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A Fundamental Study on the Hot-Pressing Mechanism of Pulp Mat Prepared for the Fiberboard

Yoshihiro MATAKI

Contents

1. Preface

The effects of hot-pressing condition on the properties of fiberboard have been investigated by Schwartz, S. L.[95], Turner, H. D. et al.[100], Baird P. K.[6], Kitahara, K.[42] and so on, who have made the experiments on the manufacturing condition of fiberboard. For example, Watanabe, H. et al.[101,102] determined the dependence of board properties on each variable of hot-pressing, and Wilcox, H.[103] explained that the hot platen temperature and the pressure have the great influences on the temperature transition in the interior of pulp mat and experimentally considered the interrelationship between hot-pressing condition and board properties.

All of these shows that the hot-pressing condition has an influence on the board properties.

Furthermore, Segring, S. B.[87] considered the physical and chemical behavior of pulp mat during hot-pressing, by summerizing the previous results by many investigators, and he mentioned in detail the diagram of hot pressing and the schale or the type of hot-press machine and the guide to design. Eucken, A.[21] inquired into the heat conductivity of porous body in which the voids are filled up with water, and then Morita, Y.[67], Saito, T. & Okagaki, O.[85], Chukhanor, Z. F.[10] and Zabrodsky, S. S.[109] theoretically and experimentally studied on the heat and mass transfer by analyzing vapor diffusion.

Ōga, T. & Okagaki, O.[72] explained the mechanism of heat transfer in the semi-hardboard on the basis of cycle process (Diffusion-Condensation-Capillarity-Evaporation-Diffusion). Johnson, K. O.[33] obtained the detail data on the temperature and moisture transition in the insulationboard during drying, and specially on the obstruction of the drying-up of both the upper and the lower face layers in the early period from the heat and vapor transfer. Kamata, H.[35] experimentally determined a drying-curve during hot-pressing of hardboard. However, because these investigations were all but considered from the theory of the steady state of heat transfer, it is very difficult to introduce their results into the hot-pressing process of fiberboard immediately, for the hot-pressing of wet pulp mat in which the boundary condition is extremely indistinct and complicated.

Wood fibers are so various in the morphological and the physical and the chemical characteristics that the heat conductivity and the compressibility are very intricate, therefore, the elucidation of thermo-plasticity by Runkel, O. H.[84] on the standpoint of the reaction mechanism in the heat and water-vapor media will be not immediately able to introduce into the endowment with the plasticity of pulp mat during hot-pressing of fiberboard.

Takamura, N.[96,97] investigated the role of water during hot-pressing of fiberboard by the chemical analysis, and Suzuki, I.[94] examined the effect of lignin on the board properties by means of blending pulp with lignin. These investigations have a great significance for the improvement in board properties, however, the mechanism of heat and mass transfer, which effects on the degeneration of chemicals, the endowment with plasticity and the drying-set in the pulp mat, have never been carried out on the basis of analyzing heat transfer and thermodynamics.

In the studies on the microscopic structure of fiberboard, Klauditz, W. & Stegmann, G.[44] and Kollmann, F. & Dosoudil, A.[48] merely examined the broken cross-section of fiberboard with the aid of a low power-microscope for the purpose of testing material. There is no investigation which is related to the microscopic behavior of internal structure of pulp mat during hot-pressing, with the exception of this experiment.

From the standpoint of a concept of high polymer relaxation, Goring, D. A. I.[26] applied a rod-plunger system to the measurement of softening points of cellulose and lignin as main components of wood, but the pulp mat as an assembly of wood fiber has never been analyzed by means of such a procedure.

The interrelationships between the characteristics of heat and mass transfer, the deformation behavior of internal structure, the endowment with plasticity and the transition of drying-set during hot-pressing of board have never been explained until the present.

The mechanism of hot-pressing from the pulp mat to the fiberboard can be considered to compose of the following manipulations; The manipulation of relaxation for cohesion is the swelling and the hydration of fiber with water and the endowment with thermo-plasticity. The manipulation of molding gives the structure and the dimensions of fiberboard to the pulp mat under the pressure, and the manipulation of bonding between fibers is due to the dring-up and the setting of fibers.

Because these manipulations occur complicatedly, the analysis of these manipulations is fundamental for the introduction of the rational hot-pressing process and the improvement in fiberboard as a wood fiber assembly, when the mechanism of board formation is explained by the theoretical and experimental approach.

Therefore, in this study, the heat and mass transfer mechanism was analyzed from the standpoint of heat transfer and thermodynamics, and the deformation behavior of internal structure of pulp mat during hot-pressing was observed with the aid of a reflex-microscope and a soft-X ray, and the thermo-plasticity and the drying-set of pulp mat were considered from the analysis of the relation of them to the relaxation of pressure during hot-pressing.

Last of all, on the basis of the behavior of pulp mat during hot-pressing analyzed by such a procedure, the growth of board properties was considered.

As pointing out by the investigations by Anisimov, S. L. & Perelmann, T. L.[1]

and Ralko, A. V.[83] which dealed with the heat and mass transfer in the porous media accompanied with the chemical reaction, such an investigation on the behavior of pulp mat during hot-pressing must be the preliminaries of the analysis by Kaumann, W. G.[38], relative to the change of the energy of activation in the case of plastic deformation and setting of wood fiber in compression, and of the consideration by Enomoto, S. et al.[17,18,19,20], dealing with the mechanism of board formation in the case of dry-process of fiberboard.

2. Mechanism of heat and mass transfer in wet pulp mat during hot-pressing.

2. 1. Introduction.

As shown in the results of Johonson, K. O.[33] and Wilcox, H.[103], the greater part of heat transfer in the wet pulp mat is in an unsteady state, gathering from the investigation of Nordon, P. & McMahon, G. B.[71] who engage in examining the effect of moisture on the forced convective heat transfer in the beds of fine fibers, and from the result of Sugawara, A.[93], relative to the moisture of pulp mat during hot-pressing which produces a powerful effect on the heat transfer.

Many investigations on the heat and mass transfer in the wet porous body have been carried out so far, for example, Luikov, A. V.[52,53] and Kazansky, M. F.[39] applied the radio-isotope Co^{60} to the non-stationary transition of heat and mass in the porous media and continuously measured the rate of drying at each position in the direction of thickness of capillary-porous body. In a word, the gradients of temperature (∇t), total pressure (∇p) and moisture content (∇u) are the potent influence on the heat and moisture transition in the porous body and it was proved that the mass transfer potential depends on f (t. p. u). Mikhailov, Y.[65] suggested that the filtration of porous body for the vapor generated in it is necessary to analyze the intense heat transfer in the wet porous body. Consequently, in expectation of such a phenomenon in the wet pulp mat during hot-pressing under the manufacturing process of fiberboard, the filtration was theoretically and empirically investigated.

Yagi, S. & Kunii, D.[105] and Kazansky, M. F.[39] studied on the dependence of effective heat conductivity on the moisture contained in the porous body and found out that distance from heat source toward each layer of the body makes the great difference in temperature transition, thus, such a characteristic of the heat and moisture transfer in the wet pulp mat during hot-pressing was made clear.

Sugawara, A.[93] systematically examined the effect of radius, shape and arrangement of ball in the plate of glass ball assembly on the heat transfer, furthermore, Gurnham, C. F. & Masson, H. J.[27] emphasized that the mechanism of emission of vapor through voids in the cotton fiber mat, the wool fiber bed and the pulp mat prepared for paper is structure-sensitive, and the filtration factor was regarded as an indicator of structural characteristic.

In the case of wet pulp mat during hot-pressing, too, it would be assumed that the dimensions and the arrangement of constituent wood fibers have an influence on the heat and mass transfer, on that account, some experiment as mentioned in 2.6. was carried out.

2.2. Experimental procedure.

2.2.1. Preparation of Asplund pulp and pulp mat.

The chip of HIMESHARA wood (Stewartia monadelpha Sieb. et Zucc.) was defibrated by the use of laboratory Asplund defibrator (8L, 7HP) under a fixed condition shown in Table 1-1[78] and the properties of pulp were tested (Table 1-2), and then the pulp of 180 ± 4 gr. in dry weight was formed in the circle of dia. 21.0 cm.

2.2.2. Measurement of temperature transition.

As shown in Fig. 1, the chromel-alumel thermo-couples (dia. 0.3 mm, Teflon cover) were embedded in each layer of pulp mat in the direction of thickness.

These chromel-alumel thermo-couples are the standard of JIS-Z8704-1960, being made by Kanthal Company. In general, the C·A thermo-couple is very acid-proof[89], and these have smaller diameter than the general for the purpose of the prevention of retardation and the reduction of contact gap. The point of contact was made by the arc-welding. In general, the indicated temperature had a permitted error of 2 °C within the range from 0 to 400 °C, therefore, if the indicated temperature was read at a accuracy of 2 °C by testing the thermo-couples in the air, the water and the vapor of 0, 100 and 190 °C, the thermo-couples were used in this experiment.

These thermo-couples were connected with the electric null balance temperature recorder (Yokogawa Electric Worker YM-type) through the reference junction. After the temperature of the interior part measured before hot-pressing, the temperature of each layer during hot-pressing recorded as soon as reaching the fixed pressure.

2.2.3. Measurement of change of moisture content.

On the experiment in the distribution of moisture in the wet body during the unsteady heat and mass transfer, Ōkuma, M.[74] used the electric resistance type moisture content meter (Kett) for the measurement of the interior temperature in the wet pulp mat during hot-pressing, but the temperature out of the compensation, the extent of contact and the other surrounding conditions of conductor resulted in the critical error of moisture content.

Arther, C.[2] indirectly measured the moisture content by the distribution of dye concentration in the pulp mat moistened with the unvolatile dye in the case of drying of paper, and he mentioned that a great error always occured with the result of initial dehydration under hot-pressing.

On the analysis of the heat and mass transfer in the mixture of cellulose and qualz sand, Kazansky, M. F. et al.[39] measured the moisture movement by tracing the change of distribution of Co^{60} γ-ray.

In this experiment, the specimens containing moisture were taken by the weight of 8∼12 gr. from the upper, the lower and middle layers, respectively, and after they were sealed up with the aluminium foil, the moisture content approximately were measured at the accuracy of 0.5 gr..

2.2.4. Hot-pressing of pulp mat.

The pressure capacity of hot press is 70 ton, the hot platen 45×45 cm, one daylight, oil-pressure and steam-heating. The error of parallelism of lower platen with the upper platen is within 0.3 mm, and the lack of uniformity of platen temperature is 1∼2 °C between the upper and the lower platen within the range from 80 to 190 °C. Particularly, the hot press was connected with the boiler which had the capacity of evaporation of 1.5 ton/hr., so that the boiler could reserve the heat sufficient to supply for the temperature fall of hot platen caused by drainage in the early period of hot-pressing. In the case of hot-pressing, the iron-netting of 16 mesh was laid on the lower side of mat and the stainless cauls were laid on the upper and the lower sides of mat.

Experiment—1: Under respective 11 kinds of hot platen temperature within the range from 80 to 180 °C and the fixed pressure of 50 kp/cm^2, the changes of temperature and moisture content distributions in the wet pulp mat were measured. The measurement about each position in the lateral direction of mat was carried out in the same procedure, using the mats of 40×40 cm (900 gr.) under the hot platen temperature of 170 °C and the pressure of 50 kp/cm^2.

Experiment—2: The measurements of the transition of temperature and moisture content were started at the same time when the fixed pressure was applied (After 20∼25 sec.), and the pressure was controlled under using the hot platen temperature of 170 °C, two kinds of hot-pressing condition as shown in Table 2.

Experiment—3: As shown in Table 3, the pressures during hot-pressing were kept up the fixed values respectively and the thickness of pulp mat in the hot-pressing was varied by the change of pulp weight under each pressure, so the thickness was measured when reaching the steady state.

Experiment—4: The Asplund pulp prepared under the condition as shown in Table 1 was classified into 5 fractions as shown in Table 4, and then the dimensions and the distribution of wet fibers and fiber-bundles were observed in detail. The fiber length was measured with the aid of a kilvimeter (1/10 mm) and the fiber width was measured with the aid of a monocle (1/10 mm), by picking up the fibers of 800∼900 in each fraction as shown in Table 4, Fig. 2 and Photo. 1.

The pulp mats from each fraction were hot-pressed under 3 kinds of pressure 20, 50 and 80 kp/cm^2 respectively, and the fixed hot platen temperature of 170 °C, with the view to examining the effect of mixing F-1 with F-2, F-3, F-4 or F-5 severally, and F-2 with F-5, their mixtures were prepared at the weight ratios of 100 to 0, 75 to 25, 50 to 50, 25 to 75 and 0 to 100, respectively. Thus, 25 kinds of pulp mat were prepared and hot-pressed under the hot platen temperature of 170 °C, the pressure of 50 kp/cm^2, herein, Experiment—1, 2, 3 and 4 were repeated 3 or 5 times.

