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Observation of Microscopic Deformation Behavior of Cork

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Cork is a material that has many characteristics, for instance, light weight, elasticity, insulation against heat, impermeability for liquid, and so forth. There are two types of cork, the natural and the agglomerated corks. In the present paper, compression tests of the natural and the agglomerated cork specimens were carried out. The compression test were done in various directions. Compressive stress was measured by a original compression apparatus, and stress-strain curves were obtained in various directions of the cork specimens. In the natural cork, there are differences between the radial and the non-radial direction. The recovery of dimensions after compression was also studied in respective directions. The structure of the deformed surface was observed by a scanning electron microscope.

1. Introduction

Although the quantity of the production of cork in Japan is reducing, Okayama is one of the most important region for the production of cork. Cork is originally planted around the Mediterranean sea and imported into Japan and changed its shape for various commercial application. Cork is light and elastic having good properties such as good impermeability, shielding ability of sound. The unique characteristics of cork is resulted from the microscopic shape and structure of cork cells. Namely, the structure of cork is composed of the small cells and closed voids.

The basic structure of the natural cork is studied by L.J. Gibson and M.F. Ashby [1,2] and M.E. Rosa et al. [3]. However, little attention has been paid on the agglomerated cork which is widely used for various engineering products. The agglomerated cork is produced by dividing the natural cork into small particles and combined them together using the bond material.

The relation between the mechanical behavior of the cork and its microstructure does not seem to have been fully clarified yet. In the present study, the structure and the deformation behavior of the agglomerated cork are investigated and compared with those of the natural cork using the scanning electron microscope and the compression testing equipment made for the present purpose. The strain recovery after deformation is also studied.

2. Experimental Procedures

2.1 Specimen

In the present study, both the natural cork specimen and the agglomerated cork specimen were prepared. The chemical components of cork is shown in Table 1. The agglomerated cork is composed of the particles of the natural cork of the size 4～8mm, and pasted together with the bond material of epoxy resin. The density of the bond is about $1 g/cm^3$, and the weight percent is 7wt% of the agglomerated cork. The shape of the compressive cork specimen used in the present study is cubic with the edge length of 10 mm [4]. The structure and the characteristic of cork are anisotropic. The natural cork has three different directions shown in Fig. 1, that is, the radial, the tangential and the axial

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Table 1 Chemical components of cork (wt%)

Suberin	40
Cerin, friedelin and wax	5
Lignin	27
Sellulose	12
Tannin	6
Glycerin	6
Ash (Na, K, Mg)	4

direction of the original cork tree. The agglomerated cork has different characteristic in the compression axis during the manufacturing process and in the perpendicular direction to the compression axis.

The specimen was cut by the micro-cutting machine or the cutter knife. The average densities of the natural and the agglomerated cork are 155 kg/m^3 and 353kg/m^3, respectively.

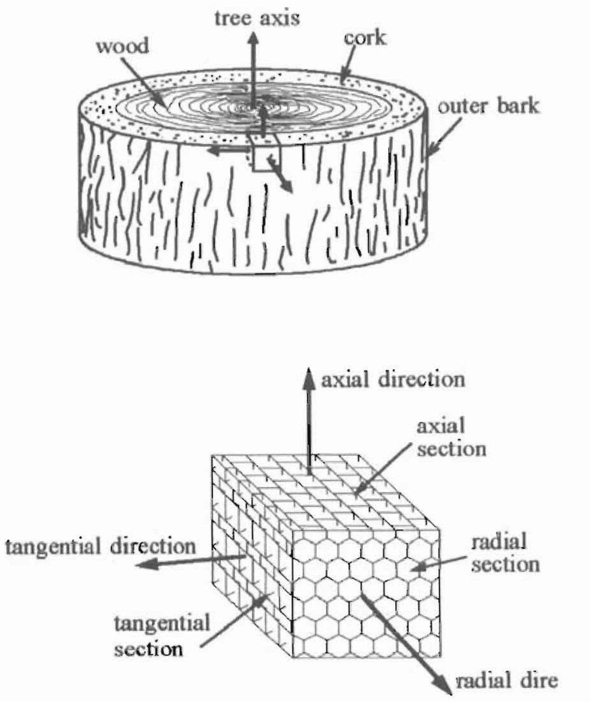


Fig. 1 Cork tree and microscopic structure of cork [1]

The deformation characteristic of the bond material is examined separately. The compressive specimen of the cylindrical shape of the size 30 mm ϕ diameter and 30 mm height is made from the epoxy resin and cut by the NC milling machine. The average density of the bond material used in the present study is 1081 kg/m^3.

