J Wood Sci (2002) 48:309–314

ORIGINAL ARTICLE

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Effects of press closing time on mat consolidation behavior during hot pressing and on linear expansion of particleboard

Received: June 1, 2001 / Accepted: August 29, 2001

Abstract Mat consolidation behavior was investigated at various press closing times (PCTs) using hinoki (Japanese cypress) particle mats. The temperature in the core layer of the mat, press pressure, and platen distance were measured. At the plateau stage during hot pressing, the core temperature decreased with increasing PCT. The core temperature did not increase before the platen distance equaled the target board thickness in the PCT range of 4–50 s and rose slightly when the PCT exceeded 100 s. There was a linear relation between the logarithm of PCT and the maximum press pressure. The density profile across board thickness was strongly affected by the PCT. As the PCT increased, the position of the peak density (PD) moved toward the core layer as the PD itself decreased. The effect of PCT on the linear expansion (LE) of the board is discussed in relation to the density profile. There was no difference in LE after high relative humidity treatment in the PCT range 4–50 s. LE appeared to be related to the low density and the precured region of the board surface. The LE after drying treatment was around −0.1%, and the thickness swelling after high relative humidity and drying treatments increased with increasing PCT.

Key words Particleboard · Press closing time · Linear expansion · Thickness swelling · Density profile

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Part of this report was presented at the 51st Annual Meeting of the Japan Wood Research Society, Tokyo, April 2001

Introduction

Mat-formed wood composites are subjected to heat and pressure during their manufacture, and various factors affect mat consolidation behavior during hot pressing. Some researchers have investigated and modeled the rheological behavior of the mat. Suchsland[1] modeled the pressure relaxation of the mat during pressing, and Arima[2] determined the stress relaxation experimentally. Oudjehane et al.,[3] and Dai and Steiner[4] modeled the compressive behavior. Heat, moisture, and pressure as a function of pressing time and location have also been investigated[5–8] to understand what happens inside a mat during pressing. For instance, Kamke and Casey[9,10] investigated the effects of press temperature and initial moisture content on gas pressure and temperature inside a flake mat. One area of interest regarding the mat consolidation process is the formation of the density distribution across the thickness of the board and evaluating how it affects the physical and mechanical properties of mat-formed panel products.

Press closing time (PCT) is one of the important parameters affecting the density profile and properties of particleboard.[11] A longer PCT means that more stress relaxation may occur before the final thickness is achieved, and this affects heat transfer, moisture distribution inside the mat, the rate of adhesive cure, and so on. Fukino et al.[12] reported that shortening the effective pressing time reduced the thickness swelling (TS) of strand particleboard. However, compared with the number of studies examining the dimensional stability of thickness, there have been fewer studies of the relation between linear expansion (LE) and pressing parameters.[13,14]

In this study, we focused on the PCT as a parameter of mat consolidation behavior. The objectives of this study were to obtain information on mat consolidation behavior during hot pressing at different PCTs and to evaluate the effect of PCT on the LE of laboratory-made particleboard by measuring its change with time under high relative humidity.

Materials and methods

Particle preparation and board fabrication

Hinoki (*Chamaecyparis obtusa* Endl.) particles with an air-dried density of 0.41 g/cm^3 were prepared from disk-flaked strands by hammer-milling and screening to remove fines. The particles used were mainly those remaining on the 5-mesh (36%) and 10-mesh (40%) sieves. The particles were dried to a moisture content of about 2% before glue spreading.

Homogeneous boards 340 × 320 × 10 mm were fabricated at a target density of 0.65 g/cm^3 under seven press speed conditions. PCT was defined as the time required for the press platens to reach the target board thickness of 10 mm from a mat height of 70 mm; it ranged from 4 to 900 s in this study. The pressing time after the press platen reached the target thickness was always 7.5 min. The platen temperature was 180°C. A liquid PF resin was applied at 8% resin content based on the oven-dried weight of the particles. Wax was not applied. Two or three replicate boards were fabricated at each PCT. The mat moisture content before hot pressing was about 11.7%. The temperature inside the mat was measured by placing a thermocouple in the center of the core layer during hot pressing. The platen distance, press pressure, and temperature were recorded at intervals of less than 0.05 s.

Measuring changes in dimensions

After pressing, the boards were conditioned at 25°C and 65% relative humidity (RH). As a pretreatment, 50 × 300 mm specimens were dried in an air-circulating dryer at 60°C for 24 h. High relative humidity treatment at 40°C and 90% RH for 200 h was used to evaluate the dimensional stability of the boards. Three specimens were tested for each condition. After treatment, the specimens were dried at 60°C in an air-circulating dryer until equilibrium was reached. In this study, practical equilibrium was defined as the state in which the change in weight during a 24-h period did not exceed 0.1%. Specimen length was measured at intervals using the equipment specified in the ASTM standard.[15] LE, TS, and weight change (WA, water absorption) were calculated from the initial measurements of specimens dried at 60°C before treatment.