2.3. Characteristic of heat and mass transfer during hot-pressing.

2.3.1. The mechanism developing during hot-pressing.

Under the hot platen temperature of lower than 100 °C, the curve of temperature (t) has access to the hot platen temperature with the progress of hot-pressing cycle, that is, the same temperature transition as a general unsteady heat transfer (Fig. 3). Under the higher than 100 °C, by observing the transition of the temperature and the moisture content (u), it was made clear that the internal mechanisms of heat and mass transfer progress as follows, in turn (Fig. 4).

Stage—I (Early unsteady heat transfer): Under the hot platen temperature of lower than 100 °C, the interior temperature of pulp mat rises as rapidly as the general unsteady heat transfer and the moisture of middle layer reduces as suddenly as that of the outer layer.

Stage—II (Non-equilibrium evaporation of vapor): The water heated in Stage—I is found in aboundance in the pulp mat, and while the evaporation occurs near the surfaces, a large quantity of vapor does not equilibrate that of the emission of vapor from the interior with the consequence that the vapor pressure rises in the interior part of mat, so that the temperature in the interior part becomes higher than 100 °C.

The temperature in the interior drops with increasing the quantity of vapor emission and then the quantity of vapor generated in the interior tends to become equilibrium with that of vapor emitted from the pulp mat.

In the consideration by Maku, T. et al.[55] on the hot-pressing process of particleboard and in the observation by Dyenisoye, O. B. et al.[16] on the hot-pressing of wet particle mat, such a phenomenon has been previously made clear, it is an important mechanism of wet pulp mat which contains much moisture and it is hermetically sealed up. During this period, the temperature in the interior part of pulp mat becomes the maximum ($t_{max.}$) and it rises with the rise of hot platen temperature (Fig. 5), therefore, the more the heat quantity per unit time, the more intensely the non-equilibrium evaporation.

Stage—III (Latent heat absorption of moisture in the middle layer): Because of heat consumption due to the evaporation from the upper and the lower surfaces of pulp mat, the quantity of heat transfered toward the middle layer decreases, furthermore, the resistance to heat conduction[52] results in the retardation of temperature transition in the middle layer with greatly evaporating the moisture content in the face layers, as pointed out by Johnson, K. O.[33]. In this period, the great quantity of moisture which remains without emitting during I and II stages absorbs the latent heat in the equilibrium state. After the moisture in the interior part sufficiently absorbs the latent heat in the course of heat transfer, the temperature in the interior part begins to rise as a result of the considerable vapor emitted from the middle layer and after the end of evaporation of vapor in the interior, the following stage develops the symptoms of the appearance.

Stage—IV (Latter unsteady heat transfer): After the evaporation of moisture which is contained in the pulp mat, the resistance of water evaporation to the temperature transition disappears. As the temperature curve follows up the same tendency as that of general unsteady heat transfer, the temperature in the interior draws closer to the hot platen temperature.

Stage—V (Steady heat transfer): The temperature in the whole pulp mat nearly equalizes with the hot platen temperature, and this stage is in the state of heat equilibrium.

2.3.2. The behavior in the lateral direction of pulp mat.

At the edge D (Fig. 6) of pulp mat during hot-pressing, the temperature always does not become higher than that in the interior part and the heat effect is small for fibers because the part contains more moisture which evaporates in the equilibrium state. However, the above-mentioned mechanisms are observed in the case of the interior part (Fig. 7).

2.3.3. The heat transfer from both hot platens toward the middle layer.

It is clearly confirmed that the heat toward the interior part of pulp mat transfers more from the upper face than from the lower face (Fig. 8).

Through the whole hot-pressing process, the temperature in the upper layer is higher than that in the lower layer, while the temperature in the lower layer is almost as high as that in the middle layer and rather the former is lower than the latter during Stage—II and Stage—IV. In general, the part affected most weakly by heat exists in the position nearer to the lower layer than to the upper layer.

On the lower surface of pulp mat, the effective contact area of heat transfer is thought to be small and the lower layer is not dense, so the resistance to the heat transfer toward the middle layer must be great. The lower layer contains more moisture which is required much heat for evaporation because the initial mechanical drainage occurs through the netting under the lower face.

2.4. Analysis of heat and moisture transfer on the basis of effect of pressure.

The process of hot-pressing could be divided into 5 stages in the case of higher hot platen temperature than 100 °C as explained in 2.3.1., hereupon, these 5 stages progress during hot-pressing of moisture-contained mat in turn under every pressure accepted in this experiment.

2.4.1. The temperature (t)-hot pressing time (τ) curve.

Both the maximum temperature ($t_{max.}$) of the middle layer in Stage—II and the minimum temperature ($t_{min.}$) of the middle layer in Stage—III rise with increasing pressure (P). This tendency is evident under the lower pressure than 60 kp/cm^2, and the relationships between the values and P can be represented in the following empirical formulae under the lower than 70 kp/cm^2,

$$t_{max.\ or\ min.} = \frac{1}{0.434} \exp(a P + b) + 100\ (^\circ C) \tag{1}$$

Where a and b are constant. The value of $t_{max.}$ shows about 170 °C under the higher pressure than 70 kp/cm^2, being out of these formulae, and $t_{min.}$ gets near 160 °C (Fig. 9). In the work by Wilcox, H.[103] on the interrelationship between the transition of temperature in the pulp mat and the pressure during hot-pressing, the maximum ($t_{max.}$) or the minimum ($t_{min.}$) temperature gets near the hot platen temperature with the consequence that our results coincide with his experimental result.

2.4.2. The theoretical analysis and its experimental result.

The Stage—II which appears during hot-pressing of wet pulp mat characteristically involves consideration by using a closed vessel.

At the arbitrary time when the liquid water coexists with the saturated vapor in a certain dryness in the vessel (A sort of thermodynamic system), the temperature (t)-entropy (S) curve can be represented in the dotted curve in Fig. 11 (Isochore change curve in closed system). The quantity of heat (q) required for the change of temperature (Δt),

$$q = S\,\Delta t$$

herein,

$$t = f(S)$$

The quantity of heat (q_i) required to rise the temperature from t_o to t_i is,

$$q_i = \int_{t_o}^{t_i} S\,dt \tag{2}$$

In this case of a vessel with a filter (Open system), when the part of heat is exhausted through the filter during the rise temperature (t), the water in the vessel must evaporate more by G than in the case of a vessel without a filter (Closed system). As the apparent entropy (S) becomes large, the relationship between t and S is changed into a curve having the less gradient than the dotted curve and the quantity of heat increases from Q_o to Q_f. The supplied heat from both faces of platens toward the middle layer during Stage—II is Q and t-S curve can be represented in a straight line with the gradient of 1/m as follows;

$$t = 1/\mathrm{m} \cdot S \tag{3}$$

when the time required to rise from t_o to t_i is defined as i,

$$\tau_i Q = \int_{t_o}^{t_i} S\,dt = \int_{t_o}^{t_i} mt\,dt = \frac{1}{2}\,m\,(t_i^2 - t_o^2) \tag{4}$$

where the temperature at the start of Stage—II is 100 °C, τ_{II} is the time from the start of hot-pressing to the arbitrary time during Stage—II.

$$t = \sqrt{100^2 + 2\,\frac{Q}{m}\,(\tau - \tau_{II})} \quad (°C) \tag{5}$$

Herein, the equation (5) shows the temperature transition during Stage—II. As 1/m is a gradient of *t-S* curve, the value of *m* increases with increasing the filtration of pulp mat for the vapor generated in the interior of pulp mat and *Q* decreases with decreasing the hot platen temperature.

Consequently, the value of *m* indicates the extent of the filtration of pulp mat for the vapor generated in the interior of pulp mat, and *Q* has an influence on the curve of temperature during Stage—II. In this experiment, if *Q* is regarded as a constant value, using the curve of t-τ obtained by the experiment, the filtration factor m/Q can be conducted. The results represent the same tendency as the above-mentioned theory and in particular, the value of m/Q becomes very small in the region of the higher than 60 kp/cm^2 with increasing pressure, (Fig. 12).

However, it can be suggested from the above results that the values of *m* change with the change of the characteristics of constituent fibers and the arrangement of fibers in the pulp mat. Under the lower pressure than 60 kp/cm^2 the intercellular gaps in the pulp mat, i.e. the ducts for the emission of vapor reduce at the large ratio, and under the higher than 60 kp/cm^2 the reduction approachs the limiting value with increasing pressure. This tendency is more obvious in the case of hot-pressing without the distance bar than with the distance bar.

2.5. Analysis of heat and moisture transfer on the basis of pulp quantity.

2.5.1. Temperature transition.

Since the maximum temperature ($t_{max.}$) increases in the case of the thinner pulp mat than a certain thickness with rising hot platen temperature (Fig. 13) and the non-equilibrium evaporation of moisture in the interior part is prolonged, the distance to the surface from which the vapor emits to the exterior of pulp mat increases, and the non-equilibrium evaporation goes on prolongly and intensely. It is made clear from this result that the distance to the lower surface from which the vapor emits to the exterior of pulp mat is closely related to the filtration, as investigated by Lund, L. M. & Berman, A. S.[54], analyzing that the flow and the diffusion of gas were affected by the diameter and the length of capillary and the gradient of total pressure in the filtration-cake.

With increasing thickness of pulp mat, the moisture content in the start of Stage—II increases and the heat conducted from both hot platens toward the interior is greatly absorbed by heating water and evaporating in the layer on the way, so the retardation of heat transfer occurs, and then for the vapor evaporates gradually, the non-equilibrium evaporation goes on slowly and prolongly. Consequently, increasing above a certain thickness of pulp mat, again $t_{max.}$ decreases clearly (Fig. 3) and the period of Stage—II increases (Fig. 14).

2.5.2. The transition of moisture in the pulp mat.

The change of moisture (u) during hot-pressing with hot-pressing time (τ) is expressed in the following reduction curves in the case of the upper, the lower layers and the middle layer, regardless of the thickness (Fig. 15).

The formula obtained by Sonnleiter, E.[53] can be applied to this case, which shows that the rate of drying is proportional to the moisture content as follows;

$$\frac{du}{d\tau} = -au \qquad (a: \text{const.}) \tag{6}$$

From the results of this experiment, a is calculated, i.e. the gradient (a_1) of the first reduction curve of moisture content in the middle layer and a_2, a_3 of the second and the third reduction curves are obtained, respectively. The value of a_1 becomes small with increasing thickness of pulp mat (Fig. 16), and because the moisture content keeps a constant value during Stage—III where the temperature of middle layer becomes the minimum, the second gradient (a_2) becomes very small, and the moisture content decreases in the comperatively great gradient (a_3) (Fig. 17).

2.6. Change of heat and mass transfer by the variation of dimension and arrangement of fibers.

The hot-pressing process progresses in the course of 5 mechanisms analyzed in 2.3.1., regardless of the length and the ratio of mixing of fiber.

2.6.1. Stage—I: The shorter the constituent fiber and the more the ratio of short fibers, the longer this period intends to become.

2.6.2. Stage—II: As the constituent fiber is shorter and the pulp mat contains more short fibers, this period is prolonged, but in the case of the pulp mat prepared from the longer fibers than 1.5 mm the period of this stage is hardly prolonged. This tendency becomes more apparent with increasing pressure. As shown by Han, S. T.[29], that in the case of the coarse glass fiber mat the gradient of capillary pressure is generally small but in the case of the beaten KP fiber mat it is always very large, the shorter fibers fill the gap between long fibers or large fiber-bundles and the porosity of pulp mat diminishs, so that the shorter fibers take part in the packing effect for the emission of vapor generated in the interior of pulp mat with the consequence that the maximum temperature ($t_{max.}$) arises with shortening fibers (Fig. 19) and the filtration factor is reduced by plenty of shorter fiber in the pulp mat (Fig. 20 and 21).

Thus, the gradient (m) of t-S curve in 2.4., i.e. the filtration factor (m/Q) can be defined as a sort of structural characteristic, and this result will be minutely investigated by observing the internal structure of pulp mat in 3..

2.6.3. Stage—III: On the contrary to Stage—II, with shortening fiber and with mixing plenty of shorter fiber, the period of this stage decreases.

2.7. Summary.

2.7.1. The heat and mass transfer in the pulp mat during hot-pressing is divided into 5 mechanisms as follows, under the higher hot platen temperature than 100 °C;

Stage—I: Early unsteady state of heat transfer.
Stage—II: Non-equilibrium evaporation of vapor in pulp mat.
Stage—III: Absorption of latent heat of water in middle layer.
Stage—IV: Latter unsteady state of heat transfer.
Stage—V: Steady state of heat transfer.

2.7.2. The quantity of heat toward the middle layer is more supplied from the upper hot platen than from the lower hot platen, because the lower surface of pulp mat has the less effective contact area of heat transfer from laying the wire-netting on the lower surface and there is much moisture in the lower face layer during the extremely early period of hot-pressing, therefore, the part subjected the less heat exists at the place near to the lower layer.

2.7.3. Considering a kind of thermodynamics system for the non-equilibrium evaporation of vapor in the pulp mat during hot-pressing, the temperature transition curve is produced from the relationship between temperature and entropy of water. It is evident that the temperature curve is affected by the filtration of pulp mat for the vapor generated in the interior part of pulp mat and the quantity of heat supplied per unit time. This tendency is agree with the theoretical analysis.