2. 2 Compression test

The compression test of the cork specimen was performed with the specially made small equipment, which can be used in SEM as shown in Fig. 2. The strain ε was calculated from the displacement measured by the micrometer. The conventional strain is used throughout the present paper.

The maximum compressive strain was -0.8 for the natural cork and -0.7 for the agglomerated cork, respectively. The compression test of the bond material was done by the compression testing machine with the maximum load 980 kN (Tokyo Kouki Co.).

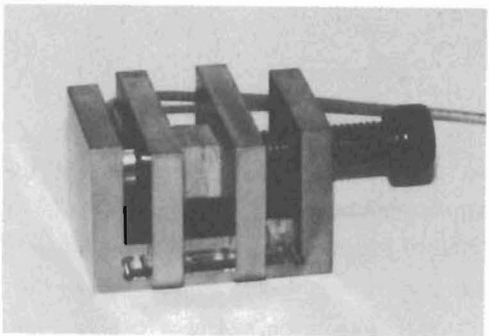


Fig. 2 Compression apparatus for cork specimen used in SEM

The stress during compression test was measured by the load cell and the amplifier (NEC Sanei Co.). The cross section A was measured at every deformation step of the compressive strain -0.05. The averaged value of the cross sections of the both surfaces was adopted. The cork is visco-elastic material and hence the stress changes with time. In the present study, the stress after 10 minutes after compression was used.

The measurement of the recovery of the specimen

-0.3 and -0.7 for one minute. Then, the compressive load was removed and the recovery of dimension of the specimen was measured in the three directions.

2.3 Observation of surface

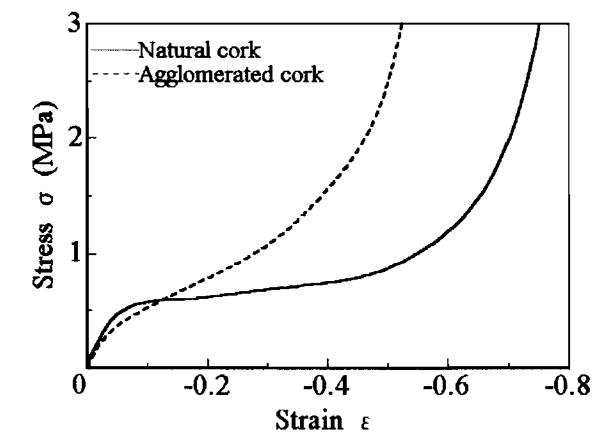
The surface observation was done with the natural type scanning electron microscope (SEM) S-3500N type made by Hitachi Co. The central part of the area of 3 × 3 mm was observed. As the cork is non-conducting material, low acceleration voltage of 15 kV was adopted for the SEM observation. The corresponding current is about 25 μ A for the natural cork, while about 47 μ A for the agglomerated cork.

3. Experimental Results and Discussion

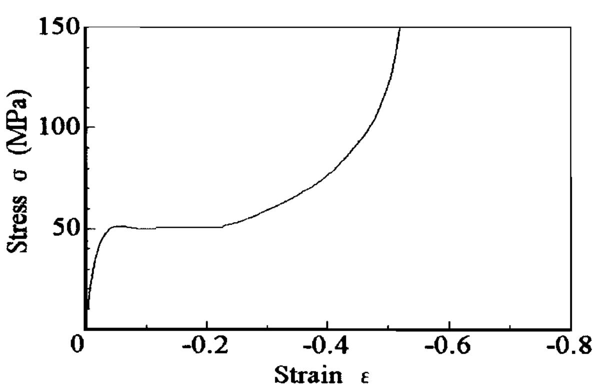
3.1 Stress-strain relation

Fig. 3 (a) shows the averaged stress-strain relation measured in various directions of the natural cork and the agglomerated cork. Fig. 3 (b) shows the relation for the bond material. The stress of the cork increases rapidly when the cell collapse with the applied strain.