Mechanical properties and density profile

The modulus of elasticity (MOE) and modulus of rupture (MOR) in bending and the internal bond strength (IB) were obtained according to the Japanese Industrial Standard.[16] Five 300 × 50 mm specimens were prepared for the bending test, and ten 50 × 50 mm specimens were prepared for the IB test. Before the IB test the density profile across board thickness was measured by gamma ray densitometry using a commercial density profiler.

Results and discussion

Effect of PCT on mat consolidation behavior

The temperature change with time in the core layer of the mat during hot pressing showed typical behavior, similar to that reported by Bolton et al.[6] and others.[9,17] It was characterized by a rapid temperature rise during the early stage of hot pressing, a plateau stage, sometimes followed by a small decrease and then a gradual increase until press opening. Figure 1 shows the relation between PCT and plateau temperature. In this study, the plateau temperature was defined as the temperature at which the rate of temperature rise became zero or negative. The plateau temperature decreased from 117°C to 105°C as the PCT increased from 4 s to 900 s. The plateau temperatures of 117 and 105°C corresponded roughly to vapor pressures of 0.18 and 0.12 MPa, respectively. The plateau temperature in the core layer was affected by the rate of water vapor gain from the layers close to the platens and by the rate of lateral vapor loss; it was thought that vapor could leak out through the edges of the mat when the PCT was long enough. These results indicated that the PCT significantly affected the temperature and vapor conditions inside the mat.

Figure 2 shows the relation between the temperature at the center of the mat and the platen distance during pressing. In the PCT range of 4–50 s, the core temperature did not rise until the platen distance equaled the target thickness of the board. For a PCT of 100 s, the core temperature began to increase gradually before the target thickness of 10 mm was reached. The platen distance at which the core temperature started to rise increased with the PCT. During hot pressing, heat transfer from the platens to the core layer depends on both heat conduction and heat convection. During the early stage of pressing, the mat is extremely permeable owing to the existence of a large void volume

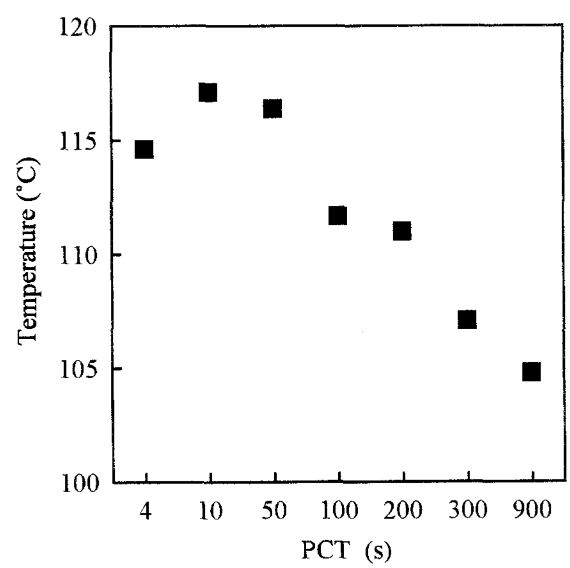

Fig. 1. Relation between press closing time (*PCT*) and plateau temperature during hot pressing of the particle mat

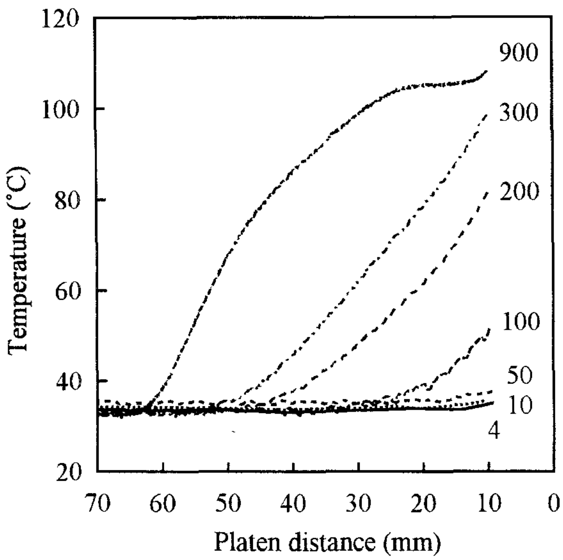

Fig. 2. Relation between the temperature in the core layer of the mat and platen movement from a mat height of 70 mm to the target board thickness of 10 mm. *Numbers* show the PCT condition

that allows water vapor to move freely toward the mat core layer, and water vapor readily leaks out through the edges of the mat. Therefore, because the vapor pressure inside the mat does not rise during the early stage of pressing, the heat transfer depends on heat conduction rather than heat convection when the PCT is prolonged. When the PCT was 900 s, the core temperature exceeded 100°C before the platen distance equaled the target board thickness. This high core temperature during hot pressing can be explained by various factors, such as conductive heat transfer, large vapor pressure, and an exothermic reaction involving the resin.[6] The main factor affecting the core temperature is conductive heat transfer from the platens. It is thought that for a PCT of 900 s the resin in the core layer started to cure before the platens reached the target thickness.

