Hygroscopic setting expansion of gypsum-bonded investment under restrictive stress in dental casting

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The phenomenon of hygroscopic setting expansion of gypsum-bonded investment under restrictive stress for dental casting was studied. The analysing method for normal setting expansion proposed in previous studies was also applied to hygroscopic setting expansion under uniaxial stress and within an acrylic ring. Furthermore, hygroscopic setting expansion within a stainless steel ring with an asbestos liner was analysed under dental casting conditions in relation to the calculation method proposed by the authors.

1. Introduction

Hygroscopic setting expansion of an investment occurs when the investment sets with an excess of water, and the value of hygroscopic setting expansion is greater than that of normal setting expansion [1, 2]. The large hygroscopic setting expansion is therefore utilized in dental casting to compensate for the shrinkage of molten metal when the value of normal setting expansion without hygroscopic setting expansion is not enough. Hygroscopic setting expansion within a casting ring is not uniform because of a restrictive stress which is provided by both the wax pattern and the casting ring [3, 4]. As a result, the distortion of the casting mould and finally distortion of the metal may occur. In dental casting, a sheet of asbestos lining inside a stainless steel ring wall is used to reduce the distortion of a casting mould [5].

It has been reported that the normal setting expansion of investment under restrictive stress can be calculated [6, 7]. It is expected that this calculation method may be applied to hygroscopic setting expansion. In this study, hygroscopic setting expansion was examined in the following conditions; (i) under uniaxial stress, (ii) within an acrylic ring, and (iii) within a stainless steel ring with an asbestos liner.

2. Materials and methods

The investment tested was a commercial gypsum-bonded cristobalite investment (G-C Co., Tokyo). Measurements were carried out at $20 \pm 2°$ C as described below.

2.1. Measurement of hygroscopic setting expansion under uniaxial stress

Hygroscopic setting expansion of a gypsum-bonded investment under uniaxial stress was measured using a dial gauge having 1 μm resolution as shown in Fig. 1a. The investment was mixed at a water/powder ratio of 0.32 with manual spatulation at 2 turns sec^{-1} for 30 sec. The slurry was poured into a wax cylinder which was made of sheet wax with a thickness of 0.28 mm, a diameter of 20 mm and a height of 30 mm, and then a glass plate was placed on the upper surface of the investment to make the upper surface parallel to the bottom surface. At 12 min after a start of mixing, the specimen was placed under the dial gauge and set within a container. At 14 min water was poured into the container to such a level that the specimen was immersed completely in water. After that, the expansion was measured from 14 to 120 min after the start of mixing. The loads applied to the investment were 0, 1, 3, 5 and 10 kg, equivalent to 0, 0.32, 0.96, 1.6 and 3.2 $kg\,cm^{-2}$ applied stress.

For the setting expansion without applied stress, the measurement was started using the strain gauge right after the slurry was poured into the wax cylinder (Fig. 1a), and also the time of the start of setting expansion without applied stress was obtained.

2.2. Measurement of hygroscopic setting expansion within an acrylic ring

The acrylic ring used had an inner diameter of 44.0 mm and a height of 10 mm, but the outer diameter was varied between values of 44.6, 46.0 and 50.0 mm to examine the effect of acrylic ring thickness on hygroscopic setting expansion. The investment powder was mixed at a water/powder ratio of 0.32 and for 30 sec, and then it was poured into each acrylic ring. At 14 min after the start of mixing, each acrylic ring was set under the dial gauge as shown in Fig. 1b.

At first the expansion of the outer diameter of the acrylic ring was measured and the result was then converted to the expansion of the inner diameter [7].

2.3. Measurement of hygroscopic setting expansion within a stainless steel ring

Two types of stainless steel ring, the M ring (32 mm inner diameter) and the L ring (44 mm inner diameter)

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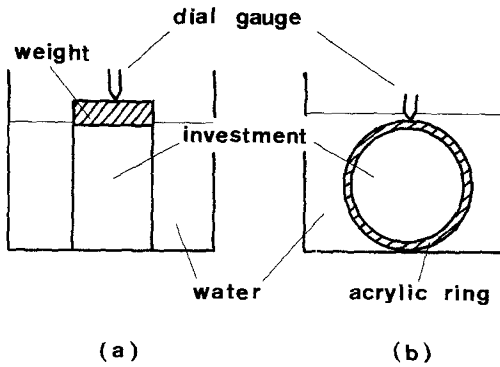

Figure 1 Measurement of hygroscopic expansion (a) under uniaxial stress, (b) within an acrylic ring.

