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

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4. Analysis of board formation on the basis of behavior of pressure relaxation during hot-pressing.

4.1. Introduction.

The mechanical properties of pulp mat have been brought to light by many investigations on the drainage of mat or the formation of mat and the prepressing.

The consideration by Jone, R. L.[34] is minutely engaged in the relationship between the internal structure of fiber bed and the compressibility, and Wilder, H. D.[66] experimentally proved that the creep recovery of wet pulp mat was linear, and Onogi, S. & Sasaguri, K.[76] analyzed the relaxation spectrum of the cellulosic material on the basis of statistical mechanics.

As previously state, the rheological characteristics of pulp mat have been investigating by many investigators, but they considered the pulp mat to be dealed as a kind of visco-elastic material. However, the relaxation behavior of pulp mat prepared for the fiberboard during hot-pressing has not been explained experimentally or theoretically. Kitahara, K.[42] obtained that the temperature transition and the evaporation of water in the particle mat have a great influence on the pressure relaxation during hot-pressing of particleboard.

Goring, D. A. I.[26] discovered that the softening point of cellulose in the wood fiber is dependent on the rate of rising temperature, the loading with the rod and the moisture content of fiber.

From the detail investigation on the effect of the mechanism of the heat and mass transfer and the behavior of internal structure on the relaxation of pressure during hot-pressing, the process of board formation has to be made clear. In particular, the rate of application of pressure produces a powerful effect on the compressive deformation of pulp mat, regarding as a kind of visco-elastic body, on the other hand, such a rate of application of pressure is generally restricted by the magnitude of initial pressure, specially, by the rate of drainage in the pulp mat in the case of wet-process and by the appearance of the low density-layer near the surface of fiberboard[18] in the case of dry-process.

Skark, L.[90] worked on the relationship between the rate of application of pressure and the drainage in the case of wet process, and Asklöf, C. et al.[3] studied on the compressibility of wet paper web and they proved that the web porocity increased with increasing the rate of application of pressure by means of recording the relaxation of pressure to thickness of web, using a oscillograph. In the hot-pressing of pulp mat prepared for the fiberboard, too, it can be assumed that the rate of application of initial pressure is powerful enough to influence the compressive deformation and furthermore the plasticity and the drying-set during hot-pressing, so the rate of application of pressure was specially picked up as one of the most important factors of hot-pressing in this experiment.

4.2. Experimental procedure.

The pulp mat of 80 ± 3 gr. in dry weight prepared under the same condition as used in 2. 2. 2. was formed in a rectangular shape of 12 × 12 cm. After the thermo-couples (Chromel-alumel, diameter of 0.3 mm, teflon-seal) were imbedded in the center of mat in the middle layer, and then these mats were cold-pressed under the fixed condition of 40 kp/cm^2, 30 sec.. Specially, the pulp prepared under the condition as shown in Table 5 was used for the experiment on the effect of various defibrating times, and the pulp mat was formed by varying the dry-weight of pulp between 35 and 125 gr. in the case of the experiment on the effect of various mat thickness.

After these mats were oven-dried under 105 ± 2 °C, the various moisture contents were conditioned and their mats were hot-pressed under the condition as shown in Table 5. The hot platens (Both the upper and the lower platens of 20 × 20 cm, 200 v and 1.6 kw) and the load cell of water cooling type (10 ton) were installed on the Olsen type universal testing machine (10 ton) (Photo. 13). The pressure becoming lax was the maximum of 0.5 % per 1 hr. without the pulp mat, the change of pressure due to the expansion and the shrinkage caused by the variation of the temperature of hot platens was less than 0.4 % within the range from 15 to 240 °C, and furthermore the pressure was observed by the error of 5 % in comparison with the aid of the testing machine, so the value could be permitted beyond doubt and the arrival time at the initial pressure could not be made constant in all the conditions, varying between 16 and 23 sec. because of the hand-operation.

A iron-netting of 16 mesh was put on the lower surface of pulp mat and the two stainless cauls of 1.5 mm were put on both surfaces of pulp mat.

While the transition of pressure was successively recorded through the load cell with the aid of a X-Y recorder (Chart speed of 50 mm/min.), the transition of temperature in the middle layer of pulp mat was recorded through the thermo-couples with the aid of a temperature recorder (30 sec./cycle).

The hot-pressing time was more than 20 min. at least, when the relaxation of pressure and the transition of temperature pass over the unsteady state.

The transition of application of pressure to the fixed initial pressure (P_0) was recorded, and as shown in Fig. 34 and Table 6, the mean rate of application of pressure (P_0/τ_0) was varied under each hot-pressing condition, and as mentioned in 5. 2., the distribution of layer-density in the direction of thickness at the end of Stage—I in the heat and mass transfer was observed with the aid of a soft-X ray.

4. 3. Characteristics of pressure relaxation.

The formation of fiberboard from the pulp mat is thought to consist of the following three manipulations;

(1) Endowment with plasticity: The fibers are swollen and hydrated with water and the fibers are endowed with the thermo-plasticity caused by heat.

(2) Molding: The internal structure of pulp mat and the shape of board

are molded by pressure.

(3) Setting of cohesion: The fibers in the pulp mat are dried by heat and the drying-set is attained.

Practically, these manipulations are performed simultaniously or successively. In general, in the case of the visco-elasticity of high polymer solid, the secondary bonding network, i.e. the deformation units due to van der Waals' force mainly takes part in the visco-elasticity,[23, 68] therefore, the mechanical behavior can be expressed in a sort of non-linear visco-elastic model which is made to introduce the viscosity of Eyring (Net flow) into the Maxwell element[75].

$$\frac{de}{d\tau} = \underbrace{\frac{1}{r}\frac{dP}{d\tau}}_{\text{elastic element}} + \underbrace{A \sinh\frac{1}{\alpha}P}_{\text{Eyring's net flow}^{8)}} \tag{12}$$

where τ is time, P is the external force (Load), e is the deformation, γ is the elastic constant, A is constant and α is the coefficient of relaxation rate. Furthermore, from the theory of rate process by Andrade on the basis of Arrhenius theorem,

$$\alpha \propto \exp\left(-\frac{\Delta H}{kT}\right) \qquad (13)^{45)}$$

where ΔH is the energy of activation, T is the absolute temperature and k is the Bolzmann's constant. From these relationships, the formula (12) can be integrated as follows, when $de/d\tau = 0$;

$$P = a - \alpha \ln \tau \qquad \text{a is const.}$$

therefore,

$$-\frac{dP}{d\tau} = \alpha \frac{1}{\tau} \tag{14}$$

This equation is correspond to the empilical formula well-known in the analysis of relaxation, and it can be made clear from the equation (14) that the rate of relaxation ($-dP/d\tau$) is proportional to the reciprocal of time ($1/\tau$), and this constant (α) is the coefficient of relaxation rate, regarding as an important indicator in the case of the analysis of the process of pressure relaxation. Hereupon, the relationship between pressure (P) and logarithm ($\ln \tau$) of hot-pressing time was experimentally obtained under the various hot-pressing conditions, referring to the heat and mass transfer and the behavior of internal structure of pulp mat during hot-pressing.

$P - \ln \tau$ could be classified into some diagrams as shown in Fig. 35 and then $\log \alpha - \log \tau$ was expressed in a spectrum.

4. 3. 1. Cold-pressing (OAD_3 in Fig. 36): The pressure relaxation was measured under the several moisture contents of pulp mat during cold-pressing in which the heat and mass transfer does not occur, and $P - \ln \tau$ is represented in the two straight lines of OA and AD_3, and the gradient of OA line (α_1) is always

larger than that of AD_3 line (α_3). In the case of hot-pressing, OA line appears for the extremely short time but the period of OA is prolonged with increasing thickness of pulp mat (Fig. 37). Considering the above-mentioned behavior of the internal structure of pulp mat during hot-pressing, the stage OA can be predicated of a relaxation characterized by the macro-structure or the fiber-unit, which is regarded as a macro-slippage between fibers and the equalization of the deformation of pulp mat in the direction of thickness.

4.3.2. Heating · oven-dried pulp mat (OAB_1D_2): $P-\ln\tau$ can be represented in the three straight lines, having 3 gradients of α_1, α_2 and α_3, in turn. The point B_1 agrees with the time when the inner temperature arrives at the steady state, and the largest gradient of AB_1 line (α_2) rapidly increases with the rise of hot platen temperature or with the increase of pressure (Fig. 38 and 39). When the change of temperature in the interior of pulp mat during hot-pressing hardly occurs because the pulp mat preheated in the state of 100 °C is hot-pressed under the hot platen temperature of 100 °C, $P-\ln\tau$ is represented in the two straight lines of OA and AD_3, excepting AB_1 line.

Thus, it is ascertained that AB_1 line appearing newly is the process where the thermo-plasticity rapidly increases due to the unsteady transition of temperature. Moreover, the defibrating time of Asplund pulp (0.5~4.5 min.) has little influence on the relationship between P and τ.

4.3.3. Heating · moisture content: Being different from the case of 4.3.2., $P-\ln\tau$ can be divided into the two types from the shapes of relaxation curve between the second line (AB_1 or AB) and the third line (C_2D_2, C_1D or CD) as follows;

(1) Lower hot platen temperature than 100 °C ($OAB_2C_2D_2$) or Higher than 100 °C · less moisture content of mat than 10 % ($OABC_1D_1$): The part of curve between the second line and the third line is convex under both hot-pressing conditions. The arrival point at the steady state of temperature transition is in the way in the case of the former, but agrees with the boundary veering from the convex curve toward the third line in the case of the latter.

The convex curve (B_2C_2) of the former means the process where the fibers in the pulp mat slightly display plasticity because of the retardation of temperature transition due to plenty of moisture contained in the interior of pulp mat. In the case of the latter, under the less moisture content than 10 %, BC_1 shows the retardation of thermo-plasticity due to the delay of temperature transition caused by the dull non-equilibrium evaporation, and the point C_1 at the end of convex curve agrees with the arrival point at the steady state of the inner temperature transition. As approaching the moisture content to about 10 %, BC_1 curve changes in the concave curve appearing under the much moisture-contained mat, i.e. in the case of the following condition (2).

(2) Higher hot platen temperature than 100 °C · more moisture content of

pulp mat than 10 % (OABCD): With the lapse of hot-prressing time, the relaxation of pressure becomes a curve as represented in Fig. 32, and the spectrum of the coefficient of relaxation rate becomes a shape as shown in Fig. 40.

In the concave curve (BC), at first, the value of α becomes small because the relaxation is reduced from generating the high pressure of vapor due to the intense non-equilibrium evaporation during Stage—II, subsequently, in Stage—III, while the retardation of the rise of temperature prevents progress in thermo-plasticity, resulting from the remarkable compression shrinkage of the constituent fibers which follows to the emission of vapor from the pulp mat, α is enlarged more than that during Stage—II.

In the latter unsteady state of heat transfer (Stage—IV), α further becomes large due to the development of thermo-plasticity because the inner temperature which temporarily stops to rise during Stage—III begins to approach the hot platen temperature. It can explained from the above-mentioned mechanism that BC is a concave curve.

After the apparent progress of thermo-plasticity and compression shrinkage, at last, the boundary point (C) intends to appear earlier than the arrival time of the inner temperature at the steady state with the rise of hot platen temperature (Fig. 41). Consequently, CD is not assumed to agree with the steady state entirely, but is the steady state of relaxation after the appreciable progress of thermo-plasticity and drying-set, i.e. the process in which the irreversible drying-set of fibers is completely achieved.

4.4. Dependence of relaxation on hot platen temperature.

When the thermo-plasticity increases with the rise of hot platen temperature, each coefficient of relaxation rate α_1, α_2 and α_3 is enlarged in the case of oven-dried mat. Specially, α_2 increases, relative to the process of noticeable thermo-plasticity (Fig. 38). On the basis of the theory of rate process by Andrade due to the Arrhenius' theorem, the relationship as shown in the formula (13) is generally realized in the thermo-plastic polymer.

In this experiment, the relation of log α to 1/T is represented in a straight line in the case of oven-dried mat and the gradient of α_2 − line is the largest of those of all the α − lines, so it is presumed that the energy of activation (ΔH) in the process of considerable thermo-plasticity is largest. While α_1 intends to increase under the lower than 130 °C in the case of the moisture-contained mat with the rise of hot platen temperature, parallel to the case of oven-dried mat, it again decreases in the case of moisture-contained mat. This tendency becomes remarkable with increasing moisture in the pulp mat (Fig. 41). As shown in Photo. 14, the rapid drying-set of surface layer, which makes no progress in the macro-slippage between fibers and the equalization of deformation in the direction of thickness of pulp mat, becomes appreciable with the increase of moisture content of pulp mat before hot-pressing or with the rise of hot platen temperature, specially under the higher than 130 °C.

α_2 tends to increase under the lower than 100 °C in the case of moisture-contained mat, parallel to the case of oven-dried mat, with the rise of hot platen temperature, and the tendency becomes dull under the higher than 100 °C in the case of the less moisture-contained mat than the fiber saturation point, and in the case of the mat containing moisture of fiber saturation point or the mat containing free water.

In the case of the free water-contained mat, α_2 decreases under the higher than 170 or 150 °C again, because the retardation of temperature transition due to the relatively rapid latent heat absorption of moisture in the surface layers makes no progress in thermo-plasticity.

The curve BC undergoes a change to the direction of arrow as shown in Fig. 35 with the rise of hot platen temperature, as considering from the tendency of reduction of period of BC and the relaxation of pressure, therefore, the coefficient of relaxation rate can be drawn in a spectrum as shown in a dotted line in Fig. 40 with the rise of hot platen temperature.

The cofficient of relaxation rate (α_3) during the steady state of relaxation in the oven-dried mat is evidently enlarged with the rise of hot platen temperature, however, it keeps constant under the lower than 170 °C and rapidly decreases under the higher than 170 °C in the moisture-contained mat, being different from the case of oven-dried mat. This tendency becomes very noticeable with increasing moisture content in the pulp mat (Fig. 46) because the drying-set and the shrinkage due to the rise of hot platen temperature are carried out as drawing near the steady state of relaxation. This behavior is clearly disclosed in the case of much moisture-contained mat.

4. 5. Dependence of relaxation on moisture contained in pulp mat before hot-pressing.

The endowment of moisture with plasticity of fiber makes α_1 to be rapidly reduced under the less moisture than the fiber saturation point, on the other hand, α_2 greatly increases under the less moisture than 10 % because of the moisture-plasticity effect, and α_2 again is reduced under the more than 10 % because the thermo-plasticity is greatly made no progress, resulting from the retardation of temperature transition due to the latent heat absorption of moisture in the pulp mat [14], however, the more moisture than 70~80 % has little influence on the process of hot-pressing because it is dehydrated under the application of higher pressure than 70 kp/cm^2 (Fig. 47).

The periods of BC_1 and BC are rapidly prolonged within the range of bound water but slowly within the range of free water with increasing moisture in pulp mat, and keeps constant under the more moisture than 70~80 % (Fig. 48). The relaxation shows the same tendency as the period of BC_1 or BC (Fig. 49), so these facts suggest that the development of thermo-plasticity begins to disappear considerably because of the retardation of temperature transition due to the prolongation of latent heat absorption with increasing moisture in the pulp mat, secondly, the relaxation is accelerated by the compression shrinkage of fibers with the consequence that it increases for a long time again with increasing moisture, whereas the relaxation is reduced, resulting from the remarkable resistance of high vapor pressure to the relaxation due to the intense non-equilibrium evaporation with increasing moisture in the pulp mat. α_3 is enlarged under the less moisture content than the fiber saturation point with increasing moisture content and keeps constant under the more than the fiber saturation point (Fig. 47) because the plastic flow, the compression shrinkage and the drying-set previously are promoted before the change of α_2 into α_3 with increasing moisture in the pulp mat.

The endowment of heat with thermo-plasticity is reduced by the retardation of temperature transition due to the existence of moisture, nevertheless the compression shrinkage of constituent fibers is made appreciable progress[73].

The free water controlled quantity by the initial pressure prolongs the period of the existence of water in the pulp mat during hot-pressing, so it has an influence on the endowment with plasticity and drying-set.

4.6. Dependence of relaxation on thickness of pulp mat.

The period of OA, which is regarded as the process of the macro-slippage between fibers and the equalization of deformation of pulp mat in the direction of thickness during the early stage of hot-pressing, is prolonged with increasing thickness of mat (Fig. 37). The period of AB in which the thermo-plasticity appears remarkably, and the period of BC which is affected by the mechanism of vapor pressure generated in the interior of pulp mat and the compression shrinkage of fibers shows the same tendency as the period of OA.

All the coefficients (α_1, α_2 and α_3) of relaxation rate are enlarged with increasing thickness, specially remarkably under the thinner thickness than 6~7 mm (Fig. 50). Every relaxation in the course of OA, AB and BC grow larger with increasing thickness of pulp mat (Fig. 51). Resulting from the friction due to the edge effect between the hot platens and the surfaces of pulp mat and from the rapid drying-set of surface layers in the extremely early period of hot-pressing as explained in 4.3. (Phoio. 14), the macro-slippage between fibers and the equalization of deformation near the surfaces are made no progress. Such a part becomes so thin with increasing thickness that the macro-slippage between fibers and the equalization of deformation in the direction of thickness of pulp mat uniformly occur in the most part of thickness of pulp mat because of the great progression of the plastic flow and the compression shrinkage.