The stress-stress relation of the natural cork is slightly higher in the radial direction than those in the axial and the tangential directions [2]. The stress of the agglomerated cork is higher in the tangential direction to the compression at the early stage of compression, which may be due to the influence of the residual strain during the manufacturing process.



(a) Natural and agglomerated cork



(b) Bond material

Fig. 3 Averaged stress-strain relations

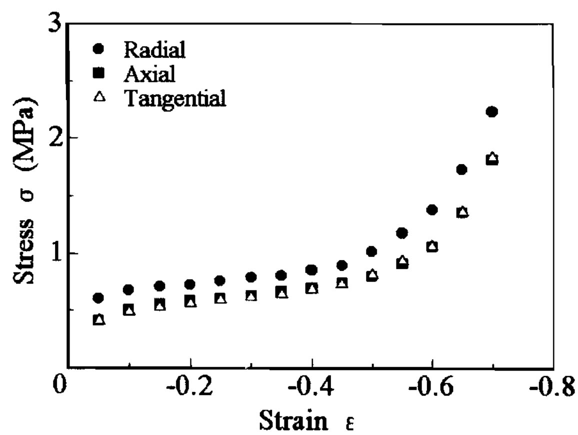


Fig. 4 Stress-strain curves for compressive and perpendicular directions of agglomerated cork

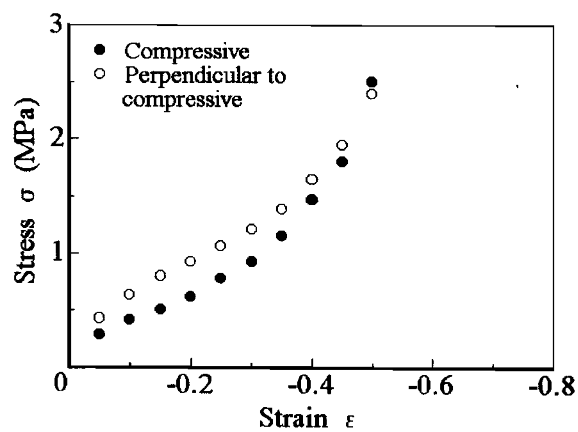
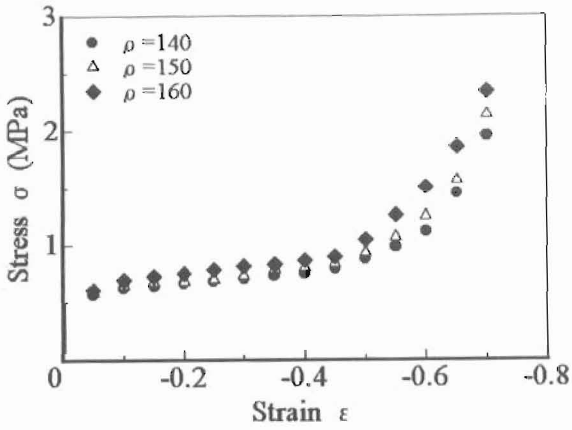
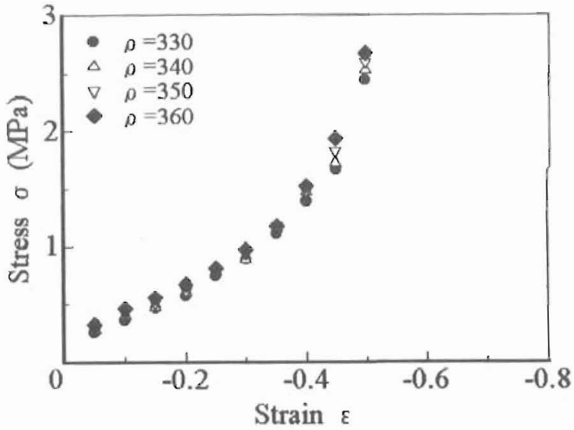


Fig. 5 Stress-strain curves of natural cork with various density in radial direction