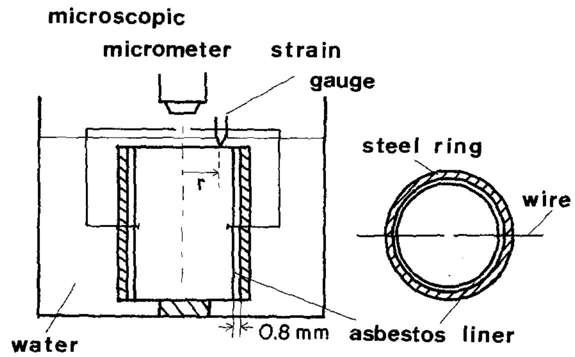

Figure 2 Measurement of hygroscopic setting expansion within a stainless steel ring.

were used and these rings had a thickness of 1 mm and a height of 38 mm. The values of hygroscopic setting expansion within the ring in both longitudinal and radial directions were measured. Furthermore the values of hygroscopic expansion within both a ring lined with asbestos and an unlined one were measured. The asbestos liner (G-C Co., Tokyo) had a thickness of 0.8 mm and a width of 42 mm.

The values of hygroscopic setting expansion in the different directions without an asbestos liner were measured as follows.

2.3.1. Measurement in the longitudinal direction of the ring

The mixed investment slurry was poured into the ring. At 12 min after mixing the specimen was placed under the dial gauge and within a container as shown in Fig. 2. 2 min later, water was poured into the container to such a level that the specimen was immersed in water, and then measurements were made from 14 to 120 min.

The value of expansion at a distance r from the centre, a_r, was calculated from the equation

$$a_r = (2x_r - x_0)/Y$$

where x_r is the displacement at a distance r from the centre in the longitudinal direction, x_0 the displacement at the centre and Y the height of the steel ring (38 mm).

2.3.2. Measurement in the radial direction of the ring

At first, two wires made of Co–Cr (diameter 0.7 mm) were placed at the half-height of the ring through a hole in the ring wall; the slurry was then poured into the ring and the wires fixed at the surface of the investment. After water was added as mentioned above, the displacements of the edges of these wires were measured using a microscopic micrometer.

For measurement of the expansion with an asbestos liner, the inside of the ring wall was lined with a sheet of wet asbestos before the investment slurry was poured into the ring.

2.4. Compression test of wet asbestos liner

The asbestos liner used was cut to a size of 40 mm × 20 mm × 0.8 mm as a specimen for a compression test. The specimen was immersed in water for 2 sec. After the specimen was placed between two acrylic plates, a compression test was carried out at a test speed of 0.5 mm min^{-1} with an Autograph DCS-500 (Shimazu Co., Kyoto).

3. Results and discussion

The change of hygroscopic setting expansion under uniaxial stress with time is shown in Fig. 3. When the stress increased from 0 to 3.6 kg cm^{-2}, the amount of expansion was reduced. The time of start for hygroscopic setting expansion was about 14.5 min, and the

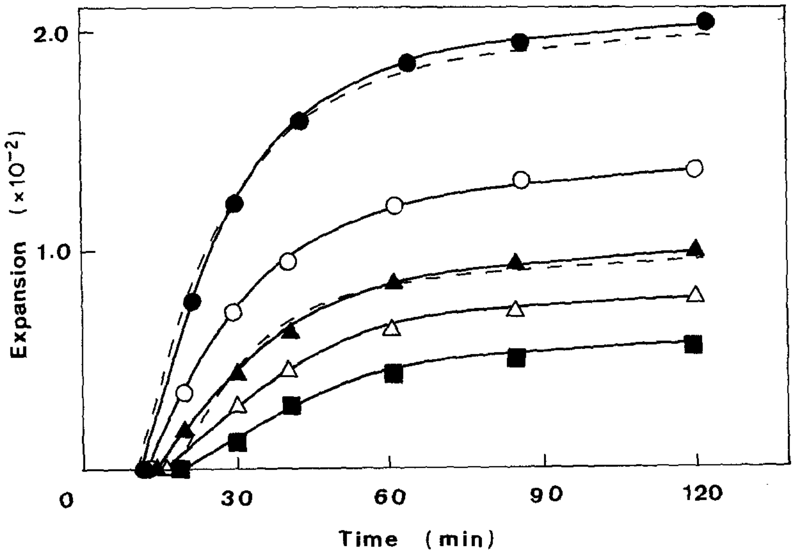

Figure 3 Expansion curves under applied uniaxial stress. Measured values; (●) 0, (○) 0.32, (▲) 0.96, (△) 1.6 and (■) 3.2 kg cm^{-2}. (– – –) Calculated values.

