend to have a much reduced slope. We think that as the water saturates the ligament, the ligament behaves more like soft rubber. We were able to show that the most saturated ligament, curve 1, behaves very much in accordance with a constitutive model for rubber proposed by Wang and Guth [7].
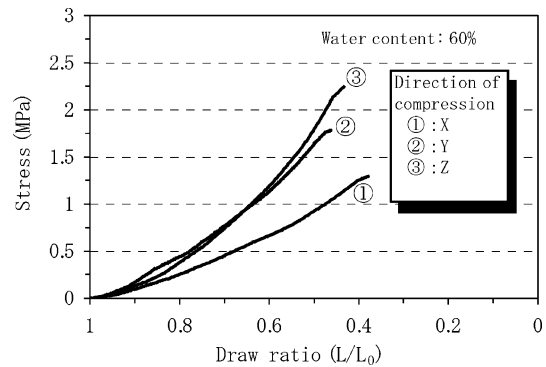

Figure 5 The compressive stress-strain curve of ligament in three direction of compression at 20 °C.
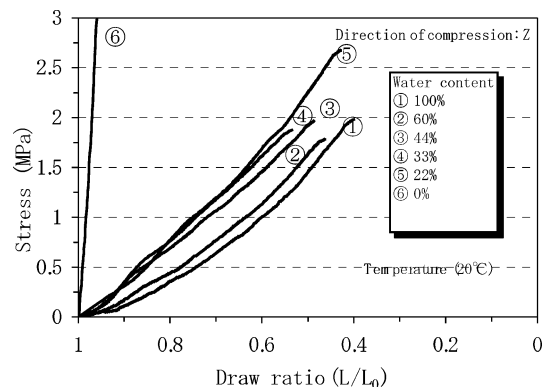

Figure 6 Effect of water content on compressive stress-strain curve along *z* direction at 20 °C.

We conclude that (1) the inside ligament of the scallop shell has a structure like a bundle of fibres, of diameter about 5 μm, and oriented along the direction of shell growth; (2) the rate of diffusion of water into the ligament increases with temperature and also increases with decreased saline concentration; (3) the compressive stress-strain curve for dried ligament material shows near-linear elasticity; but very wet ligament behaves more like soft rubber.

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