4.7. Dependence of relaxation on initial pressure.

With increasing pressure, α_1 linearly increases in the case of oven-dried mat as well as under the lower pressure than 50 kp/cm^2 in the case of moisture-contained mat, but it approximately keeps constant under the higher than 50 kp/cm^2 in the case of moisture-contained mat. The enlargement of α_2 with pressure becomes remarkable under the lower than 50 kp/cm^2 and dull under the higher than 50 kp/cm^2 in both the cases of oven-dried mat and moisture-contained mat. α_3 is nearly the same value as α_1 in the case of oven-dried mat and the change of α_3 with pressure is similar to that of α_1, on the other hand, α_3 is generally very small value in the case of moisture-contained mat and is slightly enlarged with increasing pressure (Fig. 39 and 52).

Understanding from the relation of the initial pressure to the relaxation during hot-pressing (Fig. 53 and 54) and from the deformation behavior of internal structure (Photo. 5 and Fig. 23 and 24), under the lower pressure than 30 kp/cm^2, the increase of the internal friction of pulp mat in the course of the reduction of the gaps between fibers makes no progress in the macro-slippage between fibers during the stage of OA and the relaxation increases with increasing pressure because the cross-section of fiber is scarcely deformed in compression but mainly the gap-filling effect develops greatly. The relatively unrestrainable and sufficient compression shrinkage of the constituent fibers results in the increase of relaxation during the stage of BC with increasing pressure, and the pulp mat structurally contains so much plastic flow elements that the relaxation begins to grow gradually. Within the range from 30 to 60 kp/cm^2, the distinguished enlargement of compressive deformation of fiber results in the disappearance of plastic elements in the pulp mat with the consequence that the thermo-plasticity slightly develops and the relaxation during the stage of AB decreases in a marked degree. Eventually within this region, the relaxation mostly intends to be reduced with increasing initial pressure. Under the higher than 60 kp/cm^2, as confirmed from the tendencies of α_1 and α_2 with pressure, the relaxation elements disappear to the utmost becaure of the extreme compressive deformation of fiber and the diminution of variours gaps or voids in the pulp mat. The densification of pulp mat as shown in 2. 3. originates the high vapor pressure in the interior of pulp mat results in the resistance of vapor pressure to the relaxation, so that the relaxation approachs a limiting value, specially under the higher than 60 kp/cm^2.

4. 8. **Dependence of relaxation on rate of application of pressure.**

Regarding the pulp mat as a sort of visco-elastic body [34,76,104], it is presumed that the rate of application of pressure causes to fluctuate the deformation flow of constituent fibers in the pulp mat, i.e. the compressive deformation of pulp mat and has a characteristic influence on the plastic flow and the drying-set during hot-pressing. The relaxation mechanism explained in 4. 3. must be accepted in this experiment, therefore, the effect of mean rate of application of pressure was considered by dealing with the coefficients of relaxation rate, the relaxation and the period of each process.

4.8.1. Stage of OA.

Notwithstanding the various moisture contents of pulp mat before hot-pressing, α_1 is gradually enlarged as approaching a value with increasing rate of application of pressure. The point at which the change of α_1 becomes dull swichs over to the region of high rate with increasing moisture content of pulp mat and the value of α_1 becomes large (Fig. 55). With increasing rate of application of pressure, this period is slightly prolonged in the case of oven-dried mat, however, it is greatly shortened at the lower than a certain rate and is again prolonged in the case of moisture-contained mat.

Thus, *the maximum point falls off and veers to the range of higher rate* with increasing moisture content of pulp mat before hot-pressing (Fig. 56), and the relaxation increases with increasing rate, regardless to the moisture content of pulp mat before hot-pressing (Fig. 57). Within the range of lower rate of application of pressure, the rate of relaxation evidently damps and the period of OA intends to be prolonged with decreasing rate of application of pressure, moreover, the tendency becomes considerable with increasing moisture content of pulp mat before hoi-pressing. These established facts explicate that the flow and the deformation of fibers follow very well to the pressure, resulting from the increase of moisture-plasticity of fiber and the lubrication-effect of free water on the macro-slippage between fibers, and that the constituent fibers are arranged in the relatively stable state during applying the initial pressure with the consequence that the macro-slippage between fibers gets into difficulties, however, the retardation of initial temperature transition prolongs the period of OA.

Furthermore, within the range of higher rate of application of pressure, the rate of relaxation approachs a high value and this period is prolonged with increasing rate of application of pressure. This tendency markedly appears within the lower rate with decreasing moisture content of pulp mat before hot-pressing, so it is made clear from this result that the plastic flow and the deformation of fiber do not greatly occur during applying the initial pressure in the case of less moisture-contained mat but the gap-filling of fiber for the various gaps or voids between fibers develops in the early period of hot-pressing. The oven-dried mat is not greatly affected by the rate of application of pressure because of the slight relaxation which can be generated from the macro-slippage between fibers and the equalization of deformation in the direction of thickness. The macro-structural flow of fibers does not markedly appear during applying the initial pressure, resulting from the very well following of macro-structural flow of fibers to the pressure because the moisture makes the macro-slippage between fibers to develop easily by supplying some moisture (about 10 %) to the pulp mat before hot-pressing.

4.8.2. Stage of AB.

The rate of application of pressure has a potent influence on the coefficient of relaxation rate (α_2) in the stage where the thermo-plasticity greatly appears.

α_2 slightly grows larger in the case of oven-dried mat with increasing rate of application of pressure and is evidently enlarged in the case of moisture-contained mat, particularly the mat containing the moisture of 10 %, and this tendency becomes dull with increasing more moisture content (Fig. 58).

This phenomenon suggests that the thermo-plasticity does not appear in the case of more moisture-contained mat so remarkably as in the case of less moisture-contained mat because of the large compressive deformation of fiber and the retardation of temperature transition due to the evaporation of moisture in the interior of pulp mat in the case of the former. While this period keeps constant regardless to the rate of application of pressure in the case of oven-dried mat, it tends to be shorten with increasing rate within the range of lower rate in the case of less moisture-contained mat, and conversely it tends to be prolonged slightly in the case of more moisture-contained mat (Fig. 59).

It can be affirmed from the above-mentioned results that the available following of the flow and deformation to the pressure at the low rate of application of pressure is carried out in the case of more moisture-contained mat, however, the flow-elements remaining from the imperfect following are released gradually because of the appearance of thermo-plasticity.

The relaxation during this stage is noticeable in both the case of oven-dried mat and less moisture-contained mat in comperison with that during the other stages. With increasing rate of application of pressure, the relative magnitude of relaxation during the stage of AB is more enlarged in the case of less moisture-contained mat and approachs to that during the stage of BC in the case of more moisture-contained mat (Fig. 57).

The stage of AB is a little dependent on the rate of application of pressure in the case of oven-dried mat as observed in the case of stage of OA, however, the stage of AB in the case of less moisture-contained mat most greatly depends on the rate of application of pressure, so that the tendency disappears with increasing moisture content of pulp mat before hot-pressing.

4.8.3. Stage of BC_1 or BC.

The period of BC_1 or BC intends to be greatly shortened at the lower rate than 4.0 kp/cm^2/sec. and keeps constant at the higher than that with increasing rate of application of pressure, and the tendency is perspicuous in the case of less moisture-contained mat. Such a phenomenon shows that the inner temperature rapidly approachs to the hot platen temperature so that Stage—II can be hardly observed[64,65,77] and Stage—III must be very short in the case of less moisture-contained mat. Resulting from the marked disappearance of the relaxation elements due to the available following of plastic flow to the applied pressure within the range of lower rate of application of pressure, the relaxation in the case of less moisture-contained mat is appreciable to be reduced with the decrease of rate, because of slight compression shrinkage (Fig. 60).

Within the range of higher rate in the case of less moisture-contained mat and in the whole range of rate in the case of more moisture-contained mat, the relaxation during the stage of BC_1 or BC is a little reduced with increasing rate of application of pressure in contrast with the tendency of that during the stage of OA or AB (Fig. 57). It can be made clear from these results that the diminution of various gaps or voids between fibers makes noticeable progress in the apparent compression shrinkage, since the compressive deformation of pulp mat is greatly enlarged at the low rate of application of pressure, as ascertained from the result that the pressure just at the beginning of the stage of BC_1 or BC increases with decreasing rate. The densification of pulp mat grows larger with decreasing rate of application of pressure (Fig. 61).

Thus, this stage is slightly subject to the influence of the rate of application of pressure.

4.8.4. Stage of C_1D_1 or CD.

The coefficient of relaxation rate in this stage intensely decreases at the lower rate than 3.0~4.0 kp/cm^2/sec. and gradually at the higher rate than that with increasing rate of application of pressure (Fig. 62), in contrast with α_1 and α_2. It is assumed that the whole relaxation within the range of higher rate is very much because of the remarkable flow and the compression shrinkage remarkably appears in the case of more moisture-contained mat because of the available following of flow and deformation to the pressure due to the lubrication effect and the prolongation of plasticity of fiber by the free water.

4.9. Summary.

The following results were obtained in this experiment.

4.9.1. In the process of hot-pressing formation of pulp mat as an assembly of wood fibers which have some characteristics in morphology and are swollen and hydrated with water, the following actions are carried out;

(1) The unit deformation of the secondary net-work in the non-linear viscoelastic body, i.e. the general relaxation of high polymer.

(2) The behavior of relaxation due to the characteristics in morphology and the macro-structural elements of wood fibers.

(3) The heat absorption of water, the generation of vapor pressure and the compression shrinkage of fiber, relative to the mechanism of the heat and mass transfer.

Additionally, the chemical change of pulp mat must be thought to occur from the hydrolysis and heat-decomposition and so on.

These actions are very complicatedly caused in the case of practical hot-pressing of fiberboard.

Herein, the behavior of hot-pressing formation of wet pulp mat to the fiberboard can be briefly given an outline as follows;

(1) The stage of the macro-slippage between fibers and the equalization of deformation of mat in the direction of thickness of pulp mat.

(2) The stage where the available endowment with thermo-plasticity during the early unsteady heat transfer appear greatly.

(3) The stage where the compression shrinkage and the continuous development of thermo-plasticity due to the rise of inner temperature toward the hot platen temperature during the latter unsteady heat transfer becomes remarkable, though the rise of vapor pressure resists to the applied pressure and the latent heat absorption of moisture in the pulp mat retards the temperature transition temporarily.

(4) The stage of steady relaxation which is not subject to the influence of heat and mass transfer and the effect of macro-structural behavior of fiber in the pulp mat.

4.9.2. Summerizing the relaxation of cohesion, the molding and the setting of deformation of fiber, quantitatively, the board formation is effectively carried out under the condition of the slightly more moisture content than the fiber saturation point before hot-pressing, the hot platen temperature of 170～200 °C and the initial pressure of 50～70 kp/cm^2.

4.9.3. It is made clear that the behavior of pulp mat containing the moisture of about 10 % is very unique as follows; As the latent heat absorption of moisture in the pulp mat does not apparently come on, the plastic flow due to both the development of moisture-plasticity and thermo-plasticity appears substantially, in the case of the mat containing moisture of 10 %.

From this point of view, the moisture content of about 10 % is perceived to be a parting of the ways between the dry-process and the wet-process of the fiberboard manufacturing.

4.9.4. The effect of edge between the surfaces of pulp mat and hot-platen and the rapid drying-set of surface layers in the extremely early period of hot-pressing relate to the deformation of constituent fibers in the pulp mat with the result that the plasticity and the drying-set distribute in the direction of thickness.

4.9.5. The rate of application of pressure has a potent influence on the plastic flow and the deformation of pulp mat, in particular, the plastic flow due to the development of thermo-plasticity is affected in the case of less moisture-contained mat, and the oven-dried mat having plenty of elastic element is a little dependent on the rate of application of pressure.

4.9.6. In general, it is urgently required for the fiberboard formation under the most suitable plastic flow and drying-set that the shortening of hot-pressing cycle, the qualified judgement for the process of fiberboard formation and the theoretical operation for the hot-pressing must be established as the effective diagram, therefore, the above-mentioned results are valuable.

Table 5. Conditions of pressing.

Pressing condition		Moisture content before pressing (%)		Hot platen temp. (°C)	Specific pressure (kp/cm²)	etc.
Cold pressing		* 0～155		Room temp. 14±2	70	
Hot pressing	Temp. of sheet before hot pressing 100 °C	Oven-dried condition		100	70	
		Oven-dried condition		* 40～230	70	
				170	* 10～70	
				170	70	* Thickness of sheet at hot pressing 2.2～11.2 mm
				170	70	* Defibration time of pulp 0.5～4.5 min.
	Temp. of sheet before hot pressing 13±2 °C	* 0～250		170	70	
		Fiber saturation point	25±3	* 40～230	70	
			27±3	170	* 10～70	
			24±4	170	70	* Thickness of sheet at hot pressing 2.6～7.9 mm
		Wet	145±15	* 40～230	70	
			150±15	170	* 10～70	
			140±20	170	70	* Thickness of sheet at hot pressing 3.3～8.9 mm

*: Variable factor.

Table 6. Conditions of hot pressing.

Hot platen temperature (°C)	170			
Specific pressure (kp/cm²)	70			
Moisture content of sheet before hot pressing (%)	0,	11±3,	26±4,	155±15
Mean rate of applying specific pressure (kp/cm³/sec.)	0.89～5.02	0.81～5.35	0.84～5.34	0.83～6.47
Hot pressing time (min.)	20			

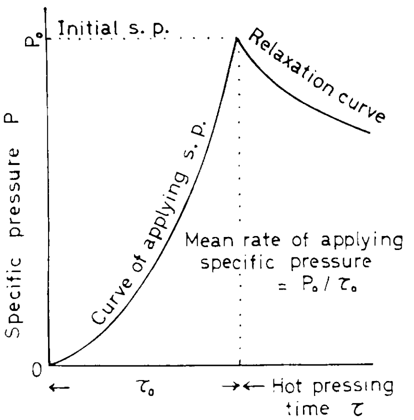


Fig. 34. Definition on mean rate of application of pressure.

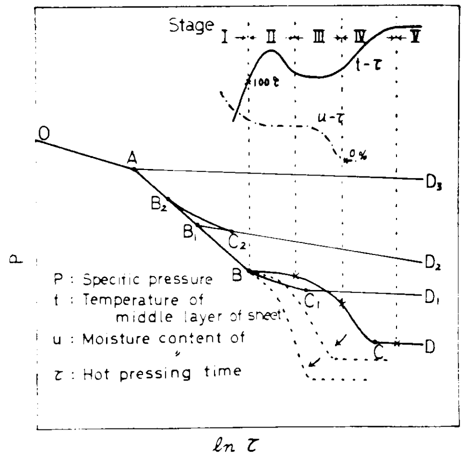


Fig. 35. Schematical diagram of relaxation curve for each condition of pressing, referring to heat-mass transfer.

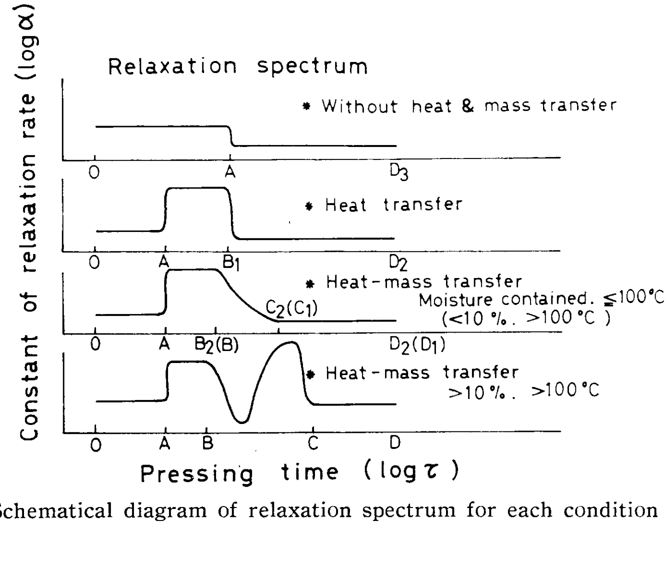


Fig. 36. Schematical diagram of relaxation spectrum for each condition of pressing.

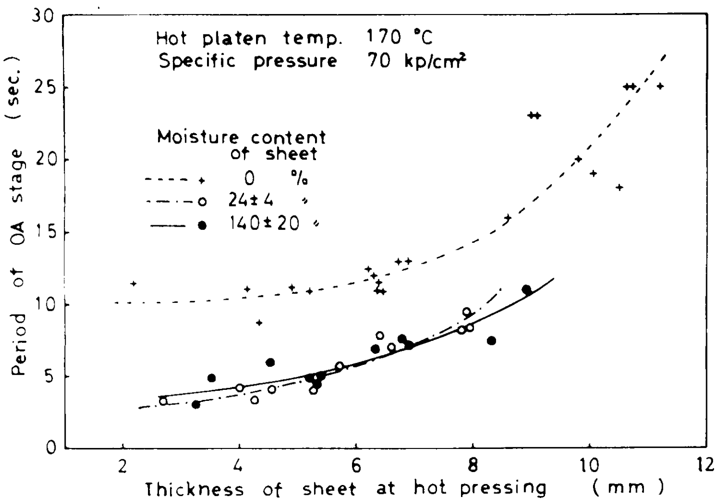


Fig. 37. Prolongation in period of Stage-OA with increasing thickness of pulp mat.