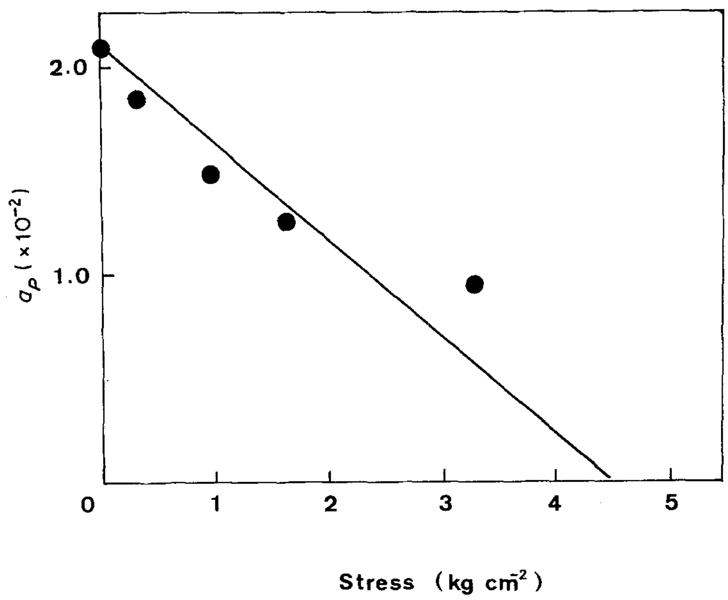

Figure 4 Relation between P and a_P. It can be represented by the straight line $a_P = a_0 [1 - (P/E')]$ where $a_0 = 0.021$ and $E' = 4.5\,\mathrm{kg\,cm^{-2}}$.

start of the expansion was delayed by increasing the applied stress. The expansion curve at zero load can be represented by the equation [6]

$$a(t) = a_0[1 - \exp(-kt)] \quad (1)$$

where $a(t)$ is the expansion at time t; a_0 (the final expansion at $P = 0$) is determined to be 0.021 in Fig. 3, and $k = 0.045\,\mathrm{min}^{-1}$ from the measured curve. This calculated curve, as shown in Fig. 3, agreed with the measured one fairly well.

The expansion curve under an applied stress P was represented by the equation

$$a(t) = a_0\left(1 - \frac{P}{E'}\right)[1 - \exp(-kt)] \quad (2)$$

where E' was obtained as $4.5\,\mathrm{kg\,cm^{-2}}$ from the relation between P and a_P in Fig. 4. The value of a_P is $a_0 \times a_{0(30-120)}/a_{P(30-120)}$, where $a_{P(30-120)}$ is the strain of expansion in the period from 30 to 120 min after the start of mixing and under applied stress P. These values are listed in Table I. The calculated curve was in good agreement with the measurement one except for the initial state of expansion, for hygroscopic setting expansion as well as for normal setting expansion [6]. The calculated curve and the measured one at $0.59\,\mathrm{kg\,cm^{-2}}$, for example, are shown in Fig. 3.

Fig. 5 shows the hygroscopic setting expansion within an acrylic ring. In all cases the value of the expansion decreased with time, compared with an unrestricted free expansion without applied stress, because the stress acting on the investment in the ring increased as the expansion proceeded with time.

In Fig. 4, the calculated expansion curve $a(t)$ is also shown according to the equation proposed by the authors [7]

$$a(t) = \frac{LE'}{1 - \nu'} \times \left[1 - \exp\left\{-\frac{1 - \nu'}{E'}\left(\frac{a_0}{L}\right)[1 - \exp(-kt)]\right\}\right] \quad (3)$$