2.7.4. With increasing thickness of pulp mat, the distance from the middle layer toward the lower surface, i.e. the main emission ducts are so longer that the filtration decreases and the non-equilibrium evaporation becomes active, however, above a certain thickness, the thick upper and lower layers absorb the heat transfered from the hot platens to the inner layer, so the temperature transition in the middle layer is strongly resisted by such a behavior.

2.7.5. In the wet pulp mat during hot-pressing, the short fibers fill the gaps between long or large fibers and fiber-bundles, and in particular, the non-equilibrium evaporation becomes active because the filtration of pulp mat for the vapor generated in the interior of pulp mat decreases. A sort of structural characteristics of pulp mat during hot-pressing is dependent on the dimension and the arrangement of constituent fibers.

Table 1. Manufacturing condition and property of Asplund pulp.

-①

Treatment		Preheating	Defibration
Steam pressure. kp/cm² (°C)		8.0 (170)	8.0 (170)
Time.	min.	3.0	2.5

-②

Freeness	Sifting analysis				
	Retained on 11 mesh	11～18	18～24	24～80	80～200
13～15 D.S.	1.5 %	16.0	35.5	20.5	26.5

Table 2. Controls of specific pressure.

Specific pressure	Distance bar	Range of specific pressure (kp/cm²)	Thickness (cm)	Weight of pulp (gr)
P_1	Without (Constant pressure)	10.0～90.0	0.60～0.43	180
P_2	With	1.0～93.0	0.50	40～200

Table 3. Hot pressing condition at temperature measurement of pulp sheet.

Hot platen temperature (°C)	170
Specific pressure (kp/cm²)	5, 10, 30, 50, 70, 90, (Kept constant during hot pressing)
Time (min.)	2.0～47.5
Dry weight of pulp (gr.)	35～370
Thickness (cm)	0.18～1.14

Table 4. Dimensions and constitution of fibers in each fraction of pulp.

Fraction		Wood fiber (including tracheid)		Vessel member		Wood parenchyma cell		Bundle of wood fibers		Bundle of wood parenchyma cells		Mean		Freeness
No.	Mesh	Length	Width	Length	Width	Length	Width	Length	Width	Length	Width	Length	Width	D. S.
F-1	Retained on 11	—		—		—		3,650±1805	150±107	—		3,650±1805	150±107	8.0～10.5
								(100.0)						
F-2	11 ～ 18	1,723±331	24±3	750±294	94±58	—		1,565±422	69±45	—		1,656±463	42±18	10.0～12.5
		(59.9)		(0.4)				(39.7)						
F-3	18 ～ 24	1,483±364	24±4	820±422	75±32	158±64	22±5	1,005±526	68±38	—		1,430±579	35±14	11.5～13.5
		(89.2)		(0.2)		(0.1)		(10.5)						
F-4	24 ～ 80	1,206±353	23±5	792±332	93±31	—		858±489	96±55	—		1,134±426	39±20	13.0～15.5
		(81.6)		(12.6)				(5.8)						
F-5	80 ～200	726±422	22±6	414±237	68±30	143±51	23±6	242±138	73±46	154±108	78±35	580±314	36±22	19.0～24.0
		(66.5)		(13.4)		(2.8)		(12.5)		(4.8)				
Himeshara wood (Defibrated with SCHULZ's solution)		1,417±464	24±4	1,016±491	99±27	109±59	22±4	—		—		1,177±437	30±17	—
		(68.3)		(19.3)		(12.4)								

Unit; μ

( ); Percentage of volume, calculated by regarding cross-section of fiber or bundle of fibers as cylinder.

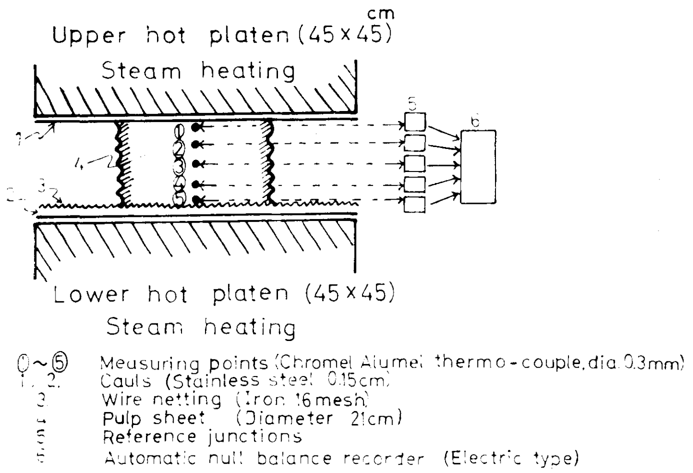


Fig. 1. Illustration of measurement of temperature.

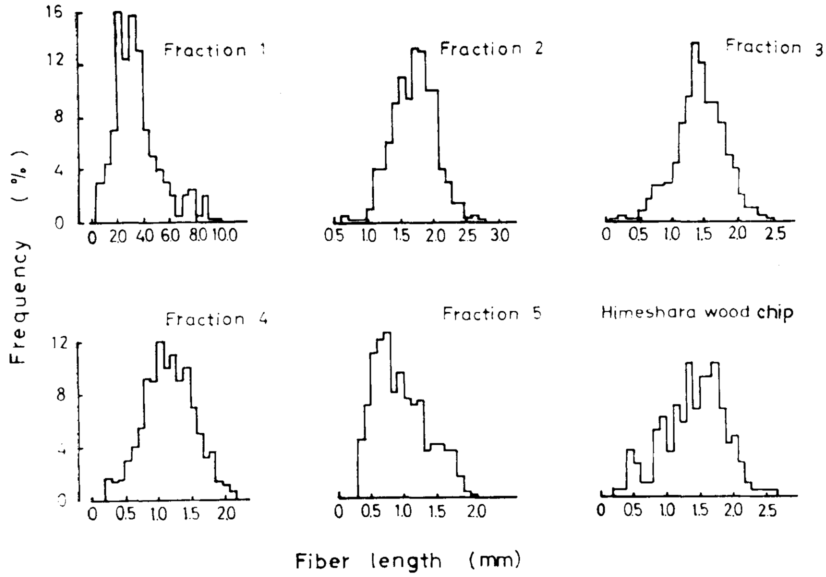


Fig. 2. Frequency distribution of fiber length in each fraction of pulp and Himeshara wood chip.

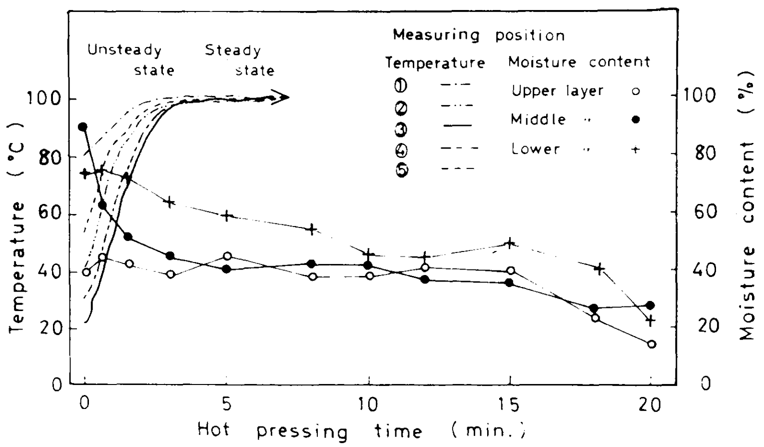


Fig. 3. Transitions of temperature and moisture content at various positions in wet pulp mat during hot-pressing at lower temperature of platen than 100 °C (Example, at 100 °C).

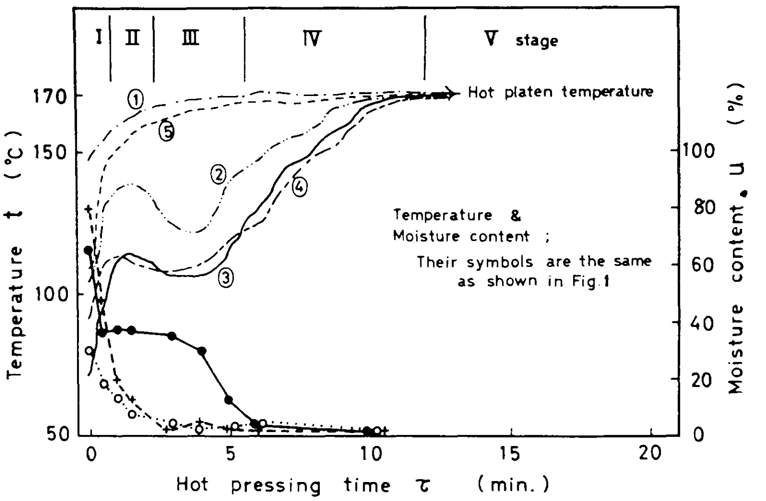


Fig. 4. Transitions of temperature and moisture content at various positions in wet pulp mat during hot-pressing at higher than 100 °C (Example, 170 °C), and representation of division into five stages of heat-mass transfer.

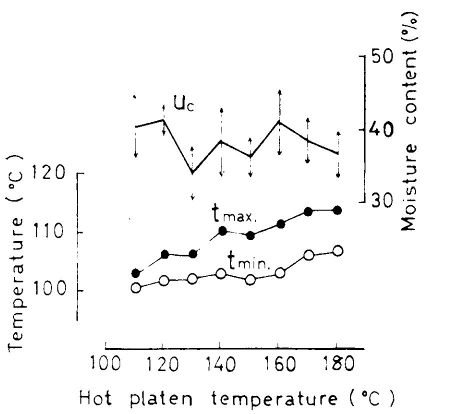


Fig. 5. Influences of hot platen temperature on maximum temperature ($t_{max.}$), minimum temperature ($t_{min.}$) and temporarily constant moisture content (u_c) at middle layer of wet pulp mat, appearing during Stage-II or -III of hot-pressing.

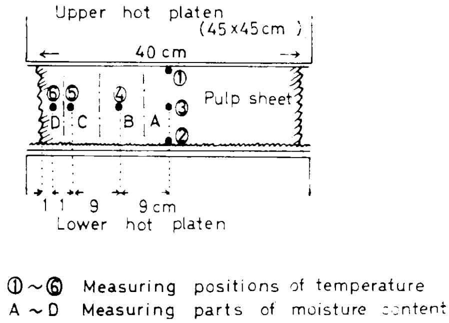


Fig. 6. Illustration of measuring positions of temperature and measuring parts of moisture content in lateral direction of pulp mat.

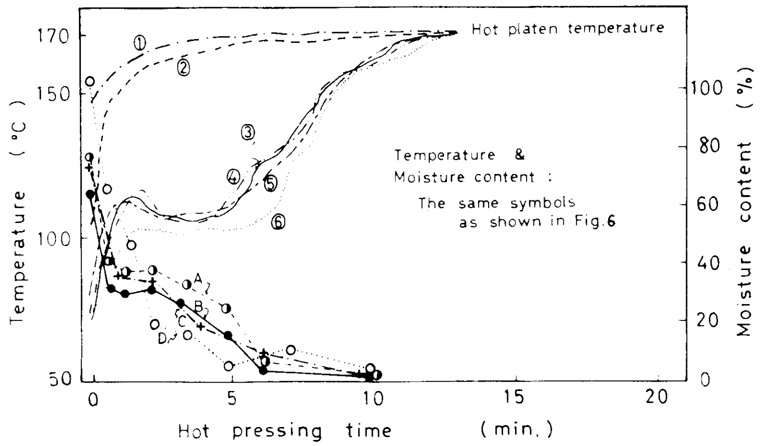


Fig. 7. Transitions of temperature and moisture content at various positions in lateral direction of pulp mat during hot-pressing at higher than 100 °C (Example, at 170 °C).

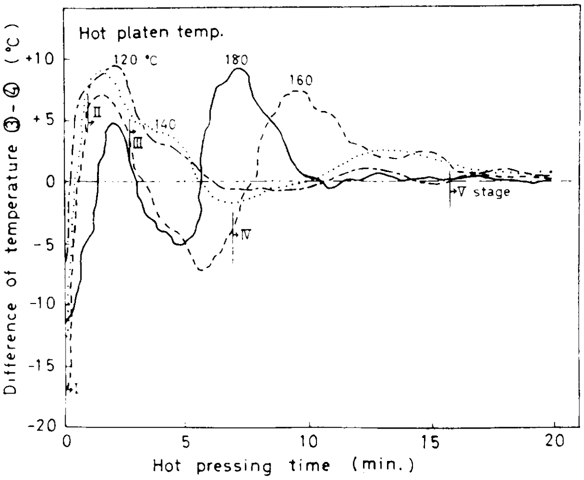


Fig. 8. Change in temperature difference between position-3 and -4 with the lapse of hot-pressing time at various temperatures of hot platen (Position-3 and -4 are signified in Fig. 4).