Pressure behavior during hot pressing was also monitored, and the results are shown in Fig. 3 for each PCT examined. The pressure curve had a nonlinear shape characterized by a long initial low-pressure stage and a steep exponential rise toward the maximum value. For a PCT of 300 s, the times at which the pressure reached 25%, 50%, and 75% of its maximum value were approximately 250, 280, and 290 s, respectively. Although it is difficult to see the shape of the curves for shorter PCTs in Fig. 3, the pressure behavior was similar when these curves were scaled to the platen distance.

The relation between PCT and the maximum pressure during hot pressing is shown in Fig. 4. There was a linear relation between the maximum press pressure and the logarithm of PCT for PCTs of 4–300 s. The maximum pressure decreased by about 20% for each 10-fold increase in PCT. The strength properties of solid wood, including the transverse compressive elasticity and strength, decrease linearly with the logarithm of the loading rate.[18] It was approximated at 5%–10%. The compressive behavior of a particle mat cannot be explained by the mechanical properties of solid wood alone. In addition, stress relaxation under non-steady-state heat and moisture transfer both inside the mat and in the wood particles themselves should both be considered in the future.

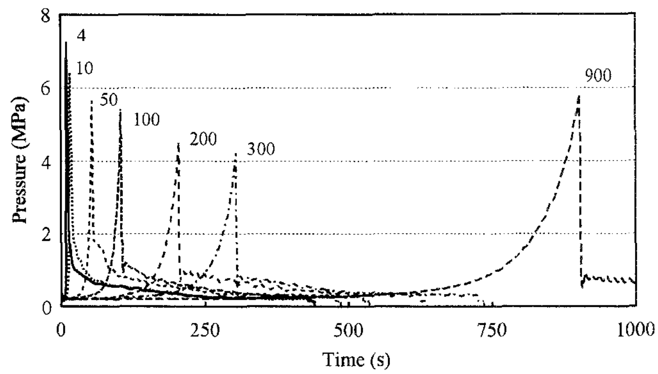

Fig. 3. Pressure behavior during hot pressing of the mat under various PCT conditions. *Numbers* show the PCT condition

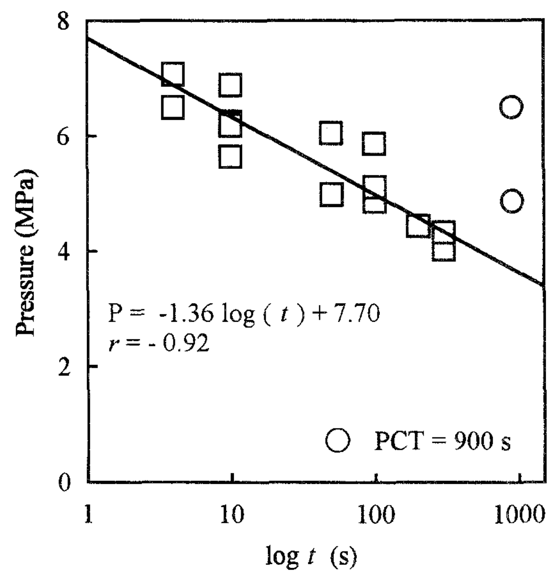

Fig. 4. Relation between PCT and maximum press pressure

On the other hand, the maximum pressure obtained for a PCT of 900 s was regarded as an exception to this relationship because of the different compressive behavior, as shown in Fig. 2. It is thought that temperatures higher than 100°C reduce the mat moisture content, lowering the plasticity of the particles and increasing resistance to compression. In a simulation, Bolton et al.[7] found that the core moisture content of the mat began to decrease at over 500 s, even after the platens reached the target thickness.