where

$$L = \frac{(1 - \nu)A^2 + (1 + \nu)B^2}{E_r(B^2 - A^2)}$$

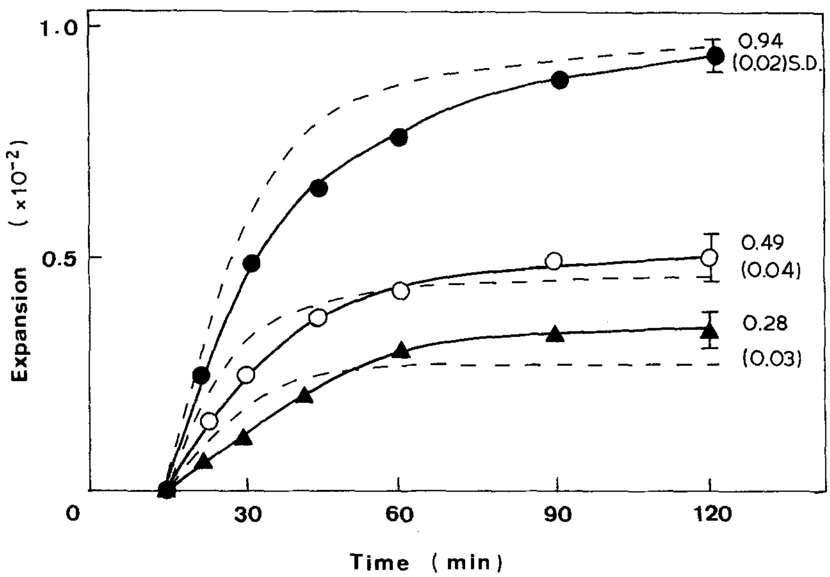

Figure 5 Measured values of expansion within an acrylic ring of thickness (●) 0.3, (○) 1.0 and (▲) 3.0 mm. (- - -) Calculated values. (S.D. – standard deviation).

TABLE I Values of $a_{P(30-120)}$ and a_P

Stress, P ($kg\,cm^{-2}$)	Expansion at 120 min	$a_{P(30-120)}$ ($\times 10^{-2}$)	$a_P = 2.1\ a_{P(30-120)}/0.81$ ($\times 10^{-2}$)
0	2.1	0.81	2.1
0.32	1.4	0.72	1.9
0.96	0.98	0.57	1.5
1.6	0.75	0.47	1.2
3.2	0.50	0.38	1.0

and A is the inner radius of the acrylic ring and B the outer radius, E_r (Young's modulus of the acrylic ring) is $30\,000\,kg\,cm^{-2}$, v (Poisson's ratio) is 0.33, $E' = 4.5\,kg\,cm^{-2}$ according to the results of expansion under uniaxial stress and v' was assumed to be 0.2 for hygroscopic expansion. Differences of 5 to 8% were found between the calculated values and the measured ones, and the calculated expansion increased more rapidly than the measured value. The result suggests that the numerical method is useful to estimate the value of hygroscopic setting expansion under an applied stress.

Fig. 6 shows the hygroscopic setting expansions within a stainless steel ring in the radial direction. The expansion in the radial direction was restricted completely when the asbestos liner was not used. The value in the radial direction within the M ring with asbestos liner was greater than that within the L ring, because the deformation of the asbestos liner was greater in the L ring than in the M ring and the restrictive stress was therefore greater in the L ring than in the M ring. In addition, these values were smaller than the value of unrestricted free hygroscopic setting expansion. The restriction still remained despite the presence of a sheet of asbestos liner.

The hygroscopic setting expansion curve without an applied stress and the curve in the radial direction within the stainless steel ring were almost the same, while the expansions were from 0 to about 0.004 for the M ring and from 0 to about 0.003 for the L ring (Fig. 6), and the difference between the unrestricted free expansion curve and the expansion curve within the stainless steel ring increased rapidly with time except for the initial state. The values of hygroscopic setting expansion of 0.004 in the M ring and 0.003 in the L ring corresponded to displacements of 0.060 mm = 15 mm × 0.004 and 0.063 mm = 21 mm × 0.003, respectively, at the inner surface of the asbestos liner, and also the values corresponded to about 8% of asbestos liner thickness. The mechanical properties of asbestos change greatly when the deformation reached about 8% of its thickness (Fig. 7).