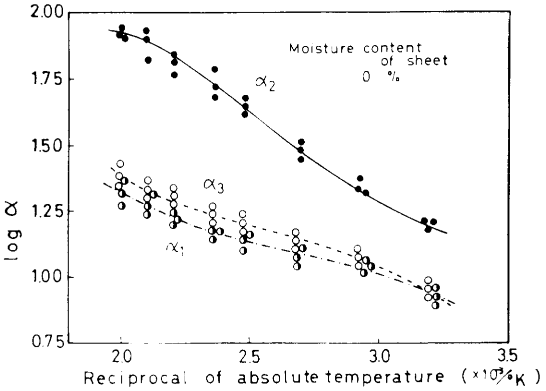


Fig. 38. Relations of logarithms of α_1, α_2 and α_3 to reciprocal of absolute temperature of hot-platen, in the case of ovendried mat.

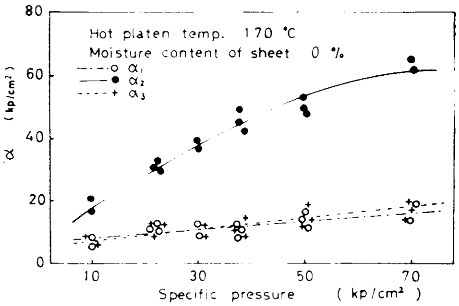


Fig. 39. Effect of pressure of hot-pressing on α, in the case of ovendried mat hot-pressed at 170 °C.

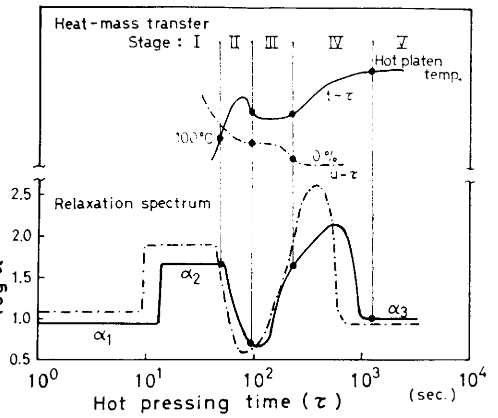


Fig. 40. Schematical diagram of relaxation mechanism comparing relaxation spectrum with heat-mass transfer, and a dotted curve in relaxation spectrum typically appearing in the case of relatively high temperature of hot platen.

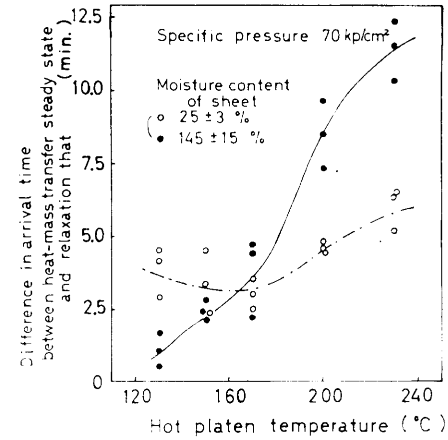


Fig. 41. Influence of hot platen temperature on difference in arrival time between steady state of heat-mass transfer and that of relaxation.

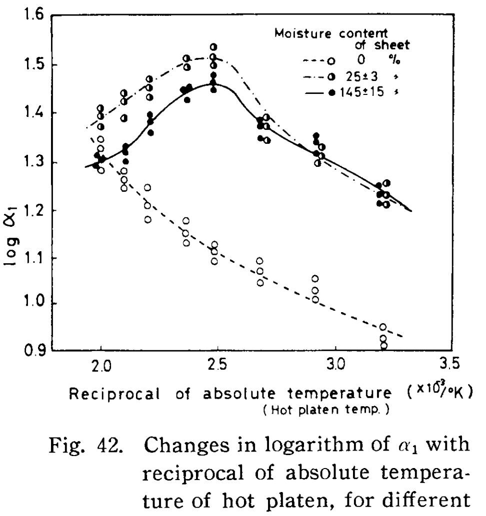


Fig. 42. Changes in logarithm of α_1 with reciprocal of absolute temperature of hot platen, for different moisture-contained mats.

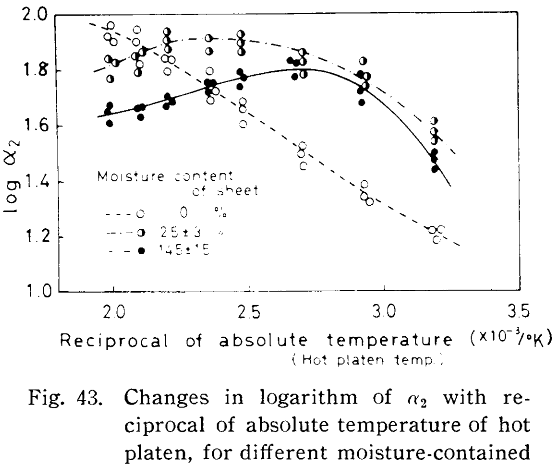


Fig. 43. Changes in logarithm of α_2 with reciprocal of absolute temperature of hot platen, for different moisture-contained mats.

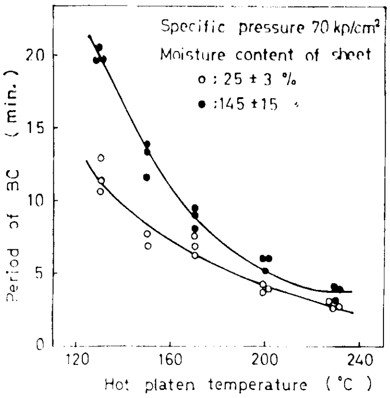


Fig. 44. Reduction in period of Stage-BC with increasing hot platen temperature.

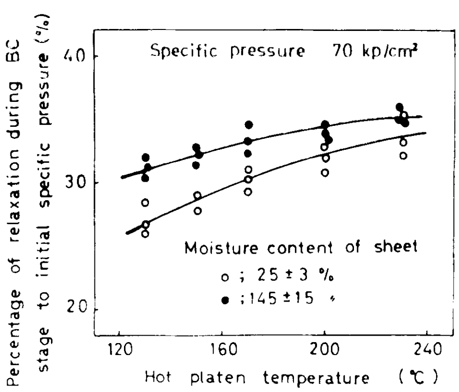


Fig. 45. Effects of hot platen temperature on percentage of relaxation during Stage-BC to initial pressure.

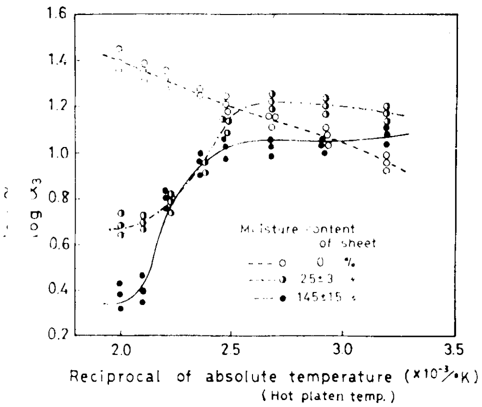


Fig. 46. Changes in logarithms of α_3 with reciprocal of absolute temperature of hot platen, for different moisture-contained mats.

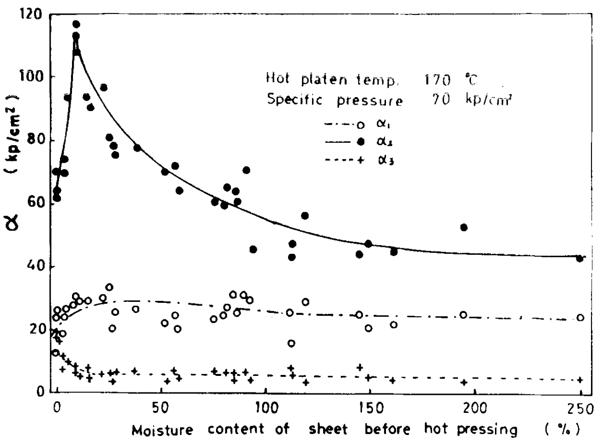


Fig. 47. Dependences of α_1, α_2 and α_3 on moisture content of pulp mat before hot-pressing.

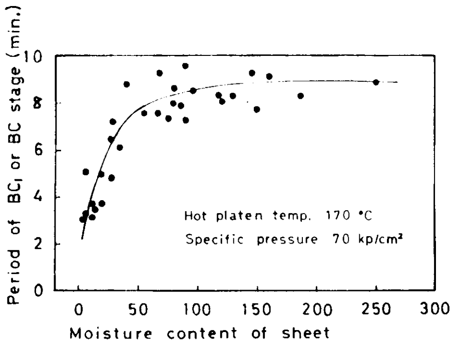


Fig. 48. Prolongation in period of Stage-BC_1 or BC with increasing moisture content of pulp mat before hot-pressing.

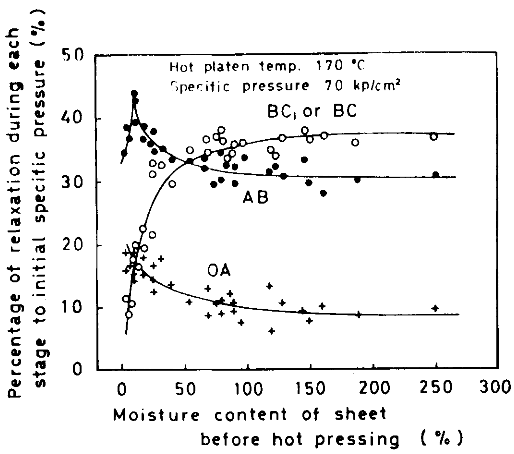


Fig. 49. Influence of moisture content of pulp mat before hot-pressing on percentage of relaxation during each stage to initial pressure.

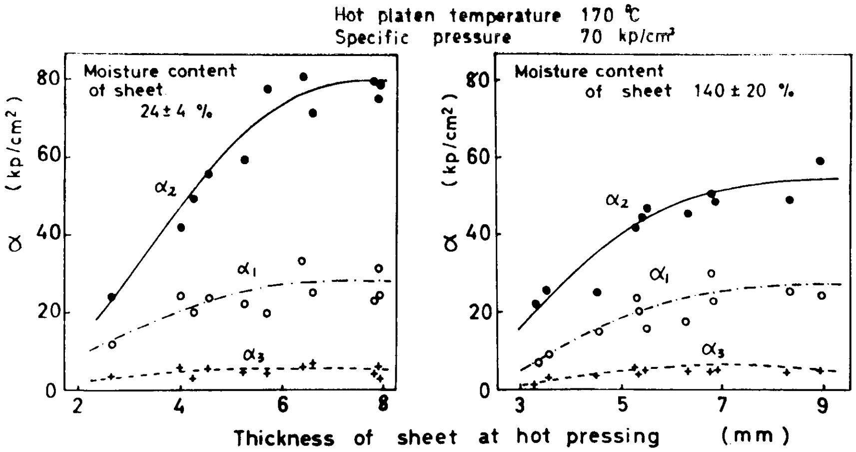


Fig. 50. Dependences of α_1, α_2 and α_3 on thickness of pulp mat, for pulp mats containing moisture of 24 or 140 % before hot-pressing.

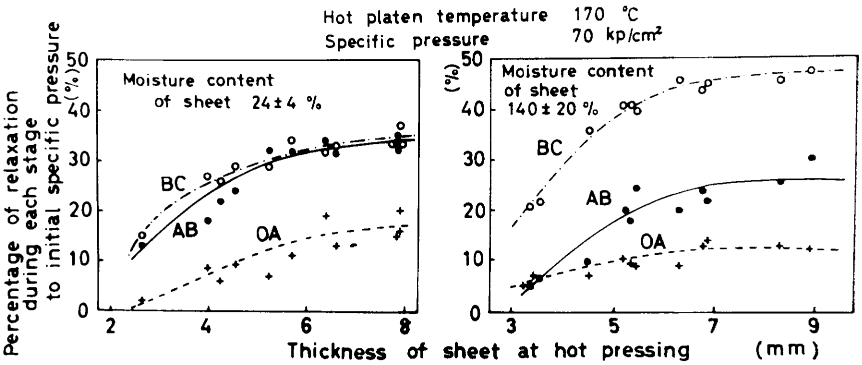


Fig. 51. Influences thickness of pulp mat on percentage of relaxation during each stage to initial pressure, for pulp mats containing moisture of 24 or 140 before hot-pressing.

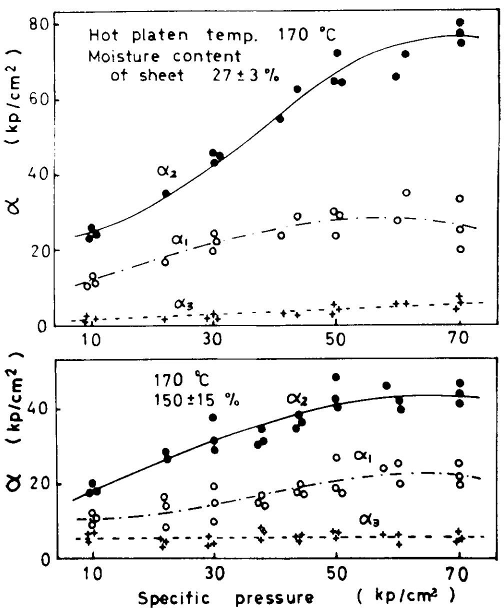


Fig. 52. Dependences of α_1, α_2 and α_3 on pressure of hot-pressing, for pulp mats containing moisture of 27 or 150 % before hot-pressing.

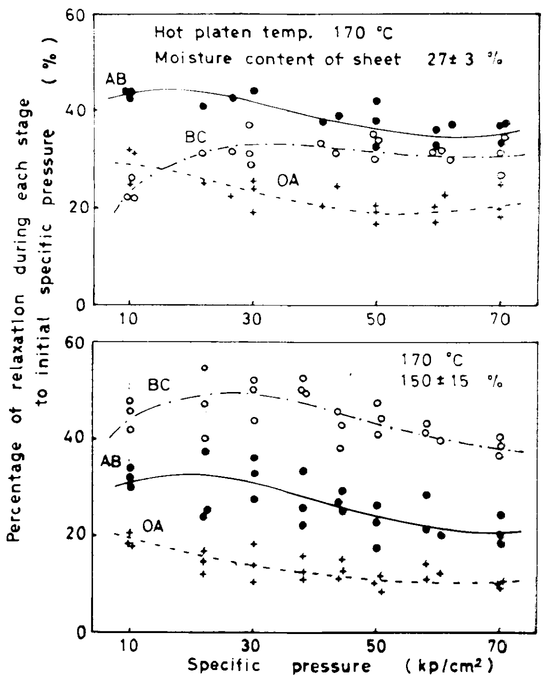


Fig. 53. Influences thickness of pulp mat on percentage of relaxation during each stage to initial pressure, for pulp mats containing moisture of 24 or 140 before hot-pressing.

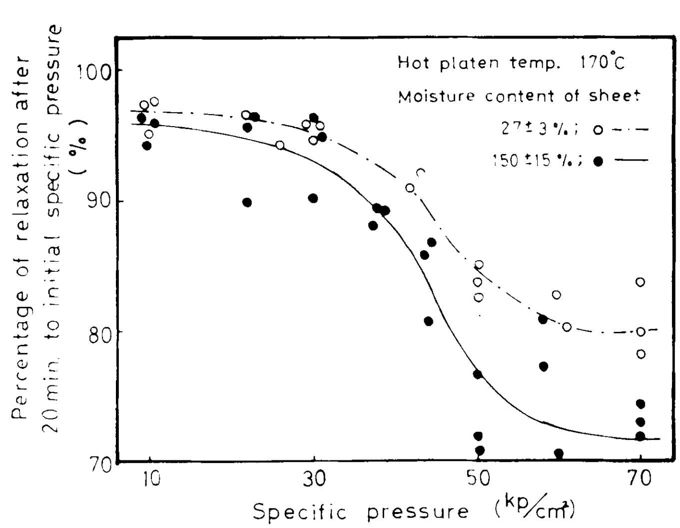


Fig. 54. Decrease in percentage of relaxation after 20 min. to initial pressure with increasing pressure of hot-pressing.

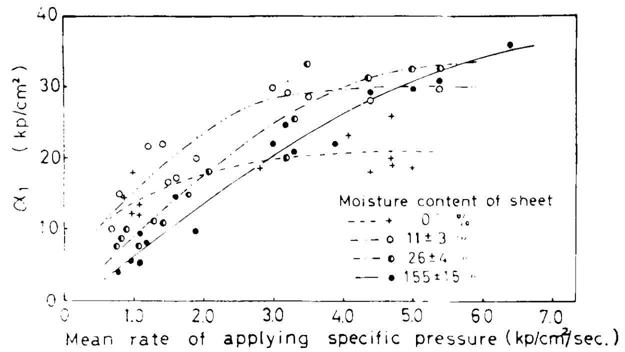


Fig. 55. Increase in α_1 with increasing rate of application of pressure, in the case of various moisture-contained mats.