Effect of PCT on mechanical properties

Figure 5 shows the density profiles of boards at different PCTs. Wong et al.[11] examined various density profile-defining factors in detail, including peak density (PD) and core density (CD). As shown in Fig. 5, the PD decreased with increasing PCT, and the position of the PD moved

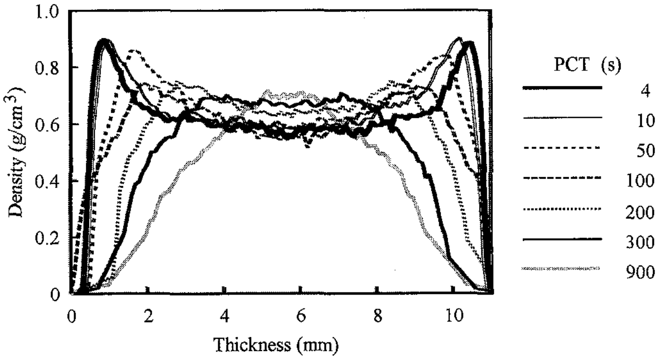

Fig. 5. Effect of PCT on the density profile across board thickness

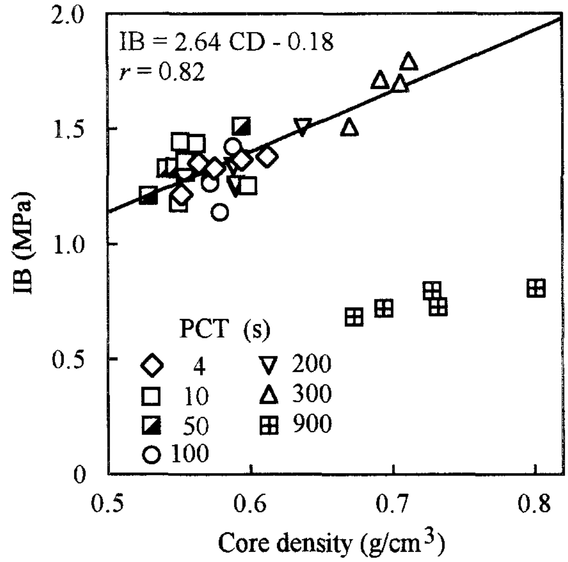

Fig. 6. Relation between core density and internal bond (*IB*) strength of particleboard

toward the center layer of the board. In response, the CD, which is the average density of the central 10% of the total board thickness, increased with PCT. Two PDs were found for boards when the PCT was less than 200 s. With PCTs of 300 and 900 s, the PDs were almost the same as the CD, and the CD exceeded the mean density of the board. The outer layer of boards, regarded as precured, increased with increasing PCT.

It is well known that the density profile of a board strongly affects its bending properties. The MOE and MOR in bending are summarized in Table 1. The bending properties decreased with increasing PCT because of the low density and the precured layer in the surface regions of the board. Differences of the board densities shown in Table 1 should be considered here as a factor that would affect the mechanical properties. After a correction based on board density, it was confirmed that the PCT strongly affected these bending properties. Figure 6 shows the relation between CD and IB strength. IB strength increased with increasing CD in the PCT range 4–300 s. The lower-density area near the surfaces of the board with a longer PCT was removed by sanding to evaluate the core property. Thus, the IB strength obtained here represents the tensile strength of the core layer. This result agrees with that reported by Wong et al.[11] However, the board for a PCT of 900 s had a lower IB than the others despite its higher CD. This result confirmed that the board with a PCT of 900 s did not have enough bonding strength, because of resin precuring, which starts at a high core temperature, as shown in Fig. 2.

Table 1. Bending properties of particleboards fabricated using various press closing times

PCT (s)	MOE (GPa)	MOR (MPa)	Density (g/cm^3)
4	3.52	32.9	0.63
10	3.43	32.8	0.62
50	3.24	32.8	0.61
100	2.25	22.9	0.61
200	1.40	17.1	0.55
300	0.99	14.9	0.56
900	0.24	4.0	0.47

PCT, press closing time; MOE, modulus of elasticity; MOR, modulus of rupture

Effect of PCT on LE and TS

The high relative humidity treatment at 40°C and 90% RH took about 200 h before reaching equilibrium. Figure 7 shows the LE behavior from the start up to about 50 h. No correction based on the board density was made here because the effect of PCT seemed to be predominant compared to the effect of density. The LE for all boards increased rapidly at the beginning of the treatment and leveled off after 40 hours. No differences in LE behavior were found in the PCT range 4–50 s. However, LE increased with increasing PCT when the PCT exceeded 100 s. The LE of the boards with PCTs of 300 s and 900 s was about 1.3 and 2.2 times that of a PCT of 4 s, respectively. Although LE is a small mechanical phenomenon that is difficult to detect, the experimental results did reveal the effect of PCT on LE behavior under humid conditions.

The relation between density profile and LE is an interesting topic that has not been discussed in detail. The boards made with PCTs of 4–50 s had obvious high-density