The calculation method was also applied to the expansion within the stainless steel ring with an asbestos liner. The asbestos liner was assumed to be an elastic ring, and the outer radius of this elastic ring was assumed to be constant because the stainless steel ring was considered to completely restrict the displacement of the outer wall of asbestos. Poisson's ratio of asbestos was assumed to be 0, because the width of the asbestos remained almost unchanged even when the asbestos was deformed to a compression strain of 0.20. Fig. 7 shows the result of a compression test of a sheet of asbestos, and this stress–strain curve could be separated into stage I and stage II. The curve was approximated by two straight lines and the value of E_a was then obtained to be $1.5\,kg\,cm^{-2}$ for stage I and $15\,kg\,cm^{-2}$ for stage II as the slopes of the straight lines. The slope of this curve for stage I was so small that it was impossible to determine the zero point of stress and strain. Noting that the mechanical properties of asbestos change greatly when the deformation reaches to about 8% of its thickness as mentioned above, the value of E_a was determined to be $1.5\,kg\,cm^{-2}$ while the deformation of the asbestos was under 8%, and $15\,kg\,cm^{-2}$ when the deformation was above 8%.

The hygroscopic setting expansion $a(t)$ could also be calculated by the following equation, which is the solution of the differential equation for expansion of an investment within an elastic ring under the condition that the outer radius of the elastic ring is constant [7]:

$$a(t) = \frac{RE'}{1 - v'}\left(1 - \exp\left\{-\frac{1 - v'}{E'R} \times [C - a_0 \exp(-kt)]\right\}\right) \quad (4)$$

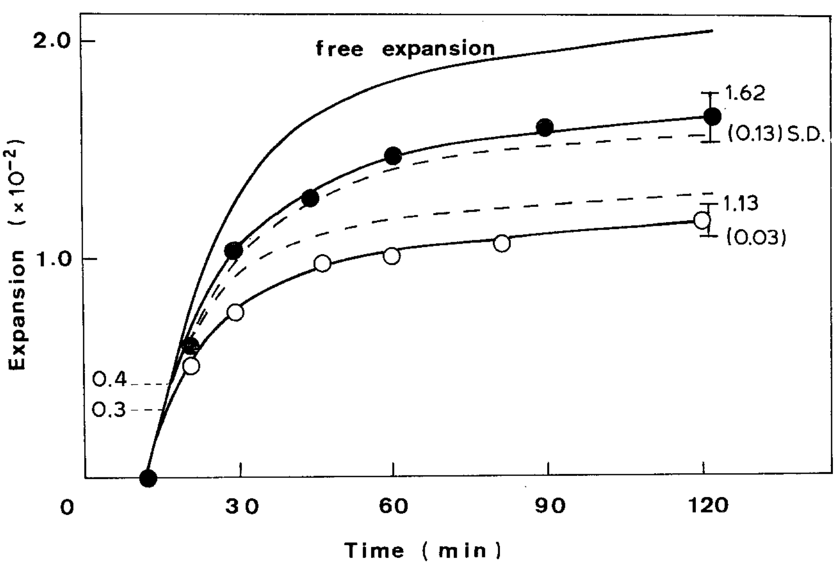

Figure 6 Expansion curves in the radial direction within a stainless steel ring with an asbestos liner. Measured values: (●) M ring, (○) L ring; (– – –) Calculated values.

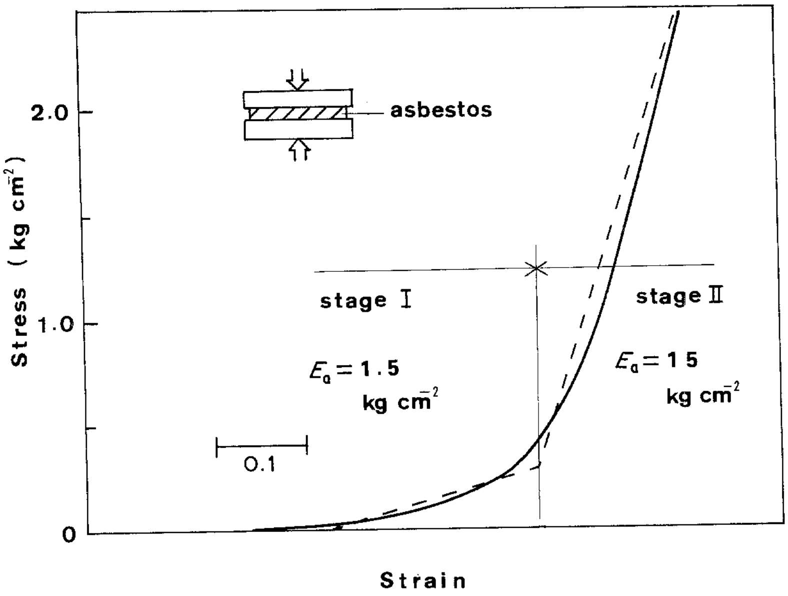

Figure 7 Compression curve of asbestos (dimensions of sample 40 mm × 20 mm × 0.8 mm).