(a) Radial compression of natural cork



(b) Agglomerated cork in compressive direction

Fig. 6 Stress-strain curves of cork with various density

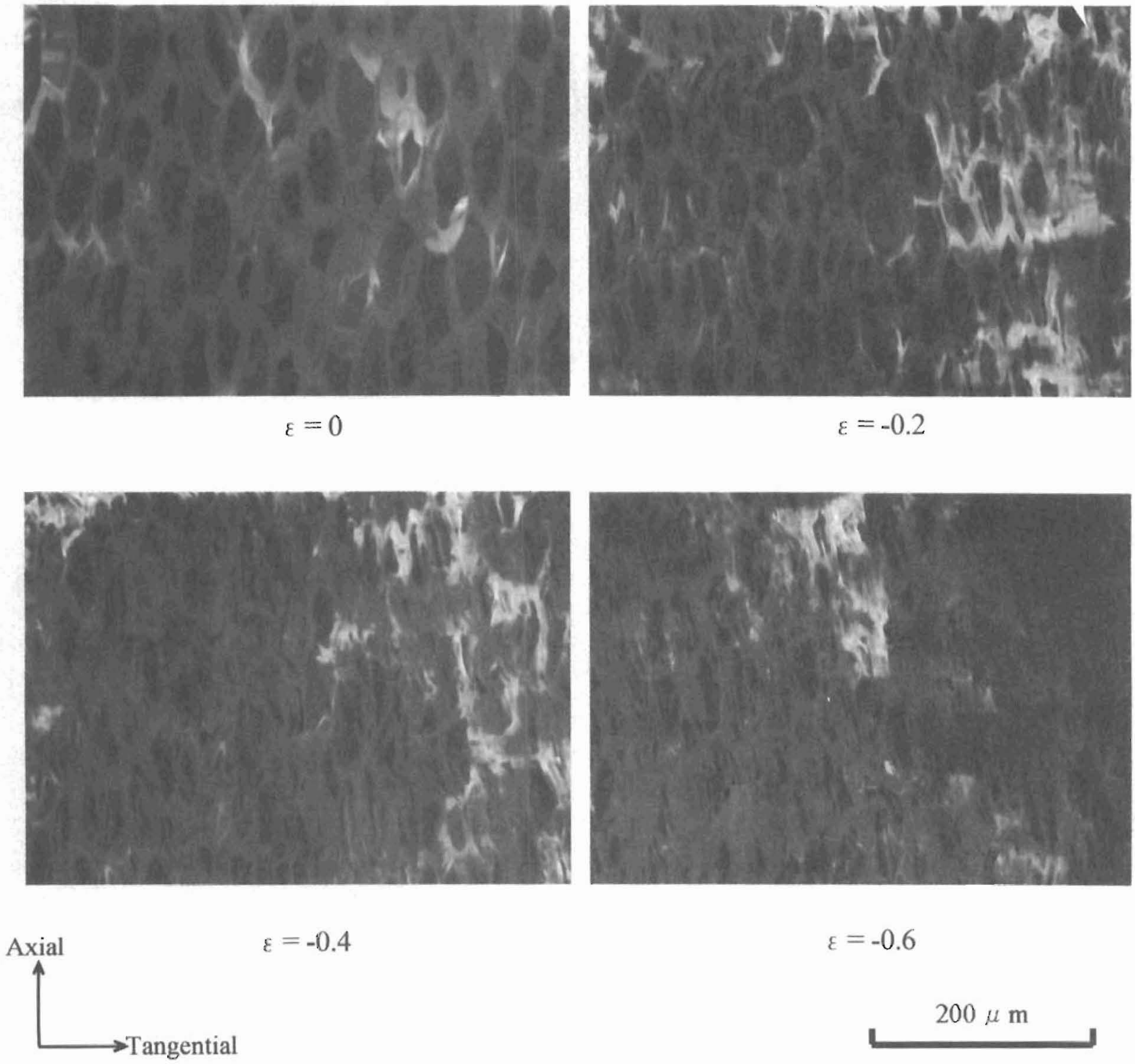


Fig. 7 SEM images of radial section of natural cork (compressive direction is horizontal)