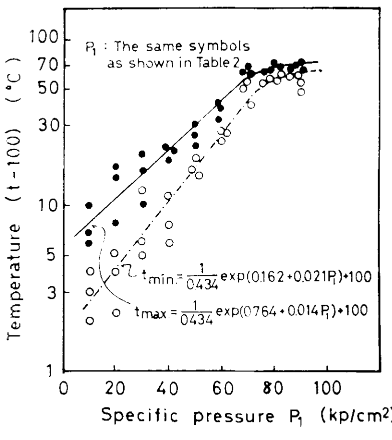


Fig. 9. Effects of pressure of hot-pressing on $t_{max.}$ and $t_{min.}$, in the case of hot-pressing at 170 °C without distance-bar.

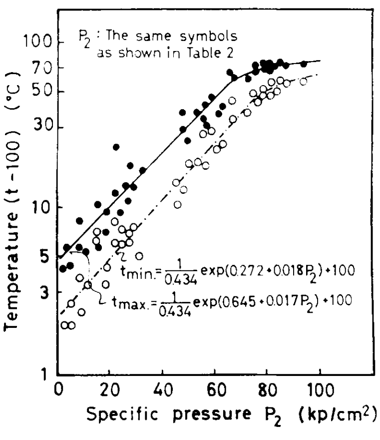


Fig. 10. Effects of pressure of hot-pressing on $t_{max.}$ and $t_{min.}$, in the case of hot-pressing at 170 °C with distance-bar.

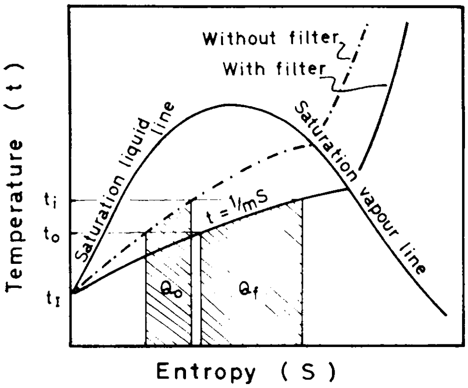


Fig. 11. Graphical representation of relationship between temperature (t) and entropy (S) in isochore change of water.

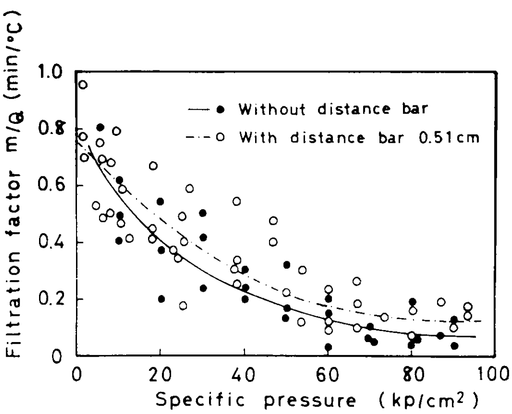


Fig. 12. Dependences of filtration factor (m/Q) on pressure of hot-pressing with distance-bar and without distance-bar.

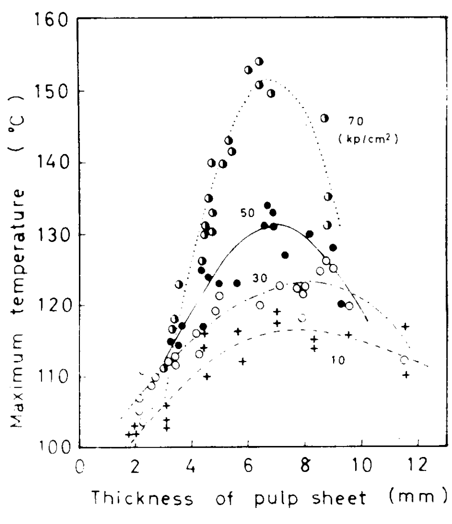


Fig. 13. Changes in $t_{max.}$ with thickness of pulp mat during hot-pressing at 170 °C under various pressures of hot-pressing.

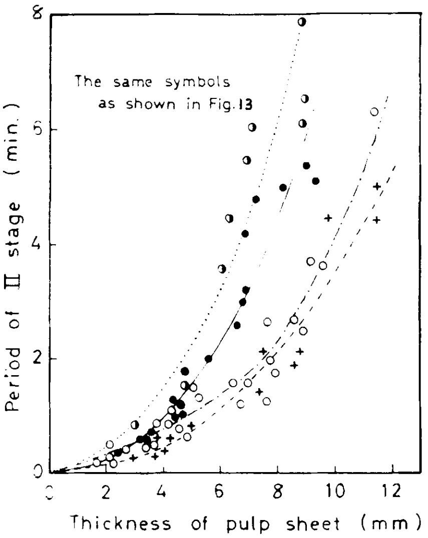


Fig. 14. Changes in period of Stage II with thickness of pulp mat hot-pressed at 170 °C under various pressures of hot-pressing.

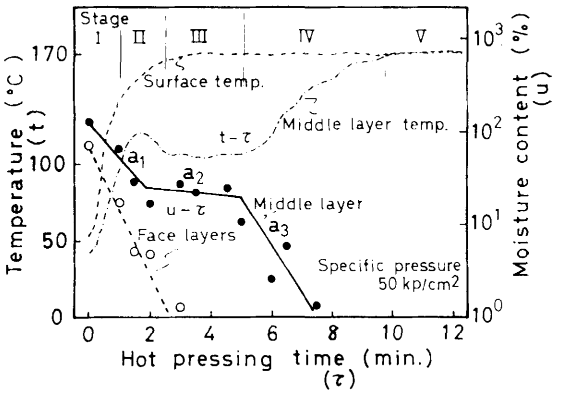


Fig. 15. Schematical analysis of reduction curve of moisture content at face layers and middle layer during hot-pressing.

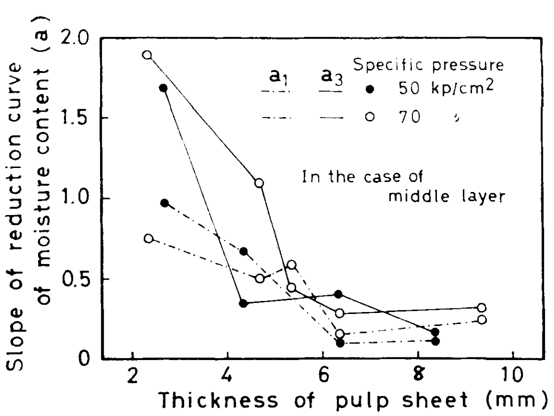


Fig. 16. Effect of thickness of pulp mat on each slope of reduction curve of moisture content in middle layer of pulp mat.

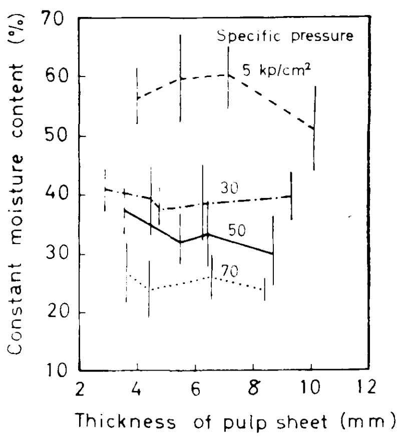


Fig. 17. Change in value of temporarily constant moisture content (u_c) with thickness of pulp mat in the case of hot-pressing at 170 °C.

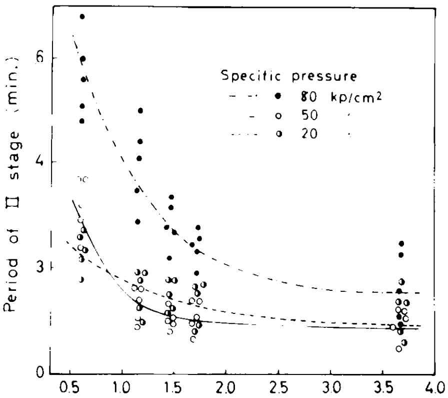


Fig. 18. Relationships between period of Stage II and length of consituent fibers in pulp mat, for various pressures of hot pressing.

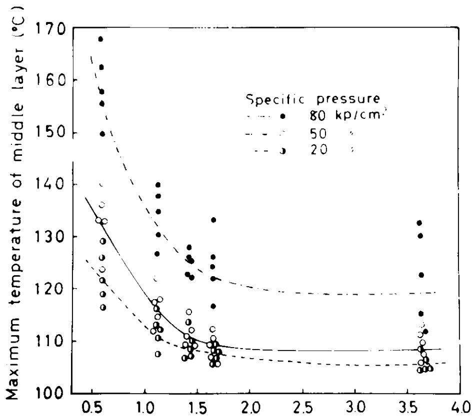


Fig. 19. Relationships between $t_{max.}$ of middle layer and length of constituent fibers in pulp mat, for various pressures of hot-pressing.

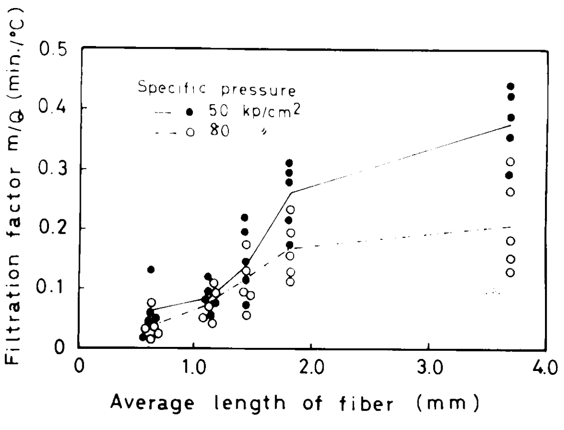


Fig. 20. Dependences of filtration factor (m/Q) on length of constituent fibers in pulp mat, in the case of hot-pressing under different pressures of 50 and 80 kp/cm^2.

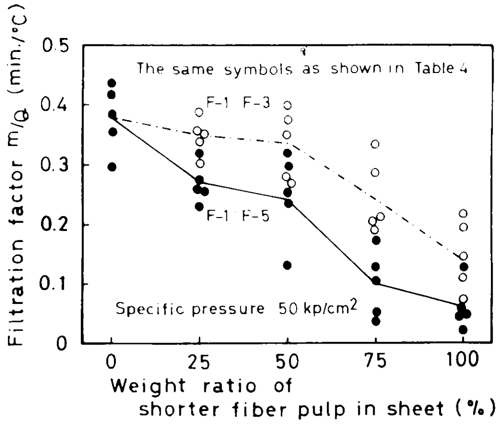


Fig. 21. Dependence of filtration factor (m/Q) on weight ratio of fine or short fibers' pulp in pulp mat.

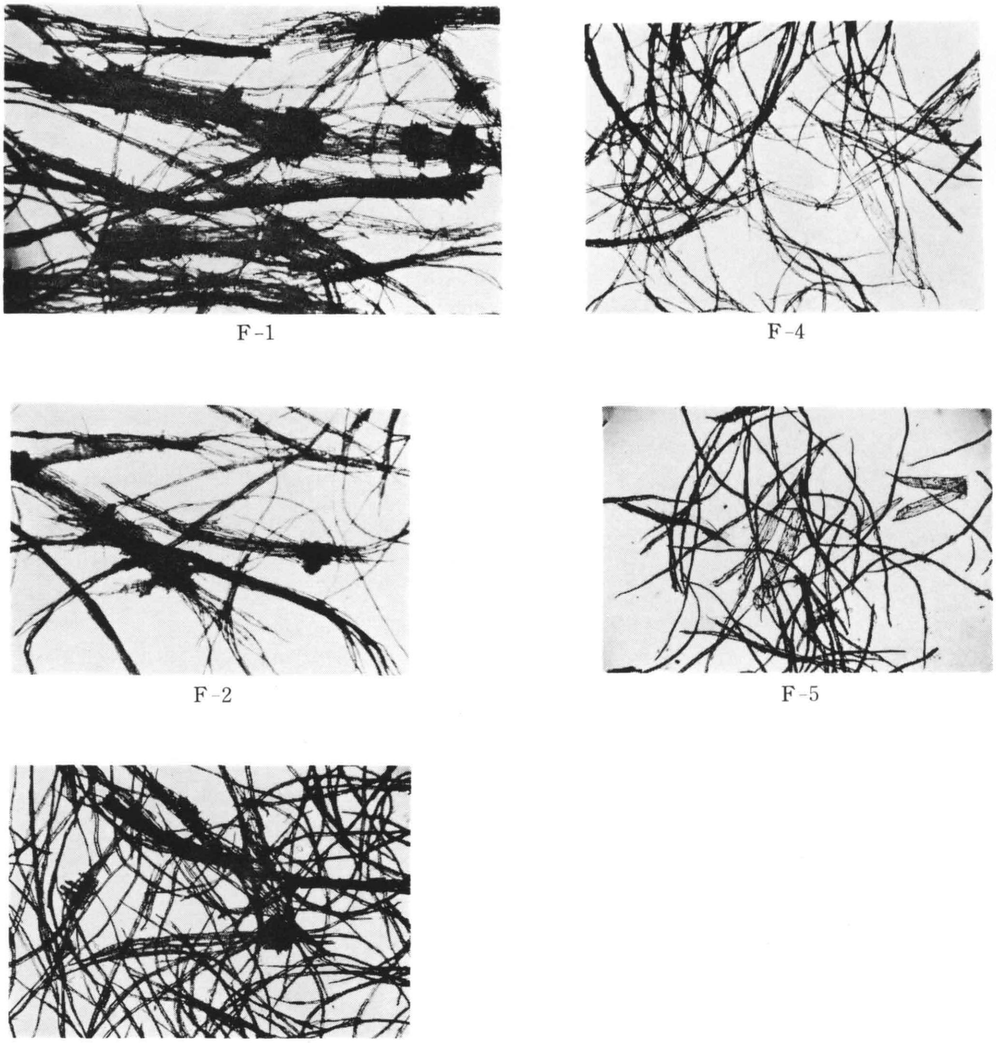

F-1
F-4
F-2
F-5
F-3

Photo. 1. Fiber or fiber-bundle of each fraction.
(Asplund pulp from HIMESHARA wood)

3. Behavior of internal structure of pulp mat during hot-pressing.

3.1. Introduction.

It has been previously observed that the heat and mass transfer in the pulp mat during hot-pressing has a close relation to the structure of pulp mat and the compressibility. The non-equilibrium evaporation of the vapor generated in the interior of pulp mat is affected by the filtration of pulp mat in the case of the intense heat and mass transfer during hot-pressing. Furthermore, the filtration will be dependent not only on the dimensions and the arrangement of fibers but on the macro-slippage between fibers and the compressive deformation of fiber. The analysis of the behavior of internal structure during hot-pressing of pulp mat would be fundamental to investigate on the mechanism of the heat and mass transfer and the board properties.