where

$$R = \frac{A^2 + B^2}{E_a(B^2 - A^2)}$$

$$C = a_0 \exp(-kt') - R\left(\frac{E'}{1 - v'}\right) \times \ln\left[1 - \frac{(1 - v')\,a(t')}{E'R}\right]$$

and A is the inner radius of the asbestos ring, B the outer radius and C an integrating constant under the condition that the value of expansion is $a(t')$ at $t = t'$. The calculation for hygroscopic setting expansion within an M ring was carried out. The deformation (8%) of the asbestos liner corresponded to an expansion of 0.0042 for the M ring, and the expansion was calculated from Equation 4 with $E_a = 1.5\,\text{kg cm}^{-2}$, $A = 1.52$ cm, $B = 1.6$ cm and $C = 0.021$, noting that $a(t) = 0$ at $t = 0$. According to this calculation the value of expansion reached 0.0042 at $t = 5$ min. An expansion of above 0.0042 was calculated using values of $E_a = 15\,\text{kg cm}^{-2}$, and $C = 0.017$, noting that $a(t') = 0.0042$ at $t' = 5$ min in Equation 4.

Finally these two calculated curves had the value of expansion which became 0.0042 at 5 min. For the L ring, the deformation value of 8% corresponded to an expansion of 0.003, and the expansion reached 0.003 at $t = 3.5$ min. The value in Fig. 6 was in fairly good agreement for the M ring, whereas a difference of 0.002 as a final value was found for the L ring.

The hygroscopic setting expansion in the longitudinal direction is shown in Fig. 8. At the centre of both M and L rings, the value of the hygroscopic setting expansion was smaller than that of the unrestricted free hygroscopic expansion (0.021). The value was smaller near the ring wall than that at the centre of the ring because of the frictional force between investment and asbestos or stainless steel ring. In addition, the hygroscopic setting expansion without the asbestos liner was smaller than that with the asbestos liner, and this result indicates that the frictional force is greater when the asbestos liner is not present.

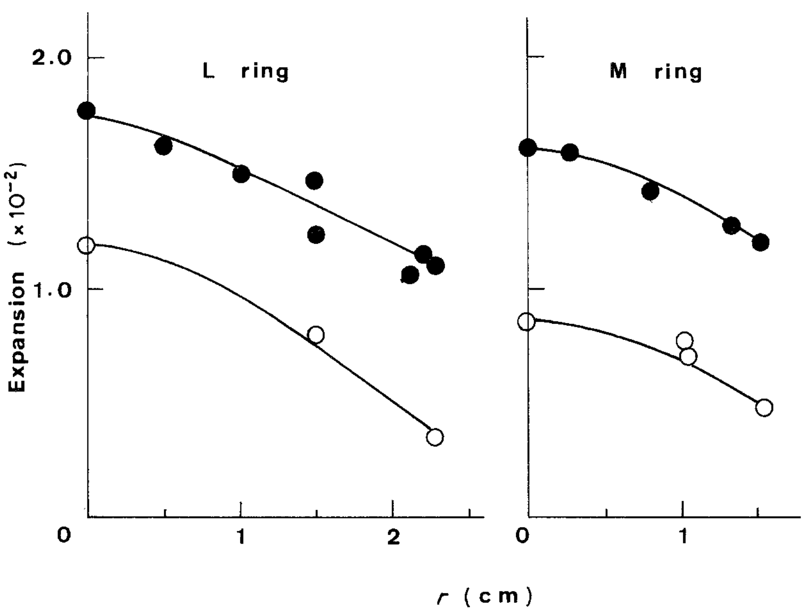

Figure 8 Expansion in the longitudinal direction within a steel ring (●) with, and (○) without an asbestos liner.

In summary, the restriction of hygroscopic setting expansion within a stainless steel ring resulted in deformation of the casting mould. To avoid this deformation, the materials such as wax, steel ring and lining material should be properly selected. The numerical method is useful to analyse it, because the investment shows a complicated expansion under more practical conditions [8, 9]. We believe that this method is also applicable to other materials with an expansion behaviour.

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