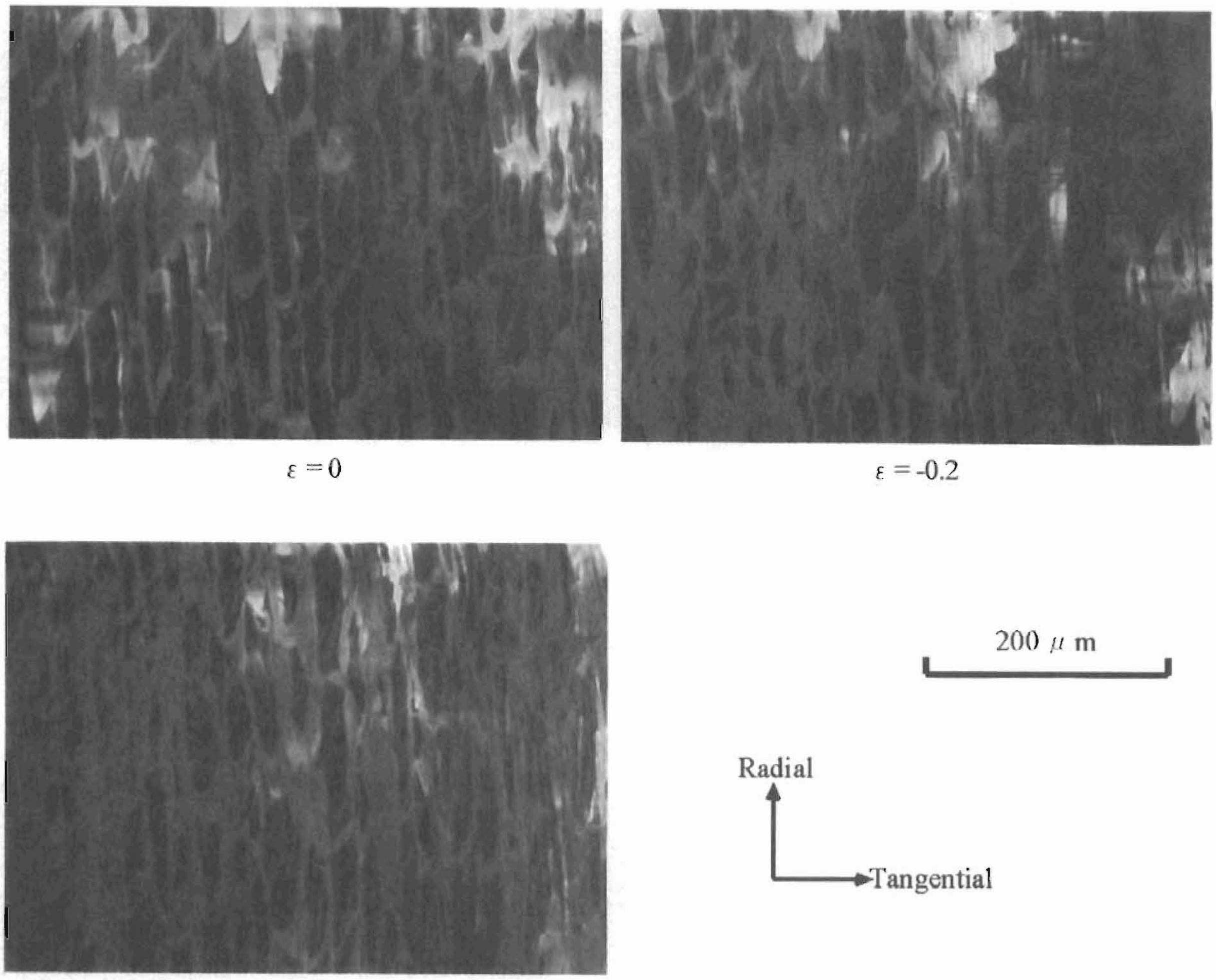


Fig. 8 SEM images of axial section of natural cork

The effects of the density ρ of the cork specimen are shown in Figs. 6 and 7 for the natural and the agglomerated cork, respectively. It is seen from these figures that the stress increases with the increase of density.