In the research of the internal structure of fiberboard, when Klauditz, W. & Stegmann, G.[44] investigated on the effect of heat-treatment for the hardboard on the breakage in tension, they observed the broken face of the cross-section of hardboard which was produced from the Asplund pulp or the KP prepared from Buche and Fichte with the aid of a microscope. Kollmann, F. & Dosoudil, A.[48] examined the surface of hardboard by the low power optical microscopic test. These experiments were carried out only for the purpose of material test.

In the occurance of the rock-base like layer, approaching to the theoretical analysis of board formation in dry-process, Enomoto, S. et al.[17,18,19,20] observed the distribution of density in the direction of thickness of hardboard with the aid of a soft-X ray.

The behavior of internal structure of fiberboard during hot-pressing has never been analyzed with the aid of a microscope, therefore in this investigation the change of internal structure of pulp mat and the deformation of fiber in the pulp mat would be in detail analyzed with the aid of a high power optical microscope ($\times 150 \sim \times 600$).

Yamai, R.[107] and Gaber, E.[25] carried out the investigation of mechanical behavior of wood in compression perpendicular to grain, and Kunesh, R. H.[50] and Fukuhara, T.[24] investigated on the characteristic of structural behavior of wood within the range of plasticity, using many species and under the various loading conditions, with the aid of a optical microscope at the less magnification than 100. In 3.4., the behavior of wood fiber, that of vessel and their interrelationship between them in the steam-treated wood within the range of plasticity will be observed with the aid of high power microscope, and on the basis of these results, the behavior of internal structure of pulp mat during hot-pressing will be investigated more apparently.

3.2. Experimental procedure.

The pulp mats prepared by the same pulping and forming methods as the case of 2.2. were hot-pressed under the following conditions and the three SIS fiberboards were produced per each condition.

3. 2. 1. Under the hot platen temperatures of 130, 150 and 170 °C respectively, the pressure was varied within the range from 10 to 90 kp/cm^2 and the hot-pressing cycle was fixed to 20 min..

3. 2. 2. The Asplund pulp was classified into 5 fractions by the same method as the experiment in 2. 6.. The mixtures of fraction 3 or 5 with fraction 1 were prepared at the ratios of 100 to 0, 75 to 25, 50 to 50, 25 to 75 and 0 to 100 %, and the pulp mats were made from these pulp and were hot-pressed under the condition of 170 °C, 50 kp/cm^2 and 20 min..

3. 2. 3. After the pulp mats preliminarily cold-pressed under the condition of 40 kp/cm^2 and 1.0 min. were oven-dried under 105 ± 2 °C, they were conditioned to the moisture content of 0, 10, 15, 30, 45 and 60 %, and were hot-pressed under the condition of 170 °C, 50 kp/cm^2 and 20 min..

3. 2. 4. The unbeaten and non-sizing Asplund pulp from Akamatsu wood (Pinus densiflora Sieb. et Zucc.) was manufactured under the defibrating condition as shown in Table 1-1, and the pulp mats formed by the same method as the case of Himeshara wood (Stewartia monadelpha Sieb. et Zucc.) were hot-pressed under the various pressures within the range from 10 to 90 kp/cm^2, 170 °C and 20 min..

After the fiberboards manufactured by the above-mentioned method were conditioned to the moisture content of 9 ± 2 % in the room temperature of 20 ± 2 °C and the room relative humidity of 60 ± 5 %, the specimens for the optical microscope examination (4 × 4 cm) were prepared from their boards.

In order to observe the internal structure of fiberboard in their original condition[22, 51)], the cross-sections of fiberboard which were smoothly with the razor were examined with the aid of a reflex-microscope (Nikon-type M) at the magnifications of 150, 300 and 600. The 30 sheets of micrograph were taken per one board.

The 4 kinds of measurement were done on the printing papers as follows;

(1) Compressive cross-sectional deformation of fiber: As shown in Fig. 22 and Photo. 2, the external diameter (a) in the direction of pressure and the internal diameter (b) in the perpendicular direction to pressure, relative to the cross-section of fiber were measured with the aid of a measuring monocle (1/100 mm).

The ratio of a to b (b/a) is regarded as an indicator of compressive deformation of fiber.

(2) The structural composition in the fiberboard: The composition of cross-section of fiberboard in the direction of thickness are classified into 3 kinds of elements (Photo. 2) as follows;

(A) Cell wall
(B) Lumen
(C) Intercellular gap

The occupation ratios of these elements in the cross-section of fiberboard were measured by the following method, that is to say, a transparent sheet dotted in the grid at intervals of 0.5 cm was placed on the printing paper and then the dots were classified into each element, thus, the occupation ratios were determined by using the ratio of number of dot belong to each element to total dots.

(3) The cracked wall of fiber: The frequency of number of fiber having the wall cracked from the lumen through the radial direction (D in Photo. 3) were determined.

(4) The irregularity of the compressive cross-sectional deformation of fiber: About 600～700 of b/a were measured per one hot-pressing condition and the coefficient of variation obtained by the statistical treatment was regarded as an indicator of the irregularity of compressive deformation.

The specimens were prepared from the same annual ring band as the sap wood used previously in the pulping, and they were saturated with water by means of the repeated submersion and depression, and the edge grain specimens were cut, having the loading plan of 25×50 mm, thickness of 3, 5 and 7 mm, the longer side was perpendicular to the grain.

Their specimens saturated with water were treated with the steam of 8 kp/cm^2 (170 °C) for 5.5 min., under the same condition as the Asplund pulping in this experiment and then were submerged in the cold water of 18 ± 1 °C. The hot-press apparatus is constructed by fitting up the Olsen type testing machine (10 ton.) with the upper and the lower hot platens and the load cell of water-cooling type (Photo. 4). The specimens were placed between the platens and were hot-pressed at the rate of application of pressure of 0.3 mm/min., and then the compressive deformation was measured at the accuracy of 0.01 mm with the aid of a dial gauge, so that the pressure-deformation diagrams were obtained.

Using the end-matched specimen, the pressure were released at these points, after their specimens were cold- or hot-pressed intermittently till the early and the latter stages of the first plasticity, the second plasticity and the third plasticity, respectively [58].

The spring-back deformation when releasing the pressure was put back in the state of pressing by the clamp, since the dimension of thickness was checked with the aid of a measureing microscope (1/20 mm) and a monocle (1/10 mm). As done before hot-pressing, the center plan of the end grain was observed with the aid of a reflex-microscope at the magnifications of 300 and 600, and then the micrographs were taken minutely. The ratio b/a was obtained and the measurements of 400～500 per one condition were statistically treated, and the coefficient of variation was obtained as an indicator of the irregularity of compressive cross-sectional deformation of fiber in wood.

3.3. Behavior of pulp mat during hot-pressing.

3.3.1. The compressive cross-sectional deformation of fiber in the pulp mat is observed to deform from a circle to an ellipse and a two-lobed shape or a flat shape with increasing pressure, as shown in Photo. 5.

Hereupon, regarding a fiber as a tubulous cylinder unrestained the periphery, when it is compressed at the upper and the lower sides, as shown in Fig. 22, the bending moment (M) acting at D point is,

$$M = \frac{Pr}{2}\left(\cos\varphi - \frac{2}{\pi}\right) \tag{7}$$ [61]

therefore, the diameter (x) of cylinder changes into $x + 2\Delta x$ in the case of x-axis.

$$\begin{aligned} 2\Delta x &= 2\int_0^{\varphi}(y_1 - y)\,\frac{M}{EI_z}\,d\varphi \\ &= \frac{Pr^3}{EI_z}\left(\frac{2}{\pi} - \frac{1}{2}\right) = 0.137\,\frac{Pr^3}{EI_z} \end{aligned} \tag{8}$$

in the same way,

$$2\Delta y = -\,0.149\,\frac{Pr^3}{EI_z} \tag{9}$$

Where E is the modulus of elasticity of fiber wall, the moment of inertia I_z can be obtained as follows; where κ is a section modulus and w is the width of rectangular-section,

$$\kappa = \frac{1}{3}\left(\frac{e}{r}\right)^2 + \frac{1}{5}\left(\frac{e}{r}\right)^4 + \frac{1}{7}\left(\frac{e}{r}\right)^6 + \cdots\cdots$$

$$I_z = \kappa w 2er^2 = 2\,\kappa e w r^2 \tag{10}$$

Hence,

$$2\Delta x = 0.137\,\frac{P}{2wE\kappa\,\frac{e}{r}} \tag{11}$$

Thus, the same equation is found out for $2\Delta y$.

As considered from the formula (11), $2\Delta x$ and $2\Delta y$ become smaller with increasing the ratio of wall thickness to diameter of fiber (e/r), so the compression of fiber becomes difficult, for example, since the wood fiber of hardwood has larger e/r than the vessel of hardwood and the trachaid of soft wood, the compressive deformation is affected by the dimension of fiber and the modulus of elasticity of fiber wall.

3.3.2. The change of internal structure due to the application of pressure was analyzed on the basis of the effect of pressure on the compressive cross-sectional deformation of fiber and the occupation ratio of the composition element, in consequence, the behavior of compressive deformation of pulp mat can be divided into 3 phases as follows;

Phase—I: The occupation ratio of cell wall increases with the decrease of intercellular gap under the lower pressure than about 30 kp/cm^2, according as the initial pressure increases, but the compressive cross-sectional deformation of fiber is not merely exerted so that the lumina are hardly deformed. In this phase, while the compressive cross-sectional deformation scarely changes, the most part of pressure energy is absorbed for the reduction of intercellular gap.

Phase—II: In the course from 30 to 60 kp/cm^2, the reduction of intercellular gap is scarcely caused now, but the occupation ratio of cell wall increases with decreasing lumina and then the compressive cross-sectional deformation of fiber makes appreciable progress.

Phase—III: Under the higher pressure than 60 kp/cm^2, the compressive cross-sectional deformation of fiber continues to increase somewhat and the smaller intercellular gaps are filled up with the protrudent part of fiber wall. The internal structure noticeably becomes dense, so that the occupation ratio of cell wall increases.

The occupation ratio of lumen and the compressive cross-sectional deformation scarcely change. In this phase, the intercellular gap almost disappears and while the compressive cross-sectional deformation increases a little, the reduction of lumen reaches the limiting, so that the packing of fiber is greatly promoted.

Didriksson, E. E. & Back, E. I.[15)] investigated on the relationship between the size of pore and the board density, and then they found out that the radius of void decreased in a power function with increasing board density. That is similar to the reduction of intercellular gap with increasing pressure in the case of this experiment.

In the case of Akamatsu Asplund pulp, the change of internal structure due to the application of pressure can be divided into 3 phases from the effect of pressure on the compressive deformation of fiber, as obtained in the case of Himeshara Asplund pulp (Fig. 25).

In general, the compressive deformation of fiber is always relatively larger in the pulp mat of Akamatsu wood, particularly the compressive deformation of pulp mat from the Akamatsu wood greatly increases under the higher pressure than 70 kp/cm^2.

As considered from the formula (11), this phenomenon is thought to be explained from the difference in compressive deformation between the wood fiber of hardwood and the trachaid of softwood, however this matter is required the more minute examinations (Photo. 6). As expressed in the theory by Ingmanson, W. L.[32)] on the filtration resistance of incompressibility body and the experimental result of Tiller, F. M.[99)] on the relationship between the change of internal void and the filtration, it must be important for the analysis of the heat and mass transfer in the pulp mat to investigate the effect of pressure on the internal structure of fiberboard.