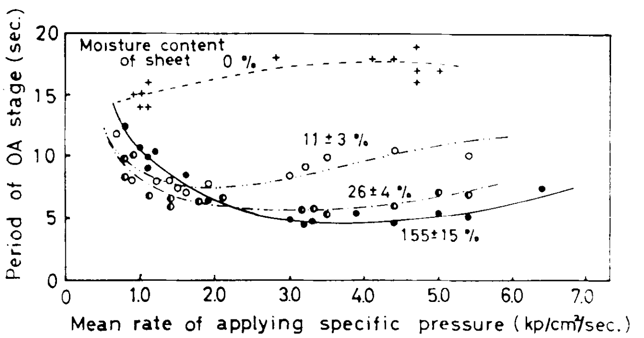


Fig. 56. Relations of period of Stage-OA to rate of application of pressure, in the case of various moisture-contained mats.

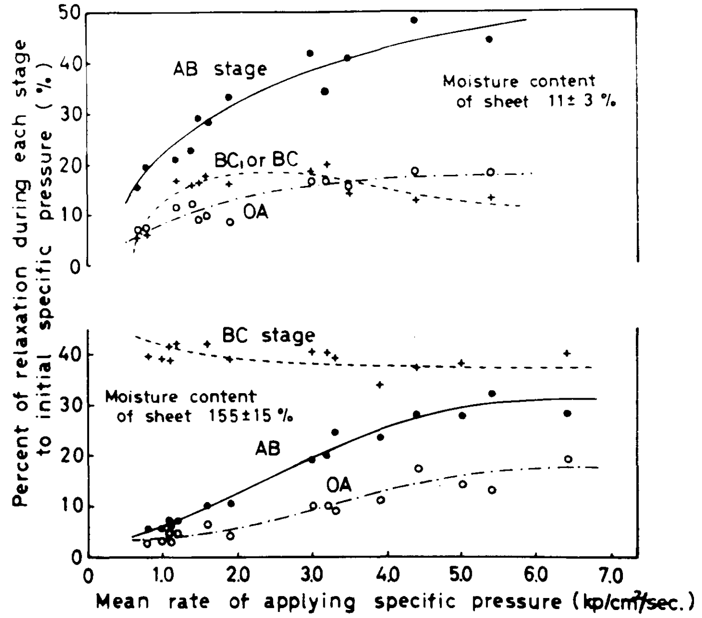


Fig. 57. Changes in percentage of relaxation during each stage to initial pressure with rate of application of pressure, for pulp mats containing moisture of 11 or 155 % before hot-pressing.

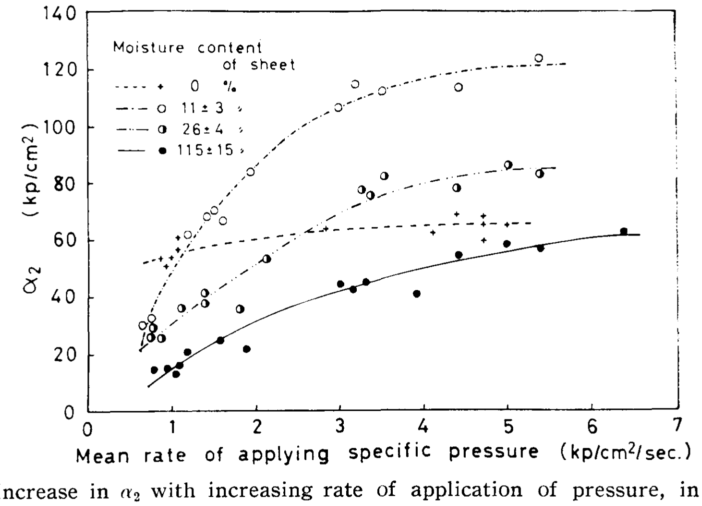


Fig. 58. Increase in α_2 with increasing rate of application of pressure, in the case of various moisture-contained mats.

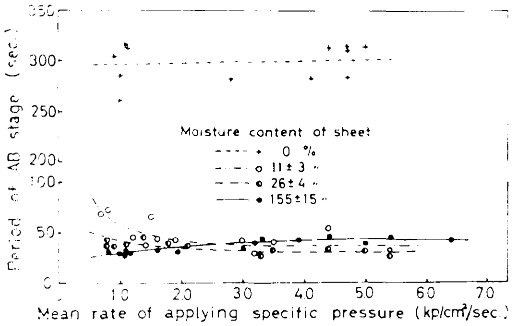


Fig. 59. Relations of period of Stage-AB to rate of application of pressure, in the case of various moisture-contained mats.

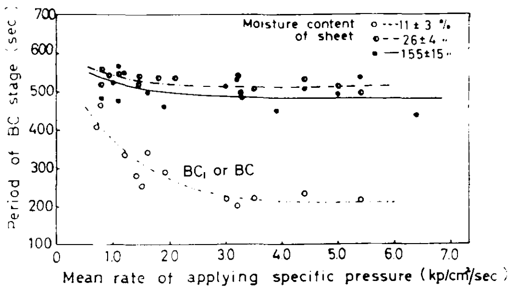


Fig. 60. Relations of period of Stage-BC to rate of application of pressure, in the case of various moisture-contained mats.

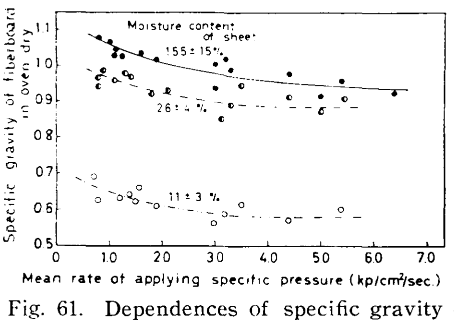


Fig. 61. Dependences of specific gravity of fiberboard in oven dry on rate of application of pressure, in the case of various moisture-contained mats.

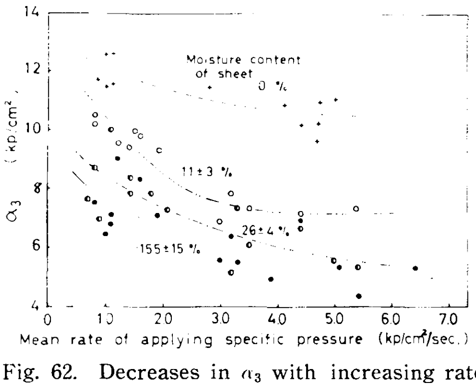


Fig. 62. Decreases in α_3 with increasing rate of application of pressure, in the case of various moisture-contained mats.

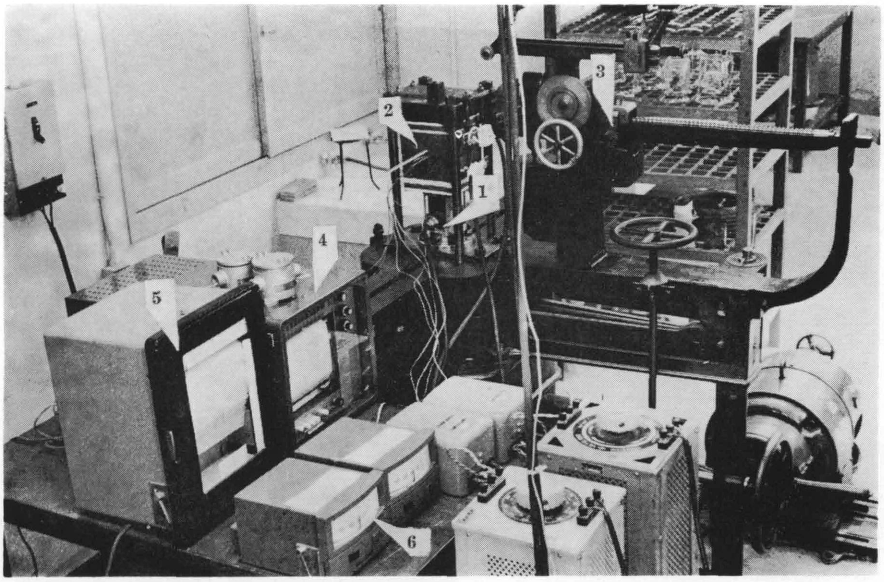
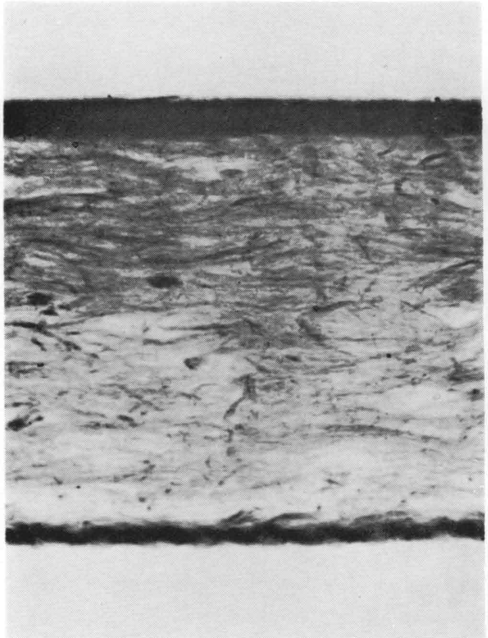
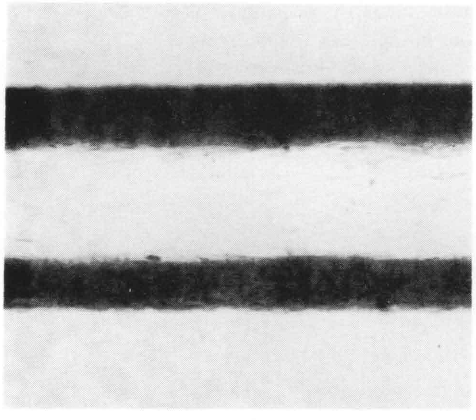


Photo. 13. Measuring apparatus of relaxation.

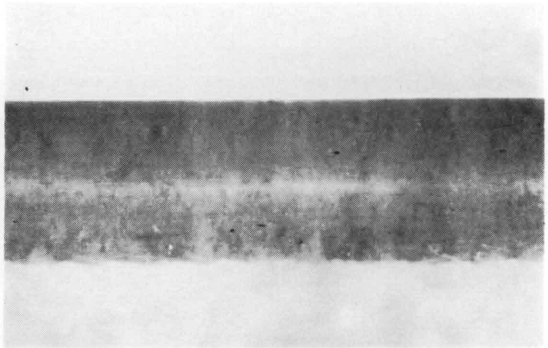
1. Load cell (Water cooling type, 10 ton).
2. Hot platens (20×20 cm, 200 V・1.6 kw).
3. Olsen type universal testing machine (10 ton).
4. X-Y recorder of pressure.
5. Temperature recorder (Surfaces and middle layer of pulp mat).
6. Temperature regulators (Upper and lower hot platen, respectively).



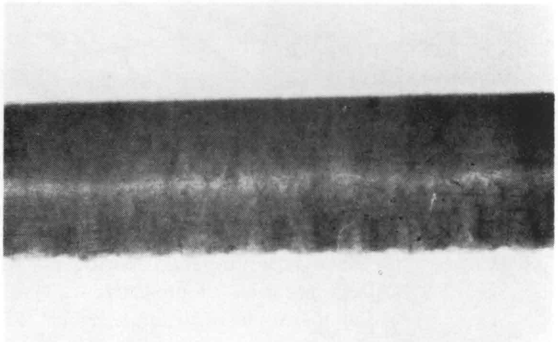
-1. During extremely early period (Hot-pressing time: 45 sec.).



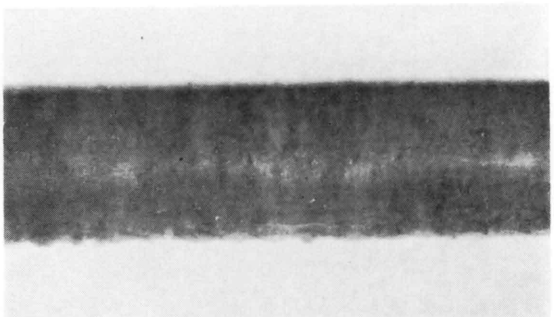
-2. During first half period of latent absorption for water evaporation in middle layer (: 2.5 min.).



-3. During latter half period of latent heat absorption for water evaporation in middle layer (: 3.5 min.).



-4. During latter unsteady state of heat transfer (: 5.0 min.).



-5. During steady state of heat transfer (: 20.0 min.).

Photo. 14. Progressive drying-set of pulp mat with heat-mass transfer during hot-pressing under a condition as shown in Table 7-(a).

5. Elucidation of fiberboard properties on the basis of behavior of pulp mat during hot-pressing.

5.1. Introduction.

Many of investigations have been throwing ligh on the relationships between the hot-pressing factors and the board properties, for example, Turner, H. D. et al.[100] presented the relations of the bending strength to the specific gravity in a formula, Wilder, H.[104] reported that the difference in the effect of temperature on the constituent fibers produced the change in the board properties, observing the temperature transitions under the various hot platen temperatures and the various pressure, and Takamura, N.[96,97] considered the change of board properties from the relation of the polimerization of cellulose to the hot platen temperature or the pressure, regarding as an indicator of the strength of individual fiber. Almost these investigations have been brought out only in explanation of the relation of hot-pressing factors to the board properties.

It is an essential object for the development of the board molding and the improvement in board properties that the formation of board properties is precisely graped on the basis of the behavior of plasticity and the drying-set of pulp mat which are analyzed from the mechanism of the heat and mass transfer in the pulp mat, the deformation of internal structure and the relation of these to the relaxation of pressure during hot-pressing.

In this chapter, the heat and mass transfer, the deformation behavior of internal structure and the characteristics of pressure relaxation of the board formation elucidate the board properties theoretically or empirically.

5.2. Experimental procedure.

The Asplund pulp prepared under the same conditions as 2.2.2. is formed in the circle shape of diameter 21 cm.

5.2.1. Hot-pressing: The three hot-pressing conditions were used as shown in Table 7. Their mats were taken out from the hot-press, simultaniously with the arbitorary arrival point of each heat and mass transfer mechanism. As recording the temperature transition in the pulp mat during hot-pressing, with a view to the investigation on the effect of the preliminary cold-pressing condition on the board properties, the pulp mats which were preliminarily cold-pressed under the various pressures (Table 8) were hot-pressed under a fixed condition (Table 9).

Furthermore, after cold-pressing the wet forming mats under the condition of 16 ± 1 °C, 40 kp/cm^2 and 30 sec., the moisture content of pulp mats was conditioned. Thus, the moisture content of pulp mat before hot-pressing, the hot platen temperature (Table 10), the initial pressure and the rate of application of pressure (Table 11) were accepted as the hot-pressing factors.

5.2.2 Testing of board properties.

After these boards were conditioned under the room temperature of 20 ± 2 °C and the relative humidity of room 65±5 % for one month (The moisture content of board : 8.0±0.5 %), the following tests were conducted.

1) The distribution of density in the direction of thickness: The soft-X ray was applied to the face of thickness of 0.51±0.02 cm with the aid of a SOFTEX type EMB (Japan Softex Ray CO.) and those X ray photographs were taken.

2) The specific gravity in the oven-dry and in the air-dry: The test pieces of 5×5 cm were dimensioned by the general method.

3) The surface roughness: The $H_{max.}$ of the smooth side of board were measured in proportion to JIS B 0601 (1961).

4) The static bending properties: The Young's modulus in bending, the bending stress at proportional limit and the modulus of rupture in bending were obtained with the aid of Instron type unversal testing machine under the span of 15 cm, the width of 5 cm.

5) The impact bending property: The absorbed energy in impact bending was tested under the span of 6.0 cm and the width of 1.0 cm with the aid of Charpy type impact bending machine.

6) The hardness: The Brinell hardness of the smooth side were measured in proportion to JIS Z 2117 (1963).

7) The water absorption: After the test pieces of 5×5 cm were soaked in the water of 25±2 °C for 24 hr., the water absorption, the thickness and width swelling were measured in proportion to JIS A 5907 (1961).

8) Tensile shearing strength of middle layer: The two grooves of middle of 0.25 cm were cut into the center of thickness at the place of 1.5 cm from the edge on both the surface sides. Both the edges were griped with the aid of the chacks used for the general adhesion-test of plywood and under the rate of 20 mm/min.

5. 3. Growth of board properties with heat and mass transfer during hot-pressing.

5. 3. 1. The growth process with the mechanism of the heat and mass transfer.

(1) Stage—I (Early unsteady heat transfer): The rapid drying-set of surface layers appears in the extremely early period (Photo. 14-1). As the whole pulp mat is still wet, the board properties are impossible to be measured.

Stage—II (Non-equilibrium evaporation of water in the interior of pulp mat): The upper and lower layers are drying-set into the state of relatively higher density. Furthermore, the thickness of these layer increases rapidly (Photo. 14-2 and Fig. 64). The fibers in the middle layer are wet during this period. It is ascertained that the bonding between fibers in the middle layer occurs little because the tensile shearing strength is very small as impossible to be measured. While the static bending properties scarcely increase during this stage (Fig. 65 and 66) in disregard of the denser layer in the upper and lower surface sides, the absorbed energy in impact bending (Fig. 67) and the Brinell hardness grow larger.

Thus, the growth of the upper and lower layers' properties becomes greatly, on the other hand, the inner layer still remains in the wet pulp mat.