3. 2 Microscopic observation of surface profile

The microscopic surface profiles of the cork observed with the natural SEM is shown in Figs. 7 ～ 9. The direction of the compression is horizontal direction. Fig. 7 shows the cross section to the radial direction where the hexagonal honeycomb structure is observed. Fig. 8 shows the cross section perpendicular to the axial direction, and Fig. 9 shows the cross section perpendicular to the tangential direction. The latter two shows the structure such that layers of bricks. It is seen in all cross sections that the cell wall deforms with the applied compressive strain and finally collapse. These behavior is resembled to those of the aluminum hexagonal structure [5,6].

The surface profile of the agglomerated cork is shown in Fig. 10, where the cork grains are bonded together. Inhomogeneous deformation is also seen in the agglomerated cork. There are some voids between the cork grains. The weight percent of the bond material is about 7wt % (volume fraction is about 2.3%).

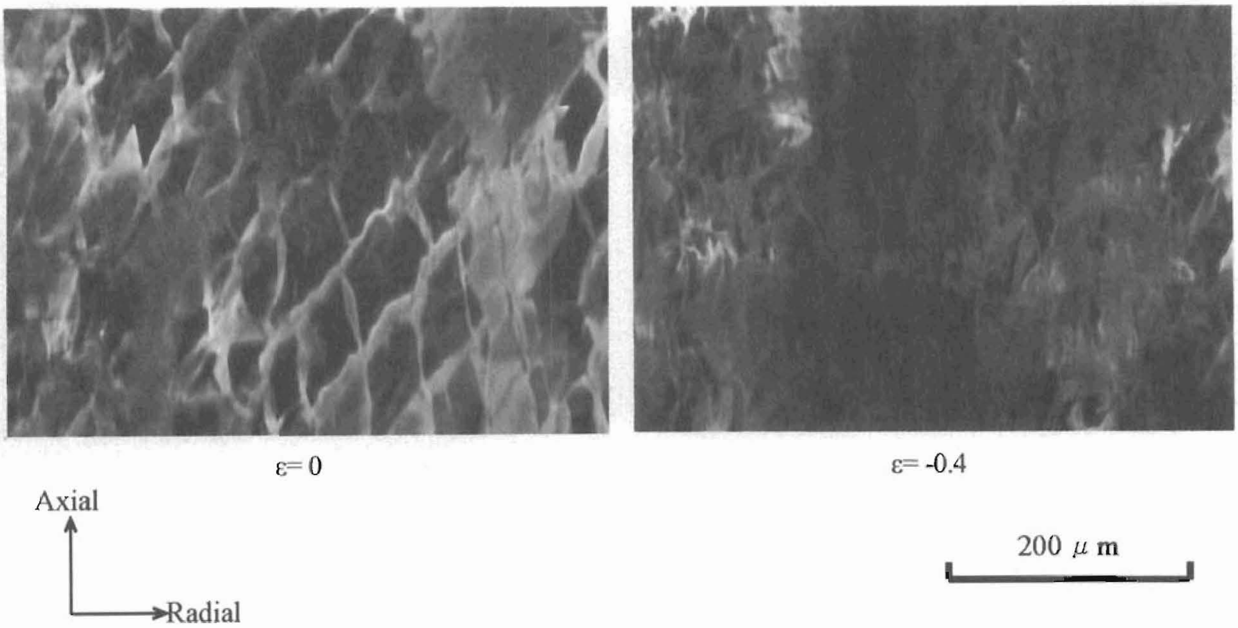


Fig. 9 SEM images of tangential section of natural cork

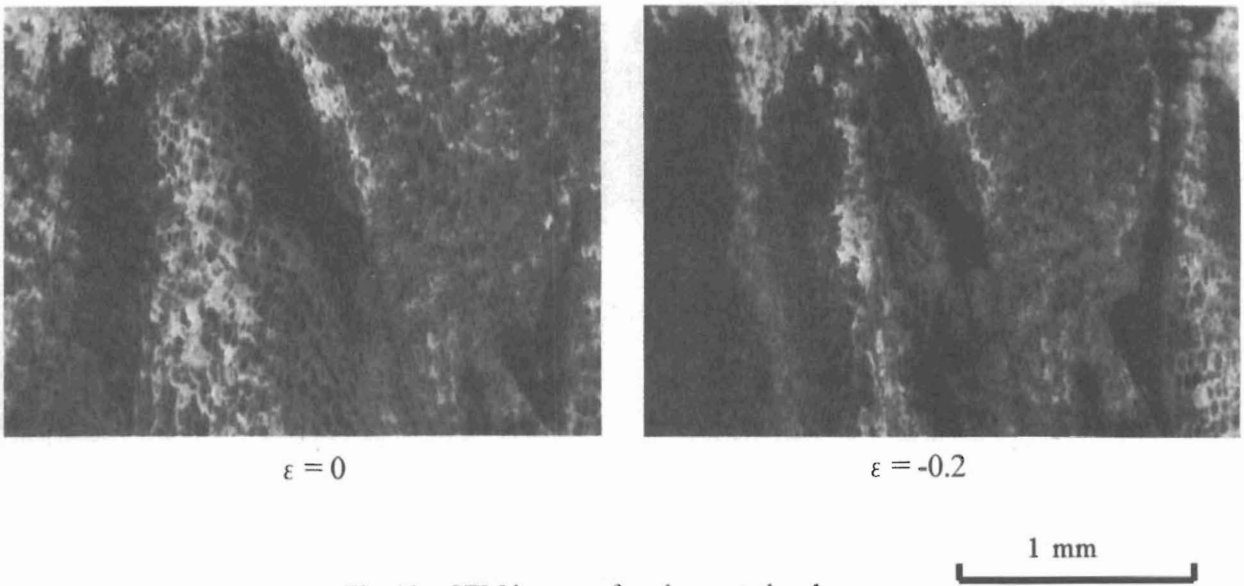


Fig. 10 SEM images of agglomerated cork

3. 3 Strain recovery after compression

Fig. 11 shows the strain recovery after compression for the natural and the agglomerated cork. Fig. 12 shows the averaged strain recovery after the applied compressive strain of 0.3 and 0.7. In the first case, recovery is almost finished after about 14days, but for 70% compression the deformation is not completely recovered after unloading. The strain recovery in the compressive direction is large for the agglomerated cork.

The directional dependence of the strain recovery is as follows. The strain recovery of the natural cork is relatively isotropic. The strain recovery in the perpendicular direction is rather anisotropic, which is considered to be related to the microscopic structure of the natural cork as shown in Fig. 13.