As previously state in 2. 4., the non-equilibrium evaporation becomes intense with increasing pressure, specially under the higher pressure than 60 kp/cm^2. This fact was ascertained from the change of internal structure.

3. 3. 3. The frequency of having cracked wall in the cross-section of fiberboard increases under the lower pressure than 60 or 70 kp/cm^2 with increasing pressure

(Fig. 26), which was cracked from the side of lumen in the radial direction (Photo. 3). The crack of fiber wall is assumed to be originated in the pulping of chip and the cutting of specimen previous to the application of pressure in the hot-pressing, too, so the origination of crack stands in need of the more detail examination.

3.3.4. The moisture contained in the constituent fibers of pulp mat before hot-pressing has potent influence on the internal structure of fiberboard.

With increasing moisture content, the decrease of intercellular gap and the reduction of lumen become so evident (Fig. 28) that the compressive deformation of fiber considerably increases in the case of the less moisture than 30 % (Fig. 27), and the tendency becomes weak within the range from 30 to 45 %. All the occupation ratios do not almost change in the case of the more moisture than 45 % and the compressive deformation of fiber increases, so that the plasticity of fiber wall increases under the less moisture than the fiber saturation point and the existence of more moisture than the fiber saturation point has a little influence on the compressive deformation and the occupation ratio of internal structure (Photo. 7).

3.3.5. The internal structure of fiberboard is greatly affected by the dimension of fiber and the composition ratio of fiber.

The large fiber-bundle is a little deformed the cross-section even under the higher pressure, as observed that even the vessel pore in the fiber-bundle keeps the opening (Photo. 8). This reason may be due to the strong resistance of wood structure in the fiberbundle to the compression.

The fibers near the large void between the fiber-bunbles is slighly deformed to be free from the pressure, on the other hand, the fiber contacting with the upper and the lower sides of fiber-bundle is greatly deformed to be subjected to the concentrated pressure with the consequence that the fiber-bundle furnishs the internal structure of fiberboard with the irregurality of compressive deformation (Photo. 9).

With increasing the single fibers in the pulp mat, the compressive deformation gradually becomes regular, so the uniform properties of board is produced because the pressure is uniformly distributed over the interior of pulp mat by the gap-filling effect of single or fine fibers (Fig. 29).

3.4. Behavior of steam-treated wood within the region of plasticity.

3.4.1. The stress-strain curve in compression perpendicular to grain.

Fukuhara, T.[24] divided the stress-strain curve in compression perpendicular to grain into the range of elastic deformation (OA), the first transition (A), the first range of plastic deformation (near B), the second range of plastic deformation (near C), the second transition (near D) and the third range of plastic deformation (near E). As pointed out by Fukuhara, T.[24], such a compression process is not always adopted to all the conditions (Fig. 30). In this experiment, with rising hot platen temperature, the first and the second transitions evidently appear within the region of low stress-large deformation, however, the first transition almost disappears from beginning to be compressed and the plastic deformation makes some progress through the indistinct second transition to the third region of plastic deformation, under the higher hot platen temperature than 100 °C (Fig. 31).

3.4.2. The behavior of deformation in compression in the tangential direction.

The larger pore of vessel than the wood fibers around the vessel is suggested to have a great influence on the compressive cross-sectional deformation of wood fibers around the vessel.

In the photographs in compression perpendicular to grain, the group of cells is distinguished the group of cells in the bilateral sides from the group of cells in the upper and lower sides near the vessel. The compression behavior is observed in each stage (Photo. 10 and Fig. 32 and 33).

Before the arrival at the first transition, the vessel and the group of cells in the bilateral sides are slightly deformed in an ellipse, while the group of cells in the upper and lower sides are a little deformed the cross-sections and goes to fall into the vessel with the compressive deformation of large pore of vessel. It can be made clear from such a behavior of wood structure that the fibers in the pulp mat is little deformed the cross-section before the pressure is applied to 30 kp/cm^2 and they shows the potent packing effect due to the macro-slippage between fibers. Regarding the pore of vessel as the large intercellular gap, the above-mentioned behavior exhibits a sort of gap-filling.

Furthermore, progressing in compression, while the vessel keeps a deformed shape, the group of cells in the bilateral sides is deformed as shown in the case of vessel in the second region of plasticity, the second transition and the third region of plasticity. On the other hand, as decreasing the compressive deformation of vessel, the group of cells in the upper and lower sides is clearly deformed to the same extent of compressive deformation as the group of cells in the bilateral sides.

It is brought to light from this behavior of the upper and lower sides of vessel that the pressure takes part in the compressive cross-sectional deformation after the gap-filling behavior of fibers in the pulp mat during hot-pressing. This special deformation behavior of wood fiber near the vessel is more considerable in the cold-pressing than in the hot-pressing (Fig. 32 and 33). In the hot-pressing, the group of cells in the upper and lower sides softened due to the thermo-plasticity is deformed with the deformation of the vessel, but the irregularity of compressive deformation greatly appears in the process of compression, because they incompletely slip into the pore of vessel. This fact has an interest as the suggestion that the gap-filling of fiber cannot be strongly occured in the state of thermo-plasticity and drying-set. With increasing to be compressed, the irregularity of compressive deformation is enlarged by the arrival at the second region of plasticity but it is reduced over this region. This phenomenon suggests that the group of cells in the upper and lower sides makes no more progress in their compressive deformation than the group of cells in the bilateral sides by the arrival at the second region of plasticity.

3.4.3. The behavior of deformation in the third region of plasticity.

In the third region of plasticity, the adjacent cells in the wood structure greatly obstruct themselve deformation each other, and the behavior in this stage is different from the smooth progress of deformation from a circlar shape to an ellipse in the case of the defibrated fiber constituting pulp mat, that is to say, the deformed cell wall pushs in the adjacent cell wall and the shape of cells becomes complicated in a three-lobed shape, so the wood changes a packed structure but the void cannot be easily disappeared because of the obstruction between adjacent cells (Photo. 11).

This result demonstrates that in the large fiber-bundle in the pulp mat, the fibers are not deformed so greatly as the single fibers. As the pulp mat is an assembly of many fibers defibrated from wood, the obstruction of deformation between fibers does not develop evidently and the compressive deformation of fiber is smoothly enlarged with the great reduction of the voids in the internal structure of pulp mat (Photo. 12).

3.5. Summary.

3.5.1. The deformation behavior of the constituent fibers in the pulp mat during hot-pressing can be approximately divided into the following three phases;

With increasing pressure, the large gaps between fibers diminish under the lower pressure than 30 kp/cm^2, the compressive cross-sectional deformation of fiber is mainly enlarged within the range from 30 to 60 kp/cm^2, and the compressive deformation reachs the limit as the minute gaps between fibers and the lumina of fiber are noticeably reduced with the consequence that the pulp mat is greatly packed, under the higher pressure than 60 kp/cm^2. This fact explains that the filtration of pulp mat for the vapor generated in the pulp mat decreases, resulting in the occurance of the intense non-equilibrium evaporation of vapor generated in the interior of pulp mat under the higher pressure than 60 kp/cm^2 as shown in 2.4.2..

The gap-filling effect of fibers in the pulp mat is similar to the internal deformation behavior of wood in compression perpendicular to grain. That is to say, in the steam-treated wood, the group of cells in the bilateral sides falls down toward the vessel pore, being free from the compressive cross-sectional deformation. This behavior makes appreciable progress in the case of cold-pressing.

3.5.2. The mutual restriction between cells during the application of pressure which greatly develops in the case of wood structure scarcely appears in the case of the pulp mat which is constituted of many defibrated fibers. Because the comperatively large fiber-bundle contains somewhate tissue of wood, it can be less deformed than the single fiber contiguous to the fiber-bundles and occurs the irregurality of compressive cross-sectional deformation of fiber in the pulp mat, however, the irregularity intends to be reduced as increasing single fibers.

3. 5. 3. With increasing moisture content in the pulp mat before hot-pressing, the compressive cross-sectional deformation of fiber is enlarged but the gaps between fibers and the lumina of fibers diminish due to the increase of plasticity of fiber under the less moisture than the fiber saturation point.

3. 5. 4. The frequency of fiber having the cracked wall from the side of lumen in the radial direction increases under the lower pressure than 60 kp/cm^2, with increasing pressure.

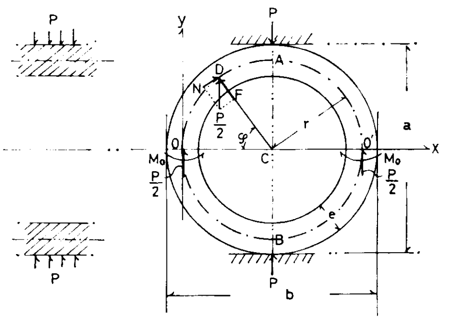


Fig. 22. Determination of deformation of a tubular cylinder applied compression load.

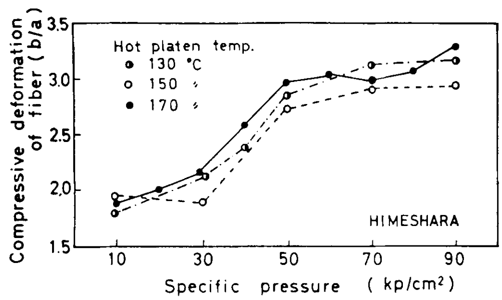


Fig. 23. Enlargements in compressive cross-sectional deformation of fiber in pulp mat with applying pressure of hot-pressing at different temperatures of hot platen, for HIMESHARA Asplund pulp.

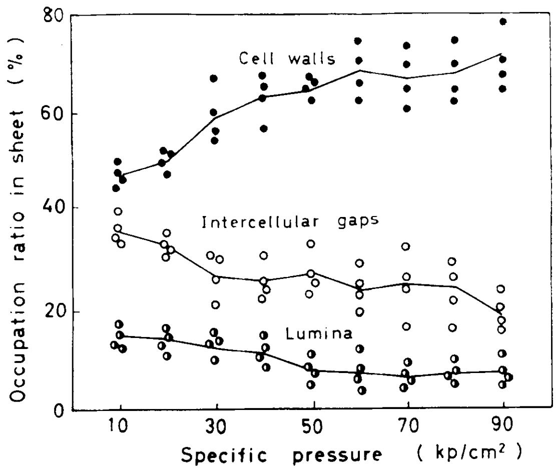


Fig. 24. Change in occupation ratio of each composition of internal structure with pressure of hot-pressing at 170 °C, for HIMESHARA Asplund pulp.

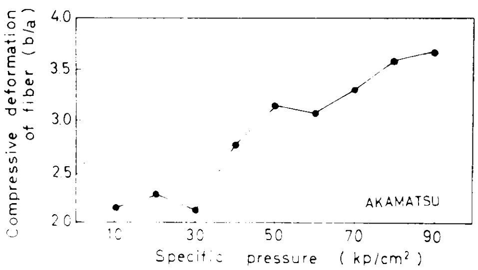


Fig. 25. Enlargement in compressive cross-sectional deformation of fiber in pulp mat with applying pressure of hot-pressing at 170 °C, for AKAMATSU Asplund pulp.

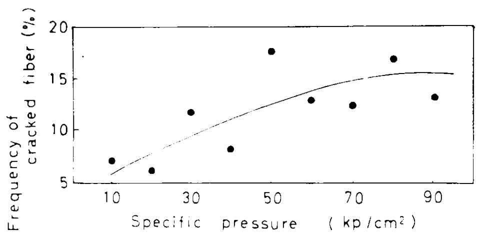


Fig. 26. Frequency of fiber having cracked wall with pressure of hot-pressing at 170 °C, for HIMESHARA Asplund pulp.

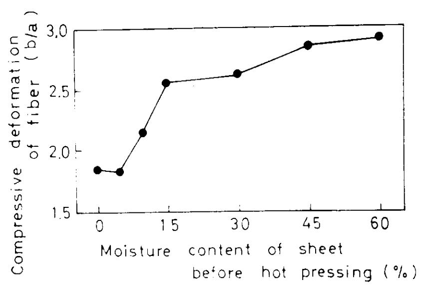


Fig. 27. Enlargement in compressive cross-sectional deformation of fiber in pulp mat with increasing moisture content of pulp mat before hot-pressing, for HIMESHARA Asplund pulp.

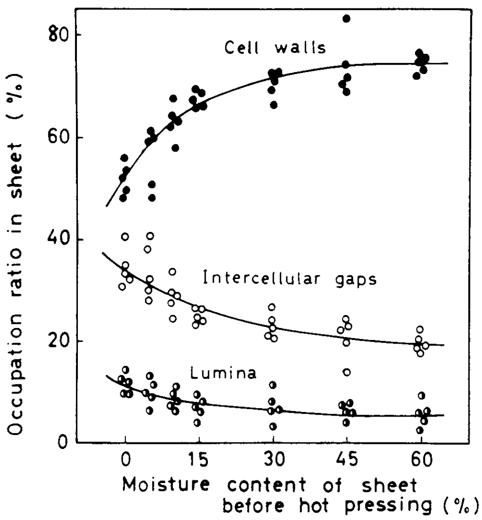


Fig. 28. Change in occupation ratio of each composition of internal structure with moisture content of pulp mat before hot-pressing, for HIMESHARA Asplund pulp.