(3) Stage—III (Latent heat absorption of moisture in the middle layer): The thickness of drying-set layer increases toward the interior at a slower pace than that during Stage—II (Photo. 14-3 and Fig. 64). In the case of keeping the fixed initial pressure without the distance-bar, the growth of drying-set layer is almost finished completely during this stage and the less dense part in the interior disappears (Photo. 15), so the board properties are improved very well (Fig. 65, 66, 67 and 68). The growth of drying-set from the upper and lower surfaces toward the interior part becomes dull in comperison with that during Stage—II, however, the drying-set of the constituent fibers in the middle layer during this stage makes appreciable progress in the board property.

(4) Stage—IV (Latter unsteady heat transfer): The growth of grying-set from both the surfaces toward the interior part of pulp mat apparently stops during this stage in the case of hot-pressing with the distance-bar with the result that there appears the lower density part in the interior of board.

The drying-set and the heat-treatment go side by side so that board properties are pretty improved (Fig. 65, 66, 67 and 68). From the latter half of this stage, the pressure relaxation becomes steady after mostly proceeding the plastic flow and the drying-set, therefore, the greater part of the growth of board properties is over till the first part of this period and from the latter part the effect of heat-treatment mainly appears.

(5) Stage—V (Steady heat transfer): The drying-set from the upper and lower surfaces toward the interior part has been over previously and the board properties change little (Fig. 65, 66, 67 and 68).

5.3.2. The appearance of the lower density part in the interior of board.

The lower density layer, developing in the interior part of pulp mat in the case of hot-pressing of SIS hardboard with the distance-bar is always situated near the lower layer (Photo. 14).

This fact clearly observed under both the hot-pressing conditions of various initial pressures and rates of application of pressure. The growth of thickness of drying-set layer from both the surfaces toward the interior part is represented in Photo. 14 and Fig. 64. In the early period of development of drying-set layer, the drying-set in the upper side is faster than that in the lower side, however, both the thicknesses of drying-set layers from the surface toward the interior part of pulp mat after the period grow larger at the pace mutually. This phenomenon proves the situation of the lower density layer to be already desided in the extremely early period of hot-pressing.

5.4. Improvement in board properties on the basis of internal deformation of pulp mat.

As shown in Table 12, the board properties noticeably increase within the range from 10 to 30 kp/cm^2 with increasing initial pressure in the case of preliminary cold-pressing.

In the state in which the thermo-plasticity and the drying-set scarcely appear, the gap-filling and the uniform distribution of deformation due to the macro-slippage between fibers are effectively carried out, furthermore, the bonding between fibers becomes very well with the consequence that the board properties become elastic because of the available endowment with plasticity and drying-set during hot-pressing (Fig. 69, 70 and 71).

It is obtained from the coefficient operation between cold-pressing and hot-pressing that the effect of cold-pressure on the surface roughness is evidently reduced with increasing pressure at hot-pressing (Fig. 72 and Photo. 16), but the effect of cold-pressure on the other properties becomes remarkable with increasing pressure at hot-pressing. Consequently, the improvement in board properties is not achieved only by the gap-filling effect of fibers and the equalization of deformation in the direction of thickness of pulp mat, but by the thermo-plasticity and the drying-set due to them.

As shown in Table 13, the change of moisture content before hot-pressing caused by cold-pressing can not be thought to have a direct effect on the board properties because the pulp mats applied the pressure in the cold-pressing always contains more than the initial moisture content of pulp mat just before hot-pressing.

The macro-slippage between fibers and the equalization of deformation of pulp mat in the direction of thickness must be made available progress during hot-pressing because the constituent fibers are not greatly compressive-deformed but the gap-filling of fibers easily occurs within the range of pressure from 20 to 30 kp/cm^2 under which the thermo-plasticity and the drying-set do not appear almost.

Consequently, in the case of practical hot-pressing of pulp mat, the macro-slippage between fibers and the equalization of deformation are accelerated by the preliminaey cold-pressing, and moreover the thermo-plasticity aed the drying-set are subject to the favorable influence of hot-pressing.

5. 5. Investigation of board properties on the basis of dependenc of board formation on the heat and moisture supplied to the pulp mat.

As shown in Fig. 73, 74, 75 and 76, the enlargement of bonding area between fibers and its setting increasingly contribute to the improvement in board properties within the less moisture than the fiber saturation point, with increasing moisture content of pulp mat before hot-pressing (Photo. 7).

The improvement in board properties within the range from the fiber saturation point to 50 or 60 % suggests that the macro-slippage between fibers is facilitated by a role of free water as a sort of lubricant with the result of the increase of contact point between fibers, and that the promotion of chemical reaction (Mainly hydrolysis of hemicellulose etc.) and the duration of moisture-existence as a plasticizer in the pulp mat are prolonged during hot-pressing and the super-heated moisture which is generated by the intense non-equilibrium evaporation has a powerful effect on the constituent fibers.

As shown in Fig. 77, 78 and 79, the board properties can be improved under the lower hot platen temperature (150～170 °C) in the case of more moisture-contained mat, and are done so under the higher hot platen temperature in the case of less moisture-contained mat (170～230 °C).

While the free water makes the bonding between fibers very well, the effective bonding between fibers is made by highly heating during hot-pressing because of the short duration of water-existence in the case of containing free water.

This result explains that the free water evidently contributes to the improvement in board properties. It is in accord with the above-mentioned results that the reduction of polymerization of cellulose due to the increase of hot platen temperature makes the fiber to be plastic, therefore, the board property is improved by the enlargement of bonding area between fibers. Under the extremely high hot platen temperature, the heat-deterioration of fiber becomes severe and the absorbed energy in impact bending rapidly decreases under the hot platen temperature of 230 °C (Fig. 80). Because of the intensely non-equilibrium evaporation in the case of more moisture-contained mat, the severe deterioration of fibers by the super-heated moisture occurs even under the lower hot platen temperature.

5.6. Investigation of board properties on the basis of dependence of board formation on application of pressure.

5.6.1. The initial pressure: The deformation behavior of internal structure of pulp mat due to the initial pressure during hot-pressing was previously mentioned in detail, therefore, it was assumed that the initial pressure was an important factor of hot-pressing. As shown in Fig. 81, 82, 83 and 84, the compressive cross-sectional deformation of fiber sarcely grows larger but the contact point between fibers increases with increasing pressure with the result of the favorable improvement in board properties. Within the range from 30 to 50 kp/cm^2, the effective bonding area between fibers is enlarged by the compressive cross-sectional deformation of fiber due to moisture-plasticity. As the irreversible setting of fiber deformation is near completion, the board is not greatly improved in its properties. In the case of more moisture-contained mat, the improvement in board properties with the increase of pressure tends to become noticeable under the lower pressure than 50 kp/cm^2.

With increasing initial pressure, the board properties are somewhate improved still within the range of the higher pressure than 50 kp/cm^2 in the case of the mat containing moisture of the fiber saturation point. That is to say, owing to the extreme reduction of the filtration of pulp mat for the vapor in the interior under the higher pressure than 60 kp/cm^2, the degeneration of constituent fibers by the super-heated moisture is more severely caused and prolonged with increasing the moisture content of pulp mat before hot-pressing, so the absorbed energy in impact bending evidently intends to be reduced by the degeneration (Fig. 83).

Consequently, the internal structure of pulp mat during hot-pressing is greatly changed by the initial pressure with result of taking part in the heat and mass transfer, therefore, the initial pressure has an influence on the board properties.

5. 6. 2. The rate of application of pressure.

It has been previously ascertained as aforesaid in 4. 6. that the behavior of pulp mat during hot-pressing is subject to the influence of the rate of application of pressure, hence, the dependence of the board properties on the rate of application of pressure shall be brought to light in this part.

At the lower rate of application of pressure, because the macro-slippage between fibers and the equalization of deformation of pulp mat in the direction of thickness sufficiently follows to the pressure, the surface roughness is reduced (Photo. 17 and Fig. 85) and the whole board uniformly becomes dense (Photo. 18). The tensile shearing strength of middle layer and the bending strength grow larger with decreasing rate of application of pressure (Fig. 86 and 87). At the higher rate of application of pressure, because the plastic flow and the equalization of deformation can not sufficiently follow to the pressure, the surface roughness increases and the low density part appears in the interior clearly. The tensile shearing strength and the bending strength are reduced. The decrease of the absorbed energy in impact bending of the board manufactured at the lower rate of application of pressure results in the formation of the packed structure and the brittleness of wood fibers which is caused by the super-heated moisture in the pulp mat due to the intensely non-equilibrium evaporation, with reducing various gaps and voids in the pulp mat (Fig. 88).

5. 7. Summary.

5. 7. 1. In the early period of hot-pressing, the drying-set layers rapidly appear in both the surface sides of pulp mat. The thickness of layer from the surface toward the interior pari evidently beging to grow larger from Stage—II, and the bonding between fibers and the drying-set of fiber tend to increase, resulting from the evaporation of vapor in the middle layer during Stage—III. In the first part of Stage—IV, the heat treatment and the drying-set make the board properties to be improved and then from the latter part of Stage—IV the board properties changes little.

5. 7. 2. The preliminary cold-pressing makes appreciable progress in the macro-slippage between fibers and the equalization of deformation of pulp mat in the direction of thickness, before hot-pressing, so that the board is improved in the properties.

5.7.3. While the increase of bound water in the constituent fibers increasingly endows the fibers with plasticity and brings out the enlargement of effective bonding area between fibers, the free water takes part in a lubricant for the macro-slippage between fibers and an influence on the packing behavior of fibers, moreover, for a long time or greatly makes up for the hydrolysis of hemicellulose and so on. Particularly in the case of the mat containing free water, the plasticity and the drying-set sufficiently increase under the lower hot platen temperature, but the super-heated moisture generated by the intensely non-equilibrium evaporation assurely causes the deterioration of fibers under the low hot platen temperature.

5.7.4. The internal structure of fiberboard is under the control of the initial pressure at hot-pressing, in particular, the initial pressure has an immediate influence on the enlargement of effective bonding area between fibers and the decrease of filtration relative to the deterioration of fiber. Consequently, the available packing behavor of fibers due to the lubrication effect of free water and the duration of plasticity due to the prolongation of moisture-existence can improve in the board properties under the relatively lower pressure.

5.7.5. The following of the macro-slippage between fibers and the equalization of deformation in the direction of thickness to the application of pressure is easily carried out in the case of the mat containing free water in which the lubrication effect of free water and the plasticity of fiber can be accelerated, however, at the extremely high rate of application of pressure, the low density-part appears in the interior with the result of the reduction of board properties.

Table 7. Hot-pressing conditions.

	Condition (a)	Condition (b)	Condition (c)
Hot platen temperature (°C)	170	170	170
Specific pressure (kp/cm²)	50	50	30
Mean rate of applying specific pressure (kp/cm²/sec.)	2.5~3.5	2.0~3.0	3.0~3.5
Distance bar (cm)	0.51	Without	0.73

Table 8. Conditions of prepressing.

Temperature of water	15 °C
Platen temperature	15~17 °C
Mean rate of applying pressure	2.0~3.0 kp/cm²/sec.
Specific pressure	0, 10, 20, 30, 40 and 50 kp/cm²
Pressing time	1.0 min.
Wire netting on lower surface	Iron of 16 mesh

Table 9. Conditions of hot pressing.

Hot platen temperature	170 °C
Specific pressure	30, 50 and 70 kp/cm²
Mean rate of applying pressure	2.5~3.0 kp/cm³/sec.
Hot pressing time	20 min.

Table 10. Hot-pressing conditions of S1S fiberboard.
(Hot-pressing time ; 25 min.
Specific pressure ; 70 kp/cm²)

Variable factor	Moisture content (%)	Hot platen temperature (°C)
Moisture content	10~250	170
Hot platen temperature	25±3 150±15	130~230

Table 11. Hot-pressing conditions of S1S fiberboards.
(Hot-pressing time ; 25 min. Hot platen temperature ; 170 °C)

Variable factor	Moisture content (%)	Specific pressure (kp/cm^2)	Rate of applying specific pressure ($kp/cm^2/sec.$)
Specific pressure	27±4 140±20	10～70	4.2±0.5
Rate of applying specific pressure	26±4 155±15	70	0.7～6.4

Table 12. Results of statistical treatment.

Properties \ Factors	Specific pressure (kp/cm^2) Prepressing	Specific pressure (kp/cm^2) Hot-pressing	Interaction
Specific gravity in air dry	* (10–30)	** (30–70)	**
Peak to valley height	** (10–50)	** (30–50)	**
Young's mrdulus in bending	** (10–30)	** (30–50)	No s.
Bending stress at proportional limit	** (20–40)	** (30–50)	No s.
Modulus of rupture	No s.	* (50–70)	**
Absorbed energy in impact banding	* (10–50)	* (30–50)	No s.
Brinell hardness	* (10–30)	** (30–70)	No s.
Water absorption	** (10–30)	** (30–50)	No s.
Thickness swelling	** (10–20)	** (30–50)	No s.
Width swelling	** (10–20)	No s.	No s.

** : Significance at the 0.99 level.
* : Significance at the 0.95 level.
No s. : No significance.
(–) : The range of specific pressure where the property of board developed significantly.

Table 13. Moisture content of pulp sheet with prepressing.

Specific pressure (kp/cm^2)	Moisture content (%)
0	890～1105
10	340～ 420
20	215～ 260
30	165～ 180
40	140～ 155
50	130～ 145

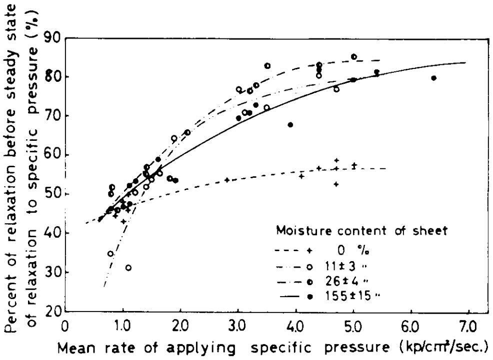


Fig. 63. Increases in percentage of relaxation before steady state of relaxation to initial pressure with increasing rate of application of pressure, in the case of various moisture-contained mats.

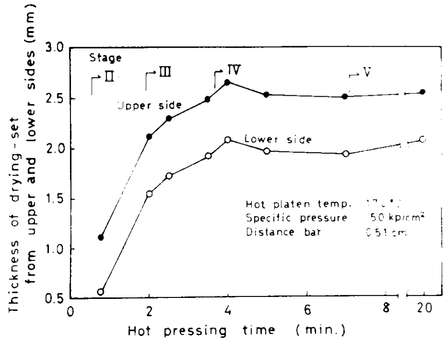


Fig. 64. Growth in drying-set layer from upper or lower side toward interior of pulp mat with the lapse of hot-pressing time.

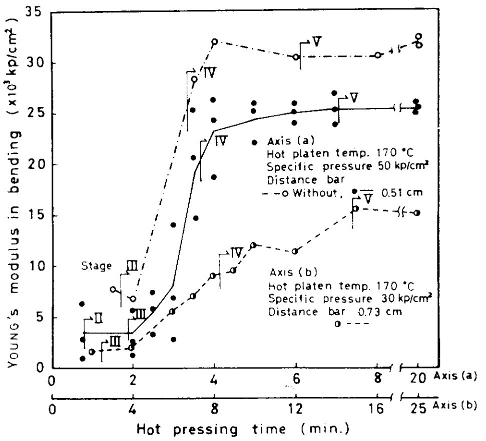


Fig. 65. Increment in Young's modulus in bending with the lapse of hot-pressing time, for different conditions of hot-pressing.

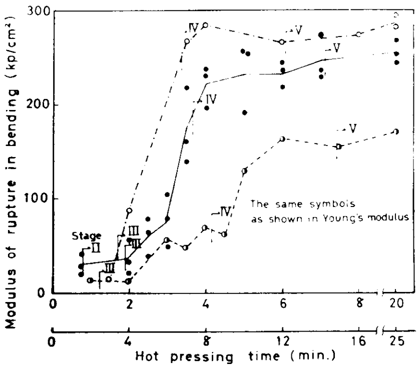


Fig. 66. Increment in modulus of rupture in bending with the lapse of hot-pressing time, for different conditions of hot-pressing.

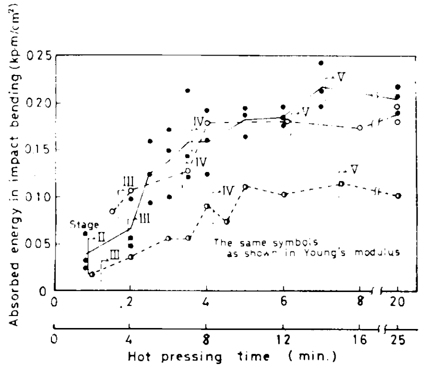


Fig. 67. Increment in absorbed energy in impacts bending with the lapse of hot-pressing time, for different conditions of hot-pressing.

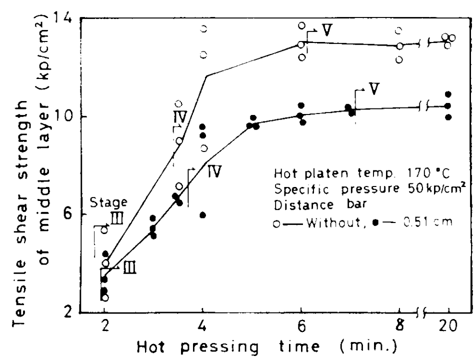


Fig. 68. Increment in tensile shearing strength of middle layer with the lapse of hot-pressing time, in the case of hot-pressing with distance-bar or without distance-bar.