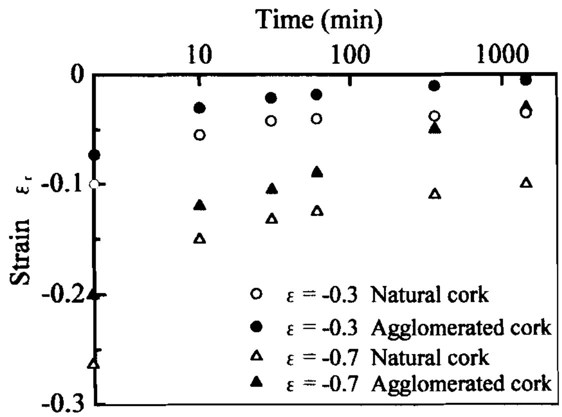


Fig. 11 Recovery of dimensions after compression in compressive direction

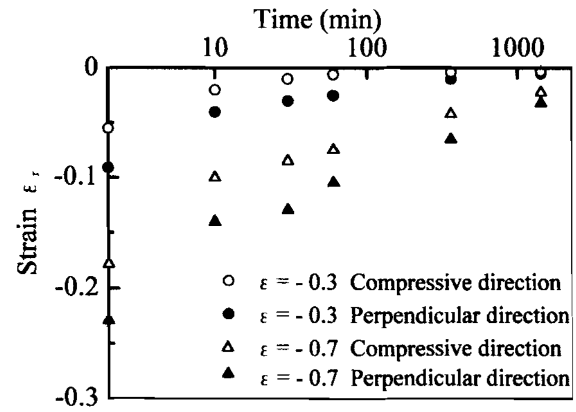


Fig. 14 Recovery of dimensions of agglomerated cork in compressive direction

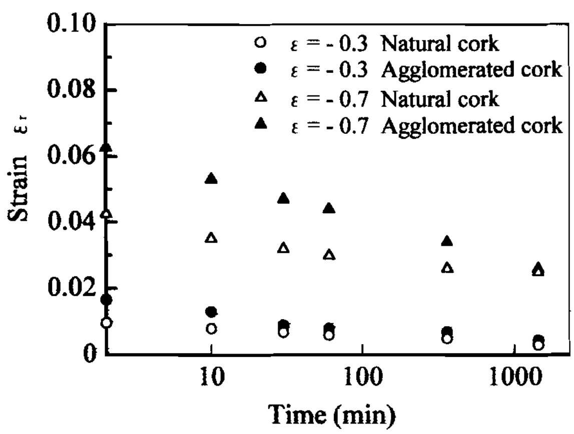


Fig. 12 Recovery of dimensions in tangential direction to compressive axis

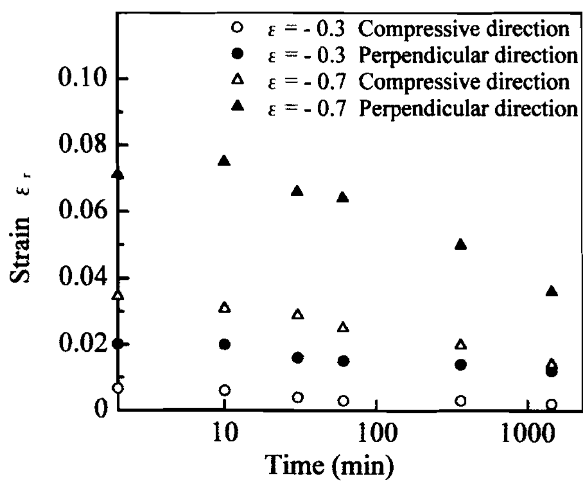


Fig. 15 Recovery of dimensions of agglomerated cork in tangential direction to compressive axis

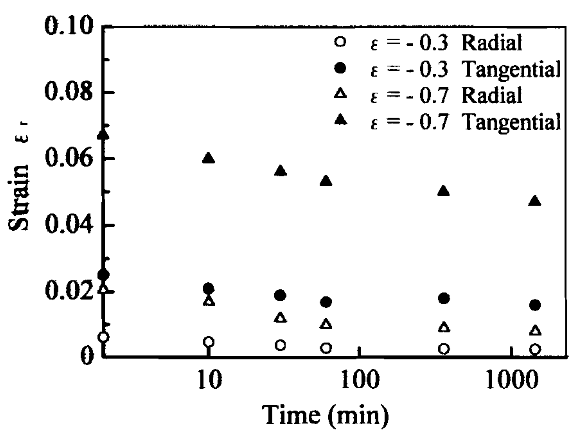


Fig. 13 Recovery of dimensions in tangential direction to compressive axis for axial compression of natural cork

In the case of the agglomerated cork, the strain recovery is large in the compressive direction than that in the perpendicular direction as shown in Figs. 14 and 15.

When cork is compared with metallic materials, the natural cork corresponds to single crystal, while the agglomerated cork corresponds to the polycrystalline metals. Similarly, the mechanical behavior of the agglomerated cork is more isotropic than that of the natural cork. Furthermore, as pointed out previously, the microscopic structure of the natural cork resembles to the aluminum honeycomb structure, and its mechanical behavior is closely related to the microstructure.

4. Conclusion

The compression test of both natural and agglomerated cork was done and the stress-strain relation was measured. The change in microscopic surface profile during compression was observed by scanning electron microscope. The strain recovery after compression was also studied. The effects of the material anisotropy and the material density on the stress-strain relation and the strain recovery were investigated. The main results obtained are as follows.

(1) The obtained stress-strain relation shows increase in stress with the density of cork for both the natural and the agglomerated cork.

(2) The structure of cork observed by SEM is cellular with different shape for the cross sections of the different direction. The voids of cork structure disappear at the strain of -0.6, where the stress increase rapidly.

(3) The strain recovery is high for heavily deformed cork.

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