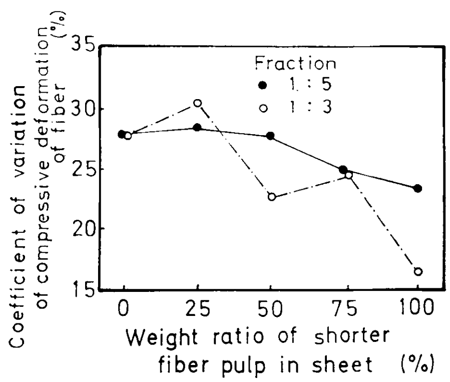


Fig. 29. Relationships between coefficient of variation in compressive cross-sectional deformation of fiber in pulp mat and weight ratio of fine or short fibers' pulp in pulp mat hot-pressed under a fixed condition of 170 °C·50 kp/cm², for HIMESHARA Asplund pulp.

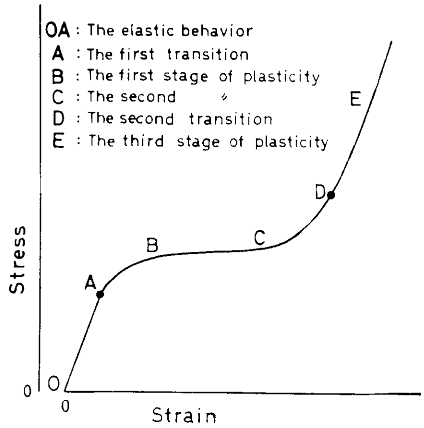


Fig. 30. Stress diagram of wood under bearing stress in tangential direction of grain.

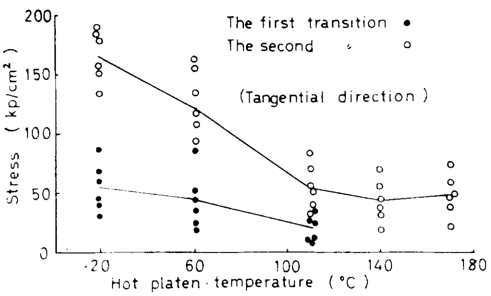


Fig. 31. Changes in first and second transition represented in stress with temperature of hot platen, for steam-treated HIMESHARA wood.

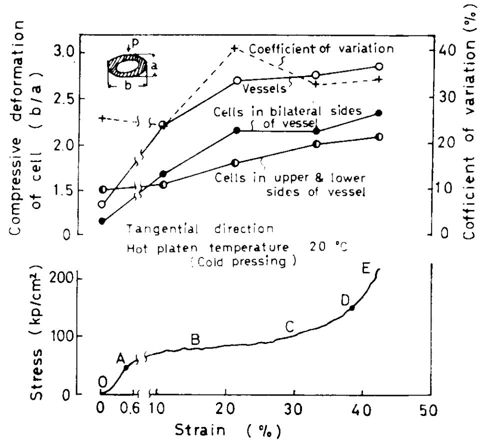


Fig. 32. Enlargement in compressive cross-sectional deformation of cell or vessel and change in coefficient of variation in its deformation with increasing whole strain of steam-treated HIMESHARA wood, cold-pressed at 20 °C under bearing stress in tangential direction.

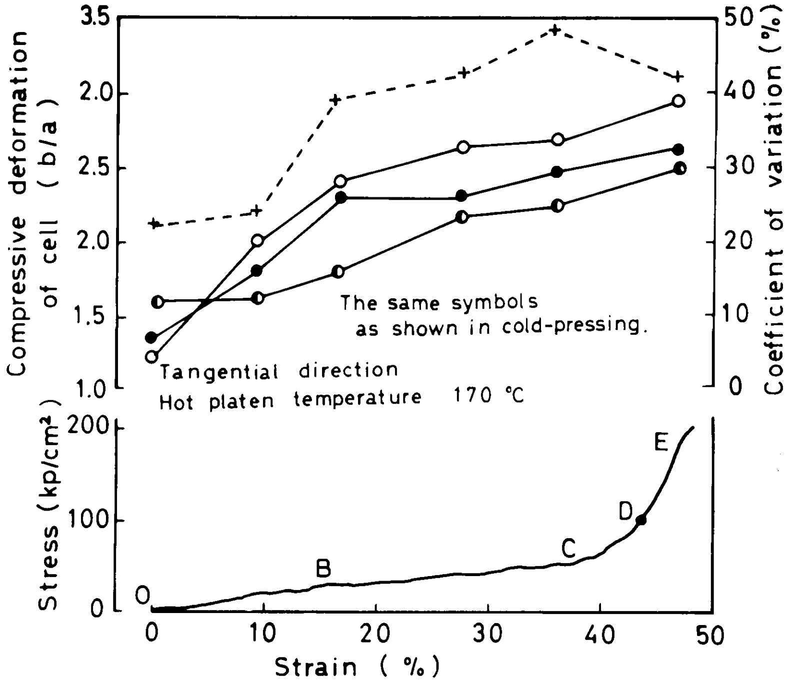


Fig. 33. Enlargement in compressive cross-sectional deformation of fiber or vessel and change in coefficient of variation in its deformation with increasing whole strain of steam-treated HIMESHARA wood, hot-pressed at 170 °C under bearing stress in tangential direction of grain.

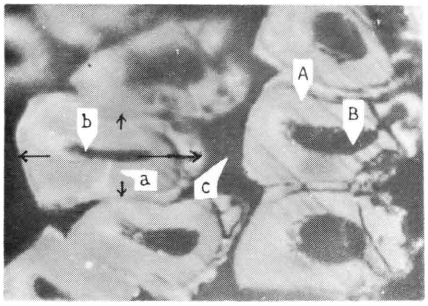


Photo. 2. Definition on each structural element or cross-sectional deformation of fiber in pulp mat.
A : Cell wall.
B : Lumen.
C : Intercellular gap.
a : External diameter of fiber in the same direction as pressure.
b : External diameter of fiber in the perpendicular direction to pressure.

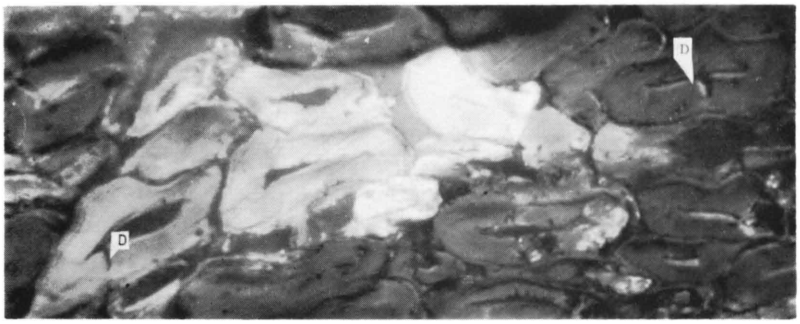


Photo. 3. Appearance of fiber having cracked wall in fiberboard produced under hot-pressing condition of 170 °C・60 kp/cm²・20 min.

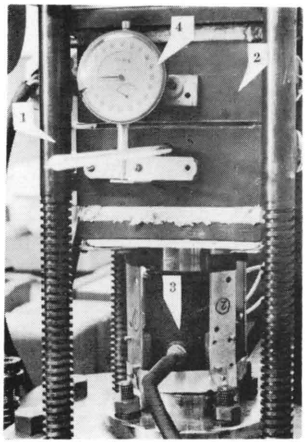
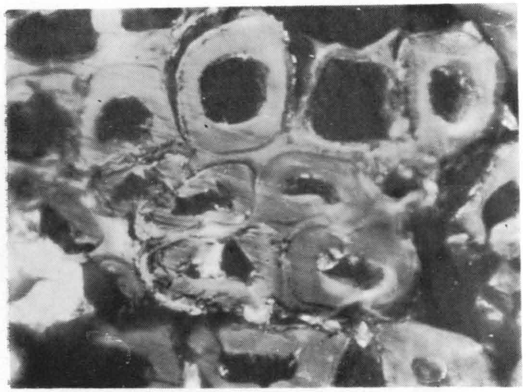


Photo. 4. Apparatus for pressing.
1 : Olsen type universal testing machine (10 ton).
2 : Hot platens (20×20 cm, 200 V・1.6 kw).
3 : Load cell (Water cooling type, 10 ton).
4 ; Dial gauge (1/1000 mm).



-1

-3

-2

-4

Photo. 5. Densification of internal structure of fiberboard hot-pressed at 170 °C for 20 min., with increasing pressure of hot-pressing.
-1. 20 kp/cm^2 -2. 40 kp/cm^2 -3. 60 kp/cm^2 -4. 80 kp/cm^2

Photo. 6. Internal structure of fiberboard prepared from Asplund pulp of AKAMATSU wood, in the case of hot-pressing under 170 °C・80 kp/cm²・20 min.

-1. Moisture content of 15 %

-2. 30 %

-3. 45 %

Photo. 7. Change in internal structure of fiberboard with moisture content of pulp mat before hot-pressing under 170 °C·50 kp/cm^2·20 min.

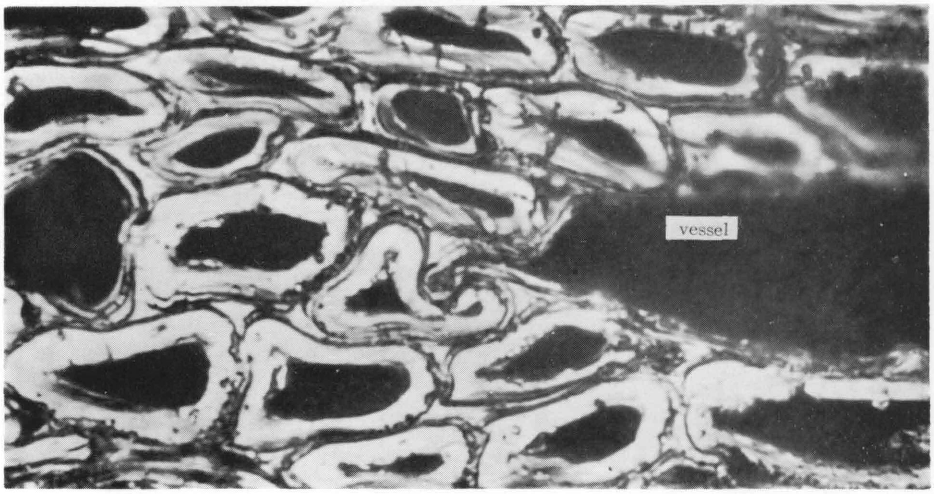


Photo. 8. Cross-section around a constituent vessel in large fiber-bundle, in fiberboard hot-pressed under 170 °C・40 kp/cm²・20 min.