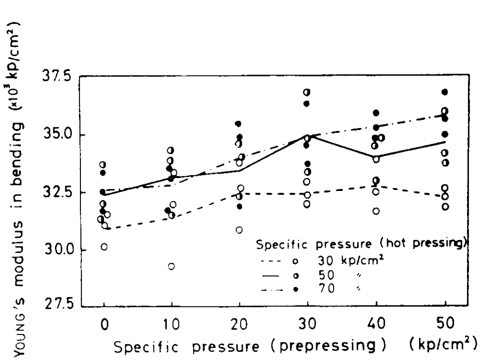


Fig. 69. Dependence of Young's modulus in bending on pressure of preliminary cold-pressing in the case of fiberboards produced under different pressures of hot-pressing.

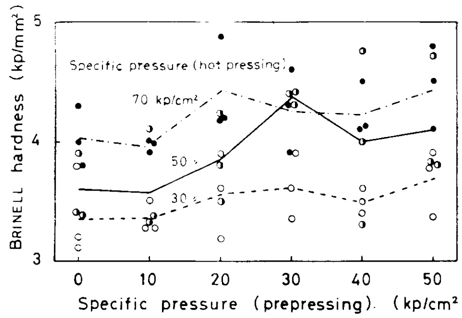


Fig. 70. Dependence of Brinell hardness on pressure of preliminary cold-pressing in the case of fiberboards produced under different pressures of hot-pressing.

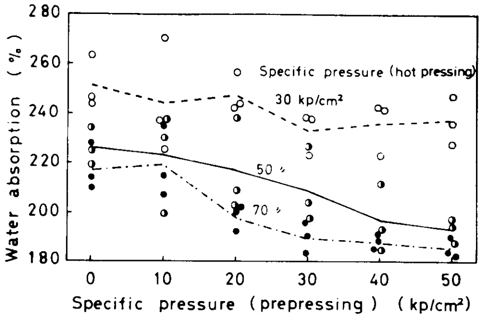


Fig. 71. Reduction in water absorption with increasing pressure of preliminary cold-pressing in the case of fiberboards produced under different pressures of hot-pressing.

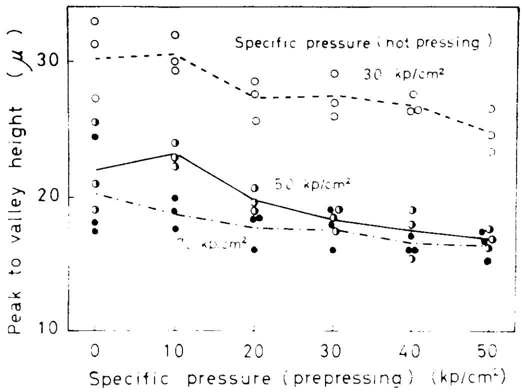


Fig. 72. Decrease in peak to valley height ($H_{max.}$) with increasing pressure of preliminary cold-pressing in the case of fiberboards produced under different pressures of hot-pressing.

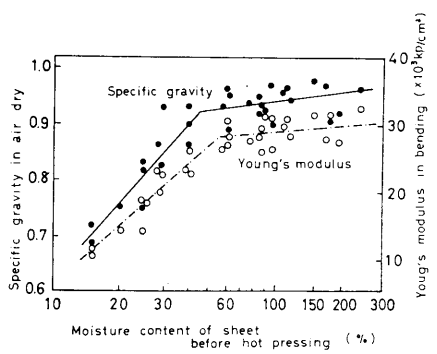


Fig. 73. Effects of moisture content of pulp mat before hot-pressing on specific gravity in air dry and Young's modulus in bending.

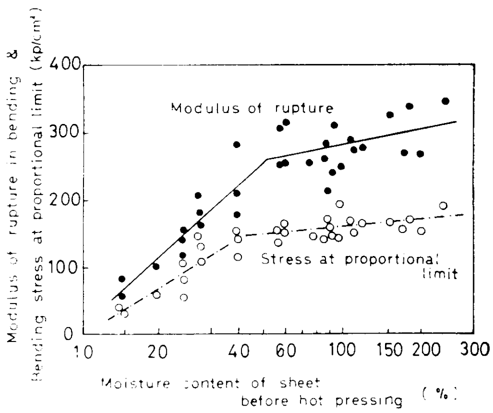


Fig. 74. Effects of moisture content of pulp mat before hot-pressing on modulus of rupture in bending and bending stress at proportional limit.

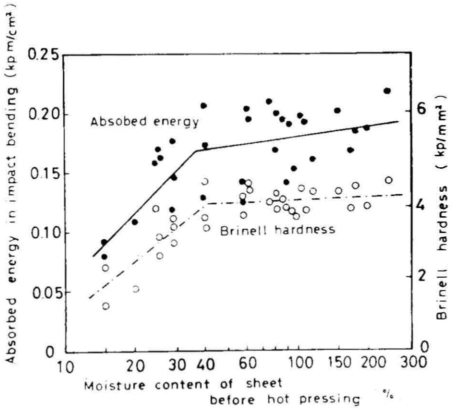


Fig. 75. Influences of moisture content of pulp mat before hot-pressing on absorbed energy in impact bending and Brinell hardness.

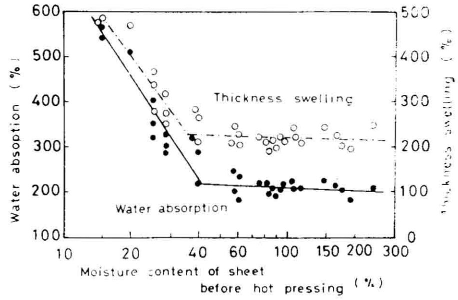


Fig. 76. Influences of moisture content of pulp mat before hot-pressing on water absorption and thickness swelling.

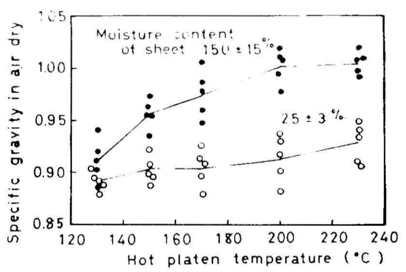


Fig. 77. Relations of specific gravity in air dry to hot platen temperature, in the case of fiberboards produced from pulp mats containing moisture of 25 or 150 % before hot-pressing.

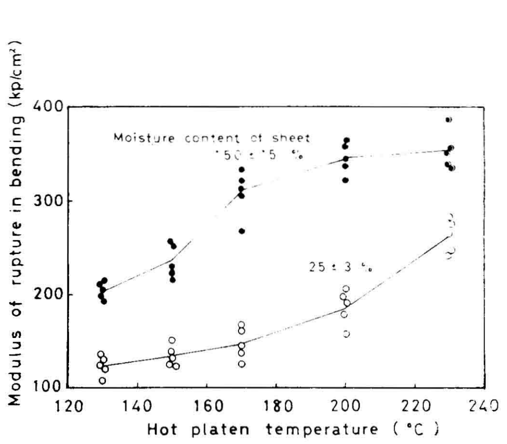


Fig. 78. Relations of modulus of rupture in bending to hot platen temperature, in the case of fiberboards produced form pulp mats containing moisture of 25 or 150 % before hot-pressing.

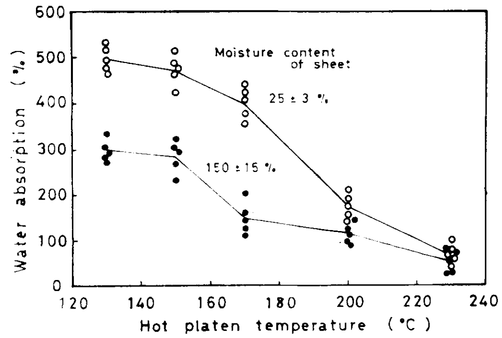


Fig. 79. Reductions in water absorption with increasing temperature of hot platen, in the case of fiberboards produced from pulp mats containing moisture of 25 or 150 % before hot-pressing.

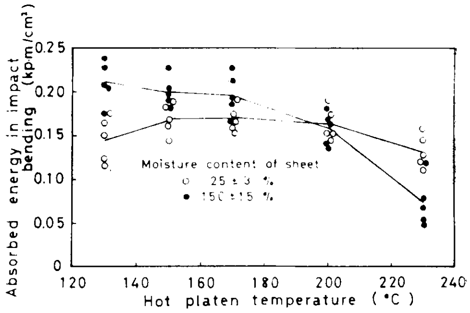


Fig. 80. Changes in absorbed energy in impact bending with hot platen temperature, in the case of fiberboards produced from pulp mats containing moisture of 25 or 150 % before hot-pressing.

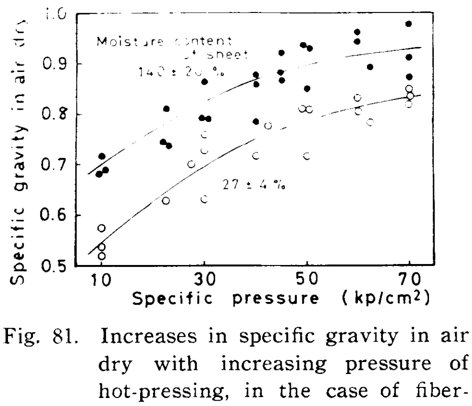


Fig. 81. Increases in specific gravity in air dry with increasing pressure of hot-pressing, in the case of fiber-boards produced from pulp mats containing moisture of 27 or 140 % before hot-pressing.

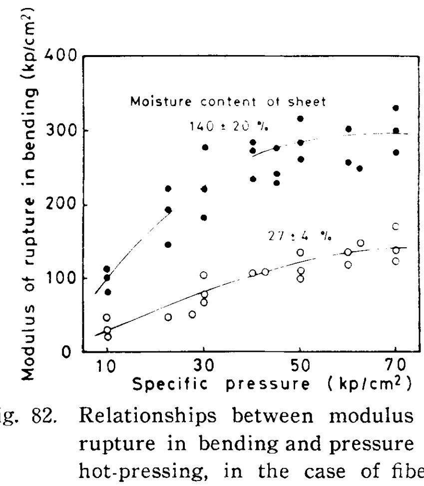


Fig. 82. Relationships between modulus of rupture in bending and pressure of hot-pressing, in the case of fiber-boards produced from pulp mats containing moisture of 27 or 140 % before hot-pressing.

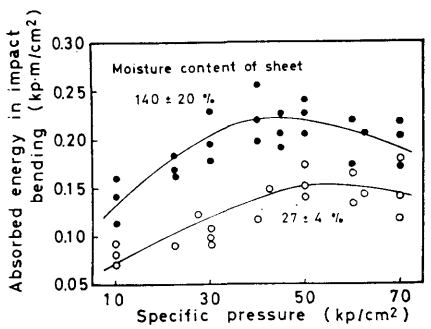


Fig. 83. Influences of pressure of hot-pressing on absorbed energy in impact bending, in the case of fiberboards produced from pulp mats containing moisture of 27 or 140 % before hot-pressing.

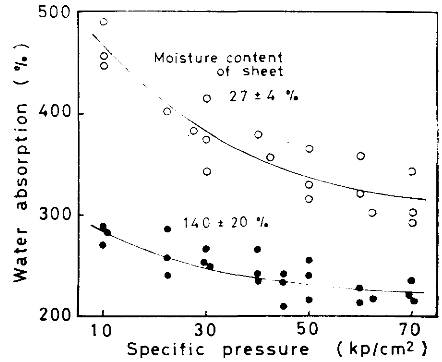


Fig. 84. Reductions in water absorption with increasing pressure of hot-pressing in the case of fiberboards produced from pulp mats containing moisture of 27 or 140 % before hot-pressing.

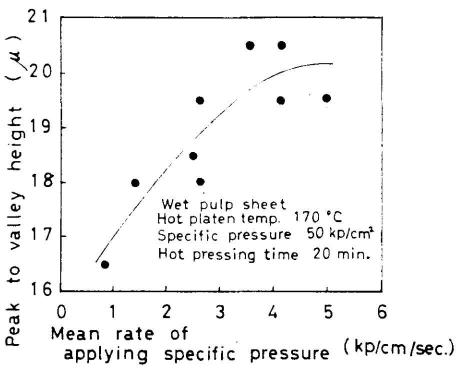


Fig. 85. Increase in peak to valley height with increasing rate of application of pressure.

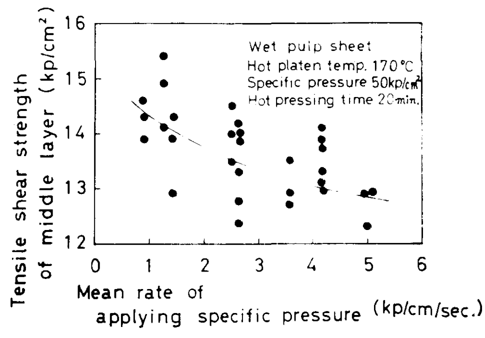


Fig. 86. Decrease in tensile shearing strength of middle layer with increasing rate of application of pressure.

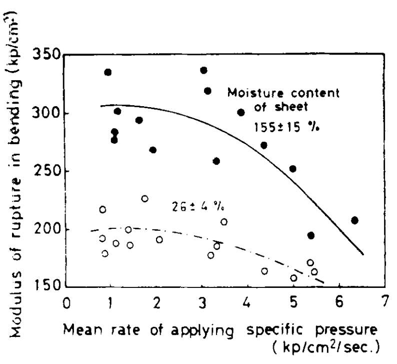


Fig. 87. Dependences of modulus of rupture in bending to rate of application of pressure in the case of fiberboards produced from pulp mats containing moisture of 26 or 155 % before hot-pressing.

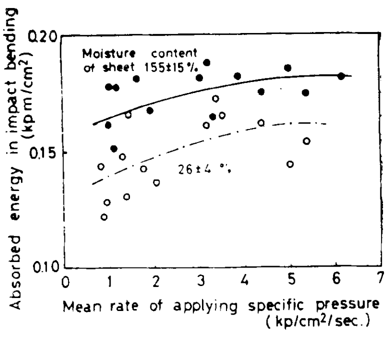
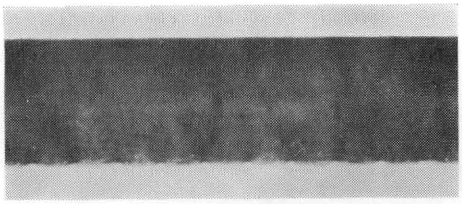
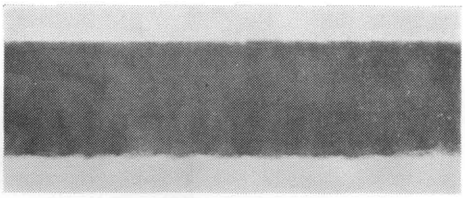


Fig. 88. Changes in absorbed energy in impact bending with rate of application of pressure, in the case of fiberboards produced from pulp mats containing moisture of 26 or 155 % before hot-pressing.



-1. In early period of Stage-III (Without distance-bar).

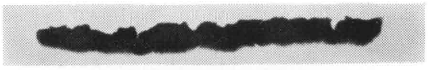


-2. In latter period of Stage-III (Without distance-bar).

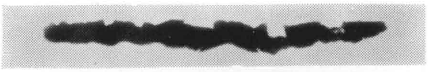
Photo. 15. Soft-X ray photographs of cross-section of fiberboard, relative to disappearance of low density part in interior during Stage-III.

-1. Stainless caul.

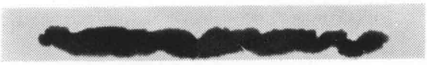
-2. Without preliminary cold-pressing.



-3. Cold-pressing 10 kp/cm²



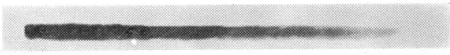
-4. Cold-pressing 20 kp/cm²



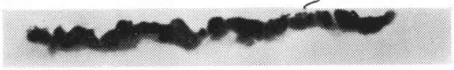
-5. Cold-pressing 30 kp/cm²

-6. Cold-pressing 50 kp/cm²

Photo. 16. Profiles of surface in smooth side of S1S fiberboard produced under various pressures of preliminary cold-pressing.
Condition of hot-pressing: 170 °C・50 kp/cm²・20 min.・2.5 3.0 kp/cm²/sec..
These photographs were projected by light section method,

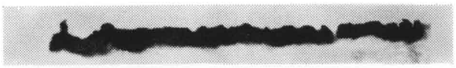


-1. Stainless caul



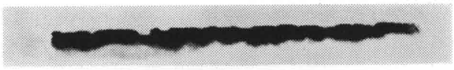
-2. 5.0 kp/cm²/sec.

-3. 4.3 kp/cm²/sec.



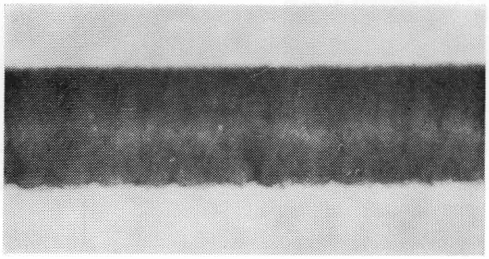
-4. 3.4 kp/cm²/sec.

-5. 1.9 kp/cm²/sec.

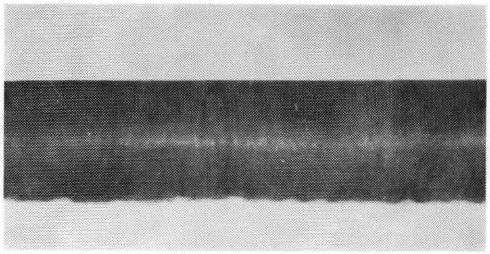


-6. 0.8 kp/cm²/sec.

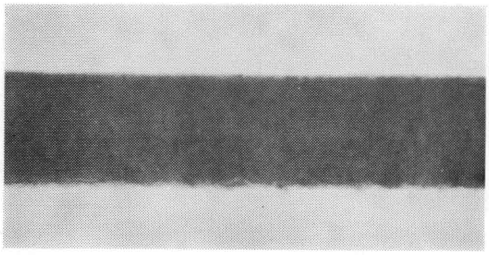
Photo. 17. Profiles of surface in smooth side of S1S fiberboard produced at various rates of application of pressure.
Condition of hot-pressing: 170 °C・50 kp/cm²・20 min..
Lateral magnification: ×130
Longitudinal magnification: ×190
These photographs were projected by light-section method,



-1. 5.0 kp/cm²/sec.



-2. 3.4 kp/cm²/sec.



-3. 0.8 kp/cm²/sec.

Photo. 18. Soft-X ray photographs of cross-section of fiberboard produced at various rates of application of pressure.
Condition of hot-pressing: 170 °C·50 kp/cm^2·20 min.

6. Conclusion.

Notwithstanding the hot-pressing process from the pulp mat to the fiberboard is one of the most important operations relative to the board properties and the economy of heat, the analytical or systematical investigation on the behavior of pulp mat during hot-pressing has never been brought out.

In this thesis, the mechanisms of the heat and mass transfer appearing in the pulp mat, the deformation behavior of internal structure of pulp mat, the mechanism of pressure relaxation and the dependence of relaxation on the main variables of hot-pressing were minutely investigated, namely, on the basis of their results, the complicated endowment with plasticity and drying-set during hot-pressing could be revealed and then the board formation process was drawn inferences from the board properties.

6.1. Mechanism of heat and mass transfer.

The heat and mass transfer during hot-pressing of wet pulp mat shows the same temperature transition as an unsteady temperature transition in the case of the general unsteady heat transfer, and it arrives at the steady state quickly under the lower temperature of hot platen than 100 °C, on the other hand, the heat and mass transfer can be divided into the following five stages in turn under the higher temperature of hot platen than 100 °C;

Stage—I : Early unsteady state of heat transfer.
Stage—II : Non-equilibrium evaporation of water in the interior.
Stage—III : Latent heat absorption of water in the middle layer.
Stage—IV : Latter unsteady state of heat transfer.
Stage—V : Steady state of heat transfer.

In the case of fiberboard formation, the interior part of wet pulp mat can be regarded as an intense heat transfer media, and the gradients of temperature (∇t), total pressure (∇p) and moisture content (∇u) refer to the heat and mass transfer in the pulp mat during hot-pressing, so the mass transfer potential is generally defined in a function of $f\ (t,\ p,\ u)$.

The analysis by means of the isochore curve of temperature (t)-entropy (S) relative to a vapor-liquid water media produces the consideration on the powerful effect of the filtration of pulp mat for the vapor generated in the interior on Stage—II. Particularly, under the higher pressure than 60 kp/cm^2, the filtration factor is greatly reduced with the result that the non-equilibrium evaporation becomes intense because of the diminution of variour gaps and voids for the emission of vapor due to the effect of gap-filling.

6.2. Deformation behavior of internal structure of pulp mat during hot-pressing.

The deformation behavior of internal structure of pulp mat during hot-pressing was minutely investigated with the aid of a reflex-microscope.

With increasing pressure, under the lower pressure than 30 kp/cm^2, the large gaps between fibers are noticeably reduced and the occupation ratio of fiber wall grows larger, however, the compressive cross-sectional deformation of fiber scarcely occurs. It certainly takes the most part of pressure energy to contract the large gaps in the pulp mat. Within the range from 30 to 50 kp/cm^2, after the gaps between fibers almost disappeared, the compressive cross-sectional deformation of fiber is increasingly enlarged with the result of the increase of occupation ratio of fiber wall and the diminution of lumina of fibers. Under the higher pressure than 50 kp/cm^2, the part of fiber wall squeezes itself into the minute voids between fibers as being subject to the extremely compressive deformation, so both the compressive deformation of fiber and the diminution of lumina reach the limiting with the result of the most densification of internal structure. The intensification of the non-equilibrium evaporation due to the noticeable decrease of filtration under the higher pressure than 60 kp/cm^2 can be proved to be a sort of structural characteristic relative to the geometry and the arrangement of fibers in the pulp mat.

As compared with the wood structure having the restraint effect between cells, the above-mentioned behavior of deformation smoothly progresses in the case of the internal structure of the defibrated fibers.

The bound water endows the fibers with moisture-plasticity with the result that it has a potent influence on the compressive deformation of fiber, on the other hand, the free water makes the macro-slippage between fibers remarkable and prolongs the duration of plasticity, so that it accelerates the packing effect fibers.

The frequency of fiber, having the wall which is cracked from the lumen in the radial direction, intends to increase under the lower pressure than 60 or 70 kp/cm^2 with increasing pressure.

The variation of the compressive deformation of fiber increases with mixing more fiber-bundles with the pulp mat, however, the variation intends to be reduced by mixing more single or fine fibers in the pulp mat, resulting in the gap-filling effect.

6.3. Mechanism of pressure relaxation and dependence of relaxation on main variables of hot-pressing.

The board formation process of hot-pressing consists of the following three manipulations, in short;

(1) Relaxation of cohesion.
Moisture (Swelling and hydration of fiber)
Heat (Endowment with thermo-plasticity)

(2) Molding.
Pressure (Deformation of internal structure, and construction of shape of board)

(3) Setting of fiber.

Heat (Irreversible setting of deformation, and drying of fiber)

In effect, these manipulation are caused complicatedly, simultaneously and continuously during practical hot-pressing of fiberboard, therefore, in order to make investigation into the behavior of the endowment with plasticity and drying-set during hot-pressing, the relaxation of pressure was minutely analyzed, referring to the heat and mass transfer and the deformation behavior of internal structure.

6.3.1 The mechanism of pressure relaxation.

In general, the visco-elasticity of solid polymer originates in the unit process of deformation due to the secondary bound network (van der Waals' force), therefore, the visco-elasticity can be represented in a model introducing the Eyring's net flow into the Maxwell's element and from the theory of Andrade's rate process derived from the Arrhenius' theorem, it is made clear that the rate ($-dP/d\tau$) of relaxation is proportional to the reciprocal ($1/\tau$) of time, where the constant (α) is a coefficient of relaxation rate which is regarded as an important factor for the analysis of relaxation. Herein, the relationship between $\log \alpha - \log \tau$ and the heat and mass transfer was expressed by means of the spectrum and then the pressure relaxation of pulp mat during hot-pressing was brought to light as follows;

1) Without the heat and mass transfer: The relaxation process consists of the initial relaxation due to the macro-slippage between fibers and the equalization of deformation of pulp mat in the direction of thickness, and the steady state of relaxation.

2) The heat transfer: The stage in which the relaxation rate develops into a great value appears newly.

3) The heat and mass transfer (Moisture-contained mat·lower temperature of hot platen than 100 °C and less moisture content of mat than 10 %·higher temperature of hot platen than 100 °C): The moisture in the pulp mat gives rise to the retardation of temperature transition with result that the insignificant thermo-plasticity is gradually reduced in the case of the former, while the considerable thermo-plasticity is caused by the rapid temperature transition in the case of the latter.

4) The heat and mass transfer (More than 10 %·higher than 100 °C): The following mechanism could be revealed, referring to the complicated change of the heat and mass transfer and the deformation behavior of internal structure during hot-pressing. After the macro-slippage between fibers and the equalization of deformation of pulp mat in the direction of thickness appear in the extremely early period of hot-pressing, in order, the considerable relaxation is caused by the thermo-plasticity and the rapid drying-set of face layers during Stage—I and —II, and then the relaxation is subject to resistance of high vapor pressure which is generated in the interior during Stage—II. In the next place, the retardation of temperature transition due to the latent heat absorption of moisture in the

middle layer turns down the appearance of thermo-plasticity, however, the relaxation increases because of the remarkable increment of compression shrinkage during Stage—III. After the evaporation is completed, the inner temperature begins to rise toward the hot platen temperature again, so the plastic flow is markedly induced by the thermo-plasticity under the high temperature during Stage—IV. Thus, achieving the macro-deformation of internal structure, the thermo-plasticity and the drying-set of fibers, the relaxation arrives at the steady state somewhate before the end of Stage—IV.

6.3.2. The dependence of board formation on the main variables of hot-pressing.

The effects of main variables of hot-pressing on the board formation were investigated by analyzing the heat and mass transfer, the deformation behavior of internal structure and the relaxation of pressure.

1) Hot platen temperature: The relationship between log α and 1/T was derived from the Andrade's rate process based on the Arrhenius' theorem.

In the case of wet pulp mat hot-pressed under the higher temperature of hot platen than 150 °C, the rapid appearance of thermo-plasticity and drying-set of thin face layers reduces the macro-slippage between fibers and the equalization of deformation of pulp mat in the direction of thickness, moreover, the retardation of temperature transition due to the relatively rapid evaporation of water in the face layers turns down the endowment with thermo-plasticity of interior part, with the result of the significant impediment to the pressure relaxation. Such a phenomenon appears under the higher temperature of hot platen than 200 °C in the case of the mat having the moisture content of the fiber saturation point and under the higher than 170 °C in the case of the mat containing the more moisture than the fiber saturation point.

Under the control of the complicated mechanism during Stage—II, III and IV, the considerable relaxation progresses for a short time, resulting from the good supply of heat per unit time with rising the temperature of hot platen.

In the case of oven-dried mat, the relationship between log α and 1/T can be represented in a straight line having the greatest gradient with the consequence that the energy of activation for thermo-plasticity shows the largest value.

2) Initial pressure: The relaxation closely relates to the deformation behavior of internal structure caused by the initial pressure. With increasing the initial pressure, many of plastic flow and drying-set elements are still contained in the internal structure of pulp mat so that the relaxation is very large under the lower initial pressure than 30 kp/cm^2, and then the plastic flow and drying-set elements are increasingly set by the application of pressure with result of the noticeable relaxation within the range from 30 to 50 kp/cm^2, furthermore, the setting of plastic flow or the irreversible deformation is nearly completed so that the relaxation approachs the limiting under the higher pressure than 50 kp/cm^2.

3) Water: The effect of water-plasticity on the constituent fibers evidently

grows larger under the less moisture content of pulp mat than 10 % with increasing moisture before hot-pressing, however, under the more than 10 %, the resistance of water as a volatile plasticizer to the temperature transition retards the thermo-plasticity of fiber, so the greatest increment of the coefficient plasticity between heat and water is observed in the case of the mat containing the moisture of about 10 %.

4) Rate of application of pressure: The following of flow and deformation of fibers to the pressure is greatly subject to the influence of the rate of application of pressure, furthermore, it participates in the whole behavior of plasticity and drying-set during hot-pressing.

With increasing the rate of application of pressure, the macro-slippage between fibers and the equalization of deformation of pulp mat in the direction of thickness are mostly accelerated during the application of pressure. The tendency is promoted as a result of the water-plasticity of fiber and the lubrication effect of water, so the plastic flow elements due to the thermo-plasticity fully follows to the pressure and then the remaining plastic flow elements remarkably responds to the relatively highp ressure. The above-mentioned phenomenon tends to become more apparent in the case of the moisture-contained mat than in the case of the oven-dried mat.

The process of board formation during hot-pressing can be analyzed as follows;

(1) The substantial relaxation of a sort of visco-elastic body.
(2) The relaxation behavior of macro-structural unit.
(3) The latent heat absorption of water and the drying-set caused by the heat and mass transfer (The irreversible deformation or the compression shrinkage of fiber)
(4) The deterioration of fiber by heat.

Thus, such an analysis of hot-pressing behavior involves the elementary investigation on the positive manipulations for the board formation, the accuracy or proper control of hot-pressing variables and the improvement in board properties.

6.4. Effects of behavior of pulp mat during hot-pressing on board properties.

6.4.1. With respect to the growth of board properties during hot-pressing with changing the mechanism of the heat and mass transfer, the thin drying-set layers rapidly appear in both the faces of pulp mat during the extremely early period of hot-pressing and then the thickness of drying-set layers toward the interior is greatly enlarged, however, the middle layer is still in the state of wet pulp mat. The drying-set and the bonding between fibers grow larger during Stage—III, on account of the evaporation of water in the middle layer.

The improvement in property of middle layer of pulp mat is somewhate due to the drying-set and the effect of heat-treatment during the first half of Stage—IV and then the board properties change little from the latter half of Stage—IV, because of the completion of most irreversible deformation, plastic flow and drying-set of constituent fibers in the pulp mat.

6.4.2. It is essential for the improvement in board properties in the case of hot-pressing process to give rise to the macro-slippage between fibers and the equalization of deformation of pulp mat in the direction of thickness during the extremely early period of hot-pressing, therefore, the preliminary cold-pressing makes appreciable progress in their macro-structural deformation with the result that the plasticity and the drying-set can be greatly achieved during hot-pressing.

6.4.3. With increasing the bound water contained in the pulp mat before hot-pressing, the fibers become more plastic and the effective bonding area between fibers is increasingly enlarged during hot-pressing, on the other hand, the lubrication effect of free water has a favorable influence on the packing behavior of fibers, additionally, the free water is able to compensate for the reduction of water-plasticity caused by the rapid diffusion and evaporation of water during hot-pressing.

Herein, in the case of the mat containing free water, while the plasticity and the drying-set are greatly promoted under the relatively lower temperature of hot platen, the super-heated water which is generated by the intensely or long non-equilibrium evaporation intends to deteriorate the constituent fibers under the relatively lower temperature of hot platen.

6.4.4. The initial pressure necessarily has a potent influence on the deformation behavior of internal structure of pulp mat, however, the higher initial pressure than 60 kp/cm^2 results in the deterioration of fiber by the superheated water which is generated in the interior by the severe reduction of filtration of pulp mat.

In the case of much free water-contained mat, the available plasticity and drying-set improve in board properties owing to prolonging the duration of water-plasticity and the coefficient plasticity of water with heat due to the super-heated water which is generated by the intensely non-equilibrium evaporation, under the relatively low pressure, while the coefficient behavior causes the deterioration of constituent fibers under the relatively high pressure.

6.4.5. The macro-slippage between fibers and the equalization of deformation of pulp mat in the direction of thickness more smoothly follow to the pressure with increasing moisture content of pulp mat, because of the water-plasticity or the lubrication effect of free water. In particular, the board is improved in its properties by the densification of whole board, least of middle layer, with decreasing rate of application of pressure.

Literature

1) Anisimov, S. I. & Perelmann, T. L.: On the Investigation of Heat Transfer in Presence of Chemical Conversions. Int. J. Heat Mass Transfer, 1, pp. 269～272 (1961).
2) Arther, C., J. R. Dreshfield & Han, S. T.: The Drying of Paper. Tappi, 39, 7, pp. 449～455 (1956).
3) Asklöf, C. A., K. O. Larsson & Wahlström, P. B.: Studies on Compressibility and Drainage Resistance of Wet Paper Webs. Pulp and Paper Magazine of Canada, 12, pp. T-339～T-347 (1964).
4) Back, E. L.: The Pore Anisotropy of Paper Products and Fiber Building Boards. Svensk Papperstidn., 7, pp. 219～224 (1966).
5) Back, E. L. & Klingo, L. O.: Reactions in Dimensional Stabilization of Paper and Fiber Bilding Board by Heat Treatment. Svensk Papperstidn., 19, 15, pp. 745～753 (1963).
6) Baird, P. K.: Effect of Molding Temperature on the Strength and Dimensional Stability of Hardboards from Fiberized Water-Soaked Douglas-Fir Chips. F. P. R. S., 16, pp. 322～326 (1950).
7) Brauns, O. & Strand, A.: Värmebehandlung av harda träfiberskivor. Svensk Papperstidn., 14, 31, pp. 437～444 (1958).
8) Bueche, F.: Physical Properties of Polymers. Interscience Publishers, pp. 251～253 (1962).
9) Carslow, H. S. & Jaeger, J. C.: Conduction of Heat in Solids. Oxford, at the Clarendon Press, pp. 421～425 (1959).
10) Chukhanov, Z. F.: Heat and Mass Transfer between Gas and Granular Material. Int. J. Heat Mass Transfer, 6, pp. 691～701 (1963).
11) Cowan, W. F.: The Mechanism of Hot-Surface Drying. Tappi, 47, 12, pp. 808～811 (1964).
12) Crawford, F. H.: Heat, Thermodynamics, and Statistical Physics. Harcourt, Brace & World, Inc., pp. 62～65 (1963).
13) Croot, S. R.: Thermodynamics of Irreversible Processes. Northholland, Amsterdam, pp. 102～110 (1952).
14) Delmonte, J.: Plastics Molding. Reinhold Publishing Co., pp. 125～132 (1951).
15) Didriksson, E. E. & Back, E. L.: The Effect of Density on the Pore Size and Pore Anisotropy of Fiber Building Board. Svensk Papperstidn., 22, pp. 769～771 (1966).
16) ДЕНИСОЕ О В, СОСНИН М И: Особенности изменения температуры и давления пара в древесностружечных плитах большого формата при их прессовании. Деревообрабатывающая Пром 16[8] 11('67).
17) Enomoto, S. & Kojima, K.: Studies on the Mechanism of Dry Process Board Formation. I. J. of Japan W. R. S. 12, 6, pp. 282～285 (1966).
18) Enomoto, S. & Kojima, K.: ibid., II. 12, 6, pp. 286～289 (1966).
19) Enomoto, S. & Kojima, K.: ibid., III. 13, 2, pp. 52～55 (1967).
20) Enomoto, S. & Ko(ima, K.: ibid., IV. 13, 2, pp. 56～59 (1967).
21) Eucken, A.: Die Warmeleitfähigkeit keramische feuerfester Stoff, Ihr Berechnung aus der Warmeleitfähigkeit der Bestandteile. VDI-Forsch-Heft 353, pp. 1～20 (1932).
22) Felton, C. D., M. C. Botty & Clark, J. J.: Microscopical Techniques for the Investigation of the Structure of Paper. Tappi, 45, 8, pp. 618～622 (1962).
23) Fujii, Y.: The visco-elasticity of paper (3), Tappi of Japan, 11, 72, pp. 188～192 (1957).
24) Fukuhara, T.: The Study on Compressive Deformation Perpendicular to Grain. Research Bul. of Tokyo Univ. Forests, 61, pp. 103～197 (1967).
25) Gaber, E.: Druckversuche quer zur Faser an Nadel- und Laubholzern. Holz als Roh- und Werkstoff, 3, pp. 103～111 (1937).
26) Goring, D. A. I.: Thermal Softening of Lignin, Hemicellulose and Cellulose. Pulp and Paper Magazine of Canada, 12, pp. T-517～T-527 (1963).
27) Gurnham, C. F. & Masson, H. J.: Expression of Liquids from Fibrous Materials. Ind. and Eng. Chem., 38, 12, pp. 1309～1324 (1964).
28) Hamelink, J.: The Effect of Fiber Distribution upon Stiffness of Paper Board. Tappi,

46, 10, pp. 151 A～153 A (1963).
29) Han, S. T.: Heat and Mass Transfer in Hot Surface Drying of Fiber Mats. Pulp and Paper Magazine of Canada, 12, pp. T-537～T-549 (1964).
30) Hart, J. A., J. Verhoeff & Gallay, W.: A New Method for Measuring the Surface Roughness of Paper. Pulp and Paper Magazine of Canada, 7, pp. T-387～T 392 (1962).
31) Hisey, R. W.: An Investigation of the Mechanism of the Dewatering of Compressible Bed. Tappi, 39, 10, pp. 690～696 (1956).
32) Ingmanson, W. L.: Filtration Resistance of Compressible Material. Chem. Eng. Pro., 49, 11, pp. 577～584 (1953).
33) Johnson, K. O.: Moisture and Temperature Distributions during Drying of Insulation Board. Tappi, 44, 1, pp. 599～605 (1961).
34) Jone, R. L.: The Effect of Fiber Structural Properties on Compression Response of Fiber Beds. Tappi, 46, 1, pp. 20～28 (1963).
35) Kamada, H.: On the Manufacturing of Hardboard I. Wood Industry, 6, 12, pp. 554 (1952).
36) Kanamaru, K. & Hukazawa, Y.: The Properties of High Polymer on the Formation. J. Ind. Chem. of Japan, 63, 3, pp. 369～405 (1960).
37) Katayama, K. & Kitabatake, N.: The Mechanics of Material II. Korona-sha, pp. 274～276 (1954).
38) Kauman, W. G.: On the Deformation of Setting of the Wood Cell Wall. Holz als Roh- und Werkstoff, 24, 11, pp. 551～556 (1966).
39) Kazansky, M. F., P. P. Lutsick & Oleynikov, V. N.: Non- Stationary Temperature and Moisture Content Fields of Porous Bodies in the Convective Heat Transfer Process. Int. J. Heat Mass Transfer, 2, pp. 231～236 (1961).
40) Kern, D. Q.: Process Heat Transfer. McGrowhill B. C., pp. 93～125 (1950).
41) Keylwerth, R.: Über das Heisspressen von Holz. Holz als Roh- und Werkstoff, 22, 11, pp. 417～415 (1961).
42) Kitahara, K.: The Studies on the Hardboard, V. Wood Industry (Japan), 6, 4, pp. 161～164 (1952).
43) Kitahara, K.: Stress Relaxation of Chip-board in Hot- Press. Bul. of Tokyo Unv. Forests, 53, pp. 161～177 (1957).
44) Klauditz, W. & Stegmann, G.: Über die grundlegen chemischen und physikalischen Borgange bei der Wärmevergutung von Holzfaserplatten. Holzforschung, 5, 3, pp. 68～74 (1951).
45) High Polymer Research Society: The Plastic Material of Formation, Chijinsha, pp. 7～10 (1965).
46) High Polymer Research Society: The Physical Properties of High Polymer, I. Kyoritsu-shuppan, pp. 29～42 (1961).
47) The editorial Staff Member of the Siries of Industrial Measurement: Temperature. Nikkankogyo, pp. 13～16 (1964).
48) Kollmann, F. & Dosoudil, A.: Holzfaserplatten. VDI-Forschungsheft, 426, pp. 1～32 (1949).
49) Kotake, F.: Organic Chemistry, 19. Asakura-shoten, pp. 174～181 (1961).
50) Kunesh, R. H.: The Inelastic Behavior of Wood, A New Concept for Improved Panel Forming Process. F. P. J., 11, 9, pp. 395～406 (1961).
51) Lehtinen, A.: Microtome Sectioning in the Analysis of Paper Structure. Pulp and Paper Magazine of Canada, 4, pp. 200～208 (1964).
52) Luikov, A. V.: Heat and Mass Transfer in Processes of Drying. Gosenergoizdat, Moscow and Leiningrad, pp. 13～21 (1956).
53) Luikov, A. V.: Heat and Mass Transfer in Capillary-porous Bodies. Pergamon Press, pp. 348～349 (1966).
54) Lund, L. M. & Bermann, A. S.: Flow and Self-diffusion of Gas in Capillary. I. J. Applied Physics, 37, 6, pp. 2489～2508 (1966).
55) Maku, T. & Hamada, R. & Sasaki, H.: The Studies on Particleboard, IV. Wood Research, 34, pp. 24～33 (1959).

56) Mataki, Y. & Ōta, M.: The Studies on the Mechanism of Thermal Conversion in the Pulp Sheet during Hot-Pressing of Fiberboard, I. J. of Japan Wood Research Society, II, 1, pp. 14～18 (1965).

57) Mataki, Y. & Ōta, M.: ibid., II. 12, 1, pp. 30～36 (1966).

58) Mataki, Y. & Ōta, M.: ibid., III. 12, 3, pp. 128～134 (1966).

59) Mataki, Y. & Ōta, M.: ibid., IV. 13, 2, pp. 46～52 (1967).

60) Mataki, Y. & Ōta, M.: ibid., V. 13, 5, pp. 188～193 (1967).

61) Mataki, Y. & Ōta, M.: ibid., VI. 13, 8, pp. 331～335 (1967).

62) Mataki, Y. & Ōta, M.: ibid., VII. 14, 2, pp. 80～85 (1968).

63) Mataki, Y. & Ōta, M.: ibid., VIII. 14, 2, pp. 86～90 (1968).

64) Matsuda, T· & Sano, Y.: Temperature during Hot-Pressing of Dry-Processed Hardboard. The 13th Japan Wood Research Society, pp. 161～162 (1963).

65) Mikhailov, Y.: Hightly Intensive Heat and Mass Transfer in Dispersed Media. Int. J. Heat Mass Transfer, 1, pp. 37～45 (1960).

66) Miyauchi, T., T. Hayashi, Watanabe, M. & Sugiyama, K.: Temperature Measurement and Automatic Control. Korona-sha, pp. 252～259 (1962).

67). Morita, Y.: Measurement of Heat Transfer Constant of Moisture-Contained Insulation Material. J. of Japan Eng. Mechanics, 62, 484, pp. 1177～1183 (1959).

68) Nakagawa, T. & Kanbe, H.: Rheology. Misuzu-shobo, pp. 457～486 (1959).

69) Nielsen, L. E.: Mechanical Properties of Polymers. Reinhold Publishing Co., pp. 168～175 (1962).

70) Nissan, A. H. & Sternstein, S. S.: Cellulose-Fiber Bonding. Tappi, 47, 1, pp. 1～6 (1964).

71) Nordon, P. & McMahon, G. B.: The Theory of Forced Convective Heat Transfer in Beds of Fine Fibers, I. Int. J. Heat Mass Transfer, 6, pp. 455～565 (1963).

72) Ōga, T. & Okagaki, O.: Thermal Conductivity of Porous Materials with Moisture Content. Bull. of Eng. Department of Hokkaido Univ., 6, pp. 219～232 (1951).

73) Okada, G.: Chemistry of Cellulose. Shibun-do, pp. 199～311 (1943).

74) Ōkuma, M. & Yoshida, A.: The Effect of Moisture-Contained in Mat during Hot-Pressing of Hardboard on its Mechanical Properties. J. of Japan Wood Research Society, 10, 6, pp. 226～229 (1964).

75) Onogi, S.: The Rheological Studies of Paper. Tappi of Japan, 11, 73, pp. 218～220 (1962).

76) Onogi, S. & Sasaguri, K.: The Elasticity of Paper and Other Fibrous Sheets. Tappi, 44, 12, pp. 874～880 (1961).

77) Ōta, M., J. Hwang & Mataki, Y.: The Studies on Hot-Pressing Mechanism of Fiberboard V. The 15th Japan Wood Research Society, p. 55 (1965).

78) Ōta, M., J. Tsutsumi & Koga, T.: Studies on the Manufacturing Conditions of Hardboard from HIMESHARA. Bul. of Kyushu Univ. Forests, 15, pp. 187～199 (1961).

79) Ōta, M. & Mataki, Y.: ibid., III. 36, pp. 105～116 (1962).

80) Ōta, M. & Mataki, Y.: ibid., IV. 37, pp. 235～242 (1964).

81) Ōta, M., Y. Mataki & Hwang, J.: The Effect of Moisture Content on Interior Temperature Transition and Board Properties. The 14th Japan Wood Research Society, p. 64 (1964).

82) Ōta, M., T. Togami & Mataki, Y.: The Transition of Temperature at Various Positions in the Particleboard Measured during Manufacture, and the Relation between Hot-press Cycle and its Properties. The Reports of the Kyushu Univ. Forests, 17, pp. 1～8 (1962).

83) Ralko, A. V.: The Experimental Investigation of Heat and Mass Transfer in the Presence of Chemical Conversions. Int. J. Heat Mass Transfer, 6, pp. 273～279 (1961).

84) Runkel, O. H.: Zur Kentnis des Thermoplastischeen Verhaltens von Holz, I. Holz als Roh- und Werkstoff, 9, 2, pp. 41～53 (1951).

85) Saito, T. & Okagaki, O.: Characteristics of Thermal Conductivity of Moisture-Contained Materials. J. of Japan Eng. Mechanics, 62, 484, pp. 741～747 (1958).

86) Sakurai, T.: The Mechanics of Material. Sangyo-tosho, pp. 178～180 (1965).

87) Segring, S. B.: Die Pressung von Hartfaserplatten. Holz als Roh- und Werkstoff, 15, 1, pp. 1~8 (1957).
88) Severs, E. T.: Rheology of Polymers. Reinhold Publishing Co., pp. 17~18 (1962).
89) Shiba, K.: Temperature. Korona-sha, pp. 62~91 (1961).
90) Skark, L.: Zur Kinetik der Druckentwasserung an Holzfaserstoffen. Holzforschung, 3, 3, pp. 76~85 (1948).
91) Sonnleitner, E.: Forschungsbereichte Holz. 1, pp. 23~35 (1932).
92) Stamm, A. J.: Wood and Cellulose Science. The Ronald Press co., pp. 317~320 (1964).
93) Sugawara, A.: On Thermal Conductivity of Porous Materials. J. of Japan Applied Physics. 30, 1, pp. 17~23 (1961).
94) Suzuki, I.: Fundamental Physical and Chemical Research on Raw Materials for Fiber-board (V). Bul. of The goverment Forest Exp. Station, 199, pp. 110~140 (1967).
95) Schwartz, S. L.: Preparation of Hardboard from White Oak. Tappi, 36, 10, pp. 80~88 (1953).
96) Takamura, N.: Studies on Hot-Pressing and Drying Process in the Production of Fiber-board (I). Bul. of the Goverment. Forest Exp. Station, 144, pp. 123~144 (1962).
97) Takamura, N.: ibid., (II). Bul. of the Goverment Forest Exp. Station, 199, pp. 141~159 (1967).
98) Tanishita, I.: The Industrial Thermodynamics. Shokabo, pp. 105~132 (1963).
99) Tiller, F. M.: The Role of Porosity in Filtration. ,Chem. Eng. Pro., 49, 9, pp. 467~479 (1953).
100) Turner, H. D., J. P. Hohf & Schwartz, S. L.: Effect of Some Manufacturing Variables on the Properties of Fiberboard Prepared from Milled Douglas-Fir. F. P. R. S., 14, pp. 100~112 (1948).
101) Watanabe, H. & Tanaka, H.: Studies on Dry Process Hardboard Manufacturing (I). J. of Japan Wood Research Society, 11, 3, pp. 92~98 (1965).
102) Watanabe, H. & Tanaka, H.: ibid., (II). 11, 3, pp. 98~103 (1965).
103) Wilcox, H.: Interrelationships of Temperature, Pressure and Pressing Time in the Production of Hardboard from Douglas-Fir Fiber. Tappi, 36, 2, pp. 89~94 (1953).
104) Wilder, H. D.: The Compression Creep Properties of Wet Pulp Mats. Tappi, 43, 8, pp. 715~720 (1960).
105) Yagi, S. & Kunii, D.: Effective Heat Transfer in a Packed Bed. Chem. Eng. of Japan, 18, 576, pp. 576~585 (1954).
106) Yamabayashi, S.: Anatomy of Wood. Morikita-shuppan, pp. 38~84 (1962).
107) Yamai, R.: On the Stress-Strain Curve of Wood (I). Bul. of the Gov. Forest Exp. Station, 77, pp. 103~152 (1955).
108) Yokobori, S. & Kuga, O.: Basic Heat Transfer Engineering (Giedt, W. H.). Maruzen, pp. 93~97 (1961).
109) Zabrodsky, S. S.: Heat Transfer between Solid Particles and a Gas in a Non-Uniformly Aggregated Fluidized Bed. Int. J. Heat Mass Transfer, pp. 23~31 (1963).

Résumé

A knowledge of the behavior of a pulp mat during hot-pressing is fundamental to the formation process of fiberboard. Suitable control of hot-pressing is essential for control of board properties.

This paper is concerned with the mechanism of heat and mass transfer, the internal structure, and the relaxation mechanism of pressure, which occur in the pulp mat during hot-pressing.

It has been observed that the plastic behavior and drying is partially responsible for the improvement of board properties.

I. The process of heat and mass transfer in the wet pulp mat during hot-pressing can conveniently be divided into the following stage:

I. Early non-steady stages.
II. Non-equilibrium state between water evaporation and vapor extrication.
III. Latent heat absorption of water in middle layer.
IV. Late non-steady state.
V. Steady state.

Using the entropy concept from thermodynamics, it was found that the filtration of the mat for generated vapor has a remarkable influence on Stage—II.

Such a filtration of the mat is dependent on the geometry of the constituent fibers and then arrangement in the pulp mat. Consequently, the extent of heat-moisture media chemically affects the properties of the board.

II. By measuring the deformation of fibers and structural elements in the fiberboard with the aid of a reflex-microscope and soft-X ray, the following results were obtained.

With the increase of pressure, the larger gaps between fibers decrease markedly. Secondly, the cross-section of the fiber undergoes external compression stress. In the latter stage of pressure application, the gaps between fibers and compressive deformation of the fiber reach a limit. At this stage the mass density reaches a maximum. Such behaviour can be explained by a theory of packed structure.

III. Using the theory of heat and mass transfer and the change of internal structure, the relaxation of specific pressure during hot-pressing was analyzed.

The unit process of deformation force in the fiber network is viscoelastic. Consequently, the relaxation during hot-pressing can be represented by a model which is constructed by means of introducing Eyring's net flow to the Maxwell element. As a result, the macro-slippage between fibers proceeds early after the application of a given specific pressure, the spectrum of rate coefficient of relaxation depends primarily on the factors of hot-pressing.

Because the pulp mat is visco-elastic, its compressive deformation is influenced by the rate of application of pressure. Therefore, cold-prepressing brings results in the improved properties of the board. Macro-slippage between fibers occurs with the equalization of mat deformation in the direction of thickness. This process occurs early after the application of a given specific pressure.