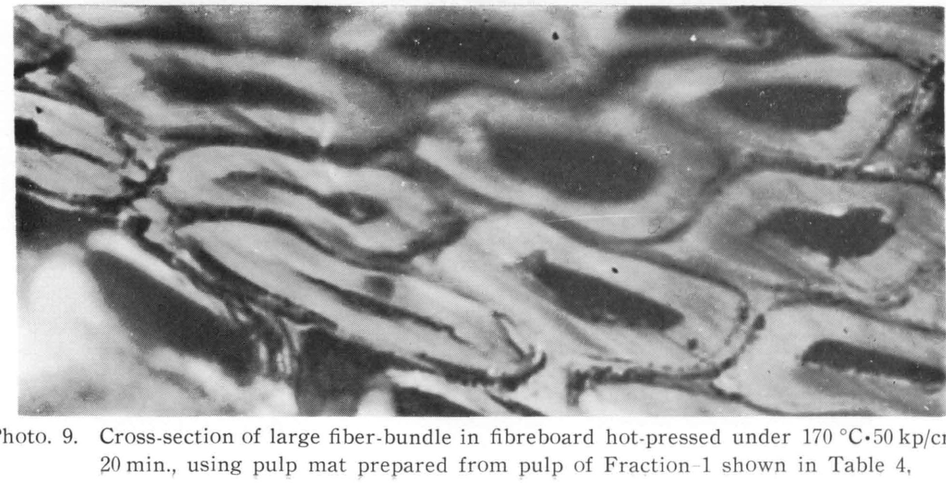
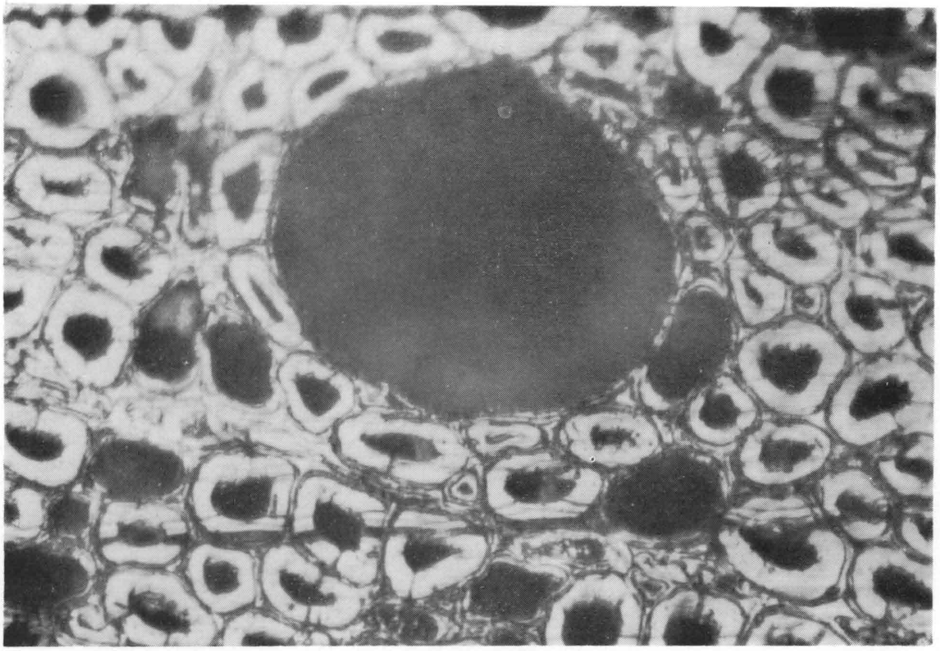
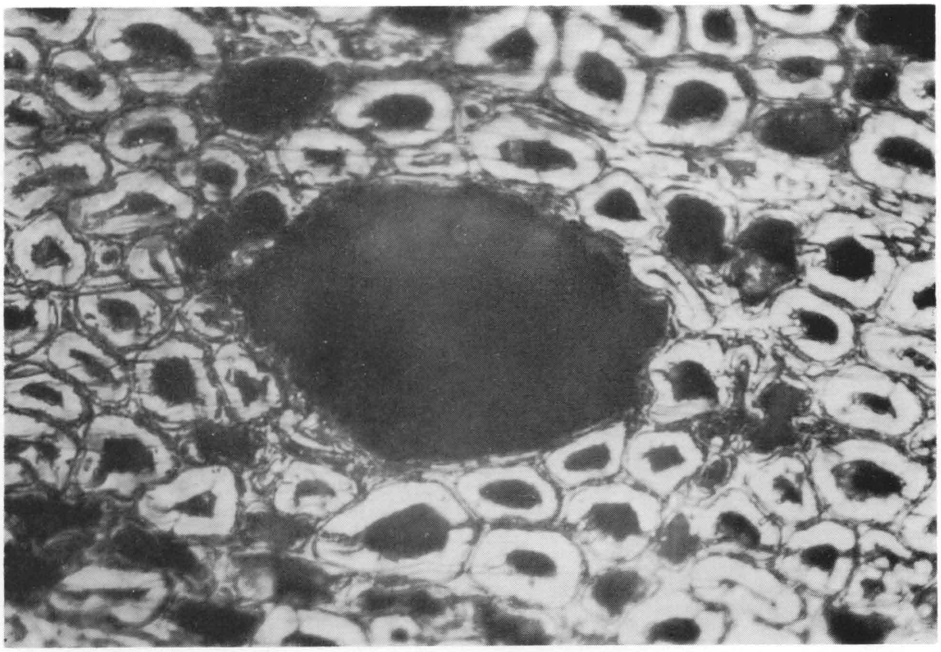


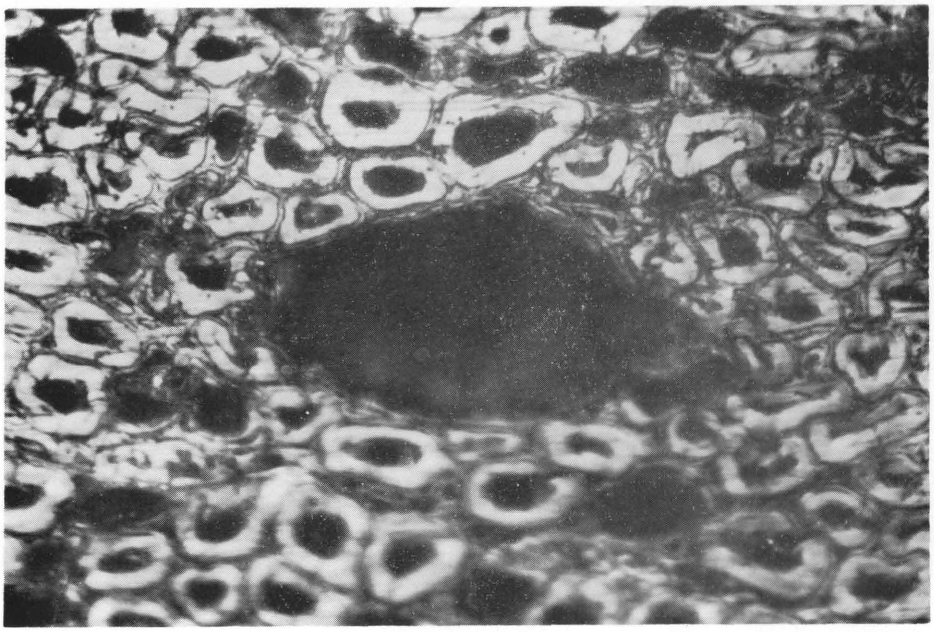
Photo. 9. Cross-section of large fiber-bundle in fibreboard hot-pressed under 170 °C・50 kp/cm²・20 min., using pulp mat prepared from pulp of Fraction-1 shown in Table 4,



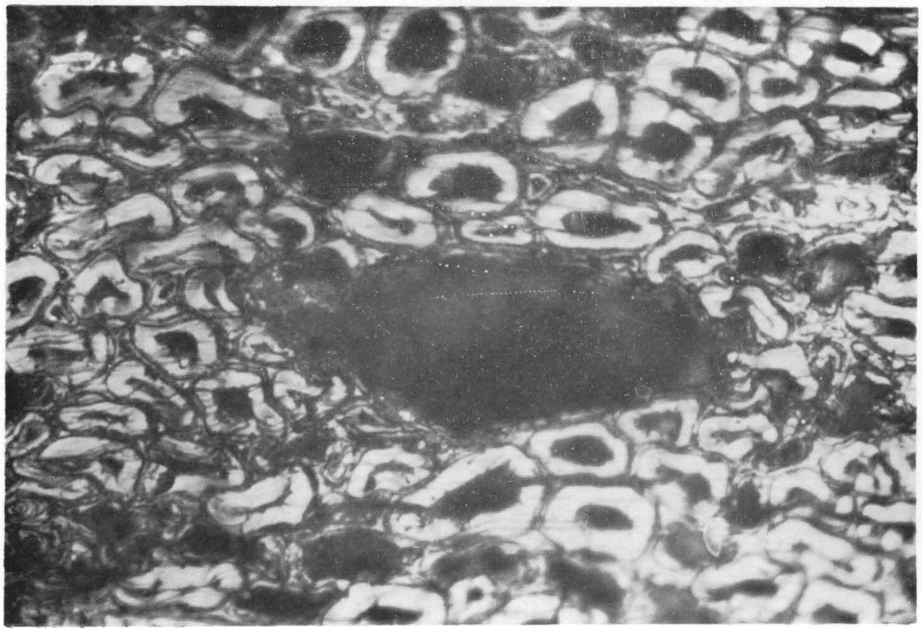
-1. Before hot-pressing.



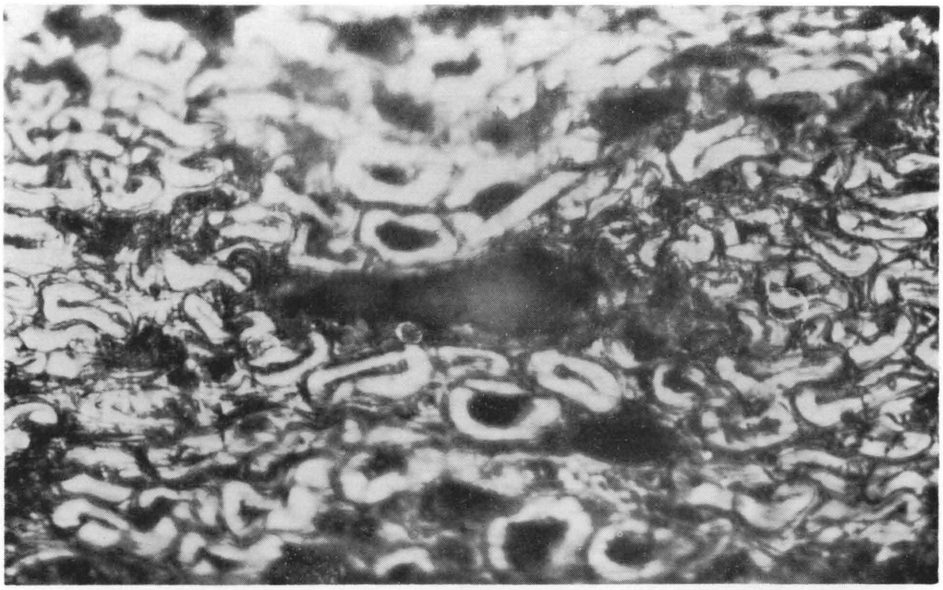
-2. In early period of first stage of plasticity.



-3. In latter period of first stage of plasticity.



-4. In second stage of plasticity.



-5. In third stage of plasticity.

Photo. 10. Behavior of internal structure of steam-treated wood during hot-pressing at 170 °C in tangential direction of grain, particular, in the case of a vessel and groups of cells around a vessel.

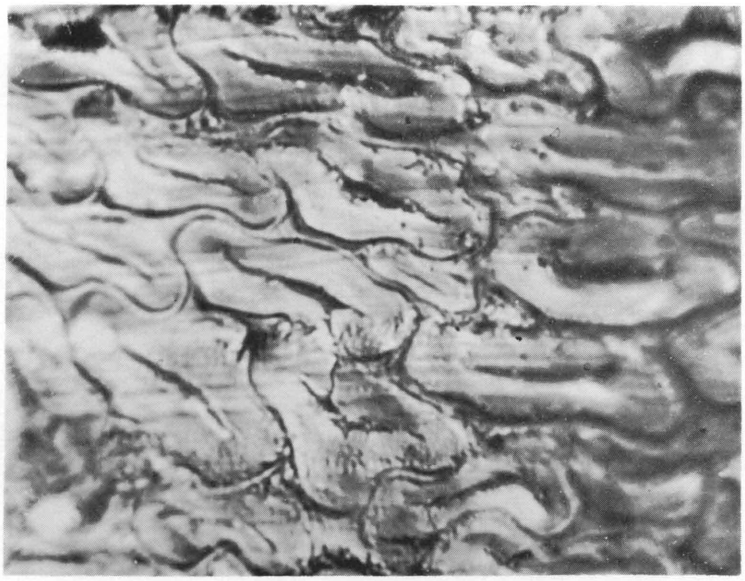


Photo. 11. Internal structure of steam-treated wood hot-pressed under 170 °C・130 kp/cm^2・20 min., relative to complicated shapes of constituent cell and various remaining voids due to coefficient restraint between cells (Magnification: ×600).

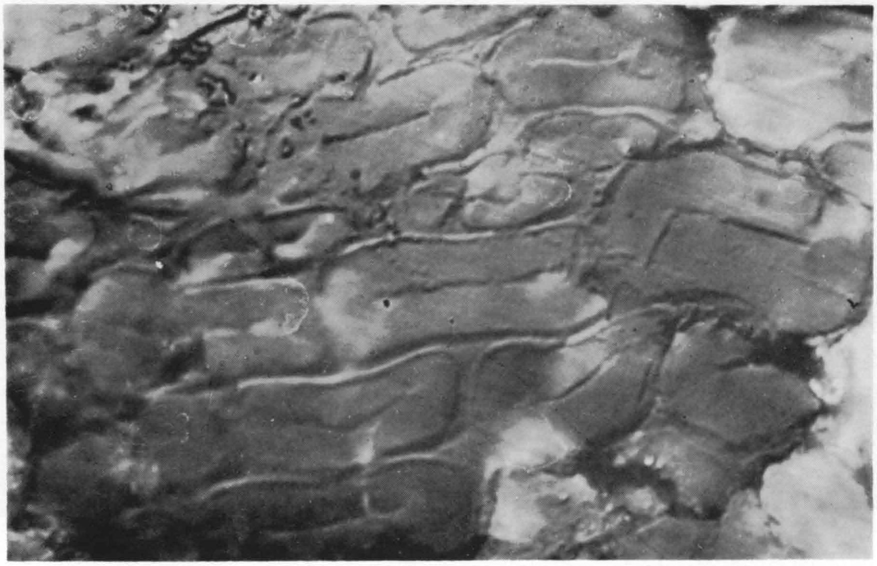


Photo. 12. Densification of internal structure of fiberboard hot-pressed under 170 °C·80 kp/cm^2· 20 min., referring to constituent fibers of pulp mat deformed more smoothly in comparison with constituent cells of steam-treated wood as shown in Photo. 11 (Magnification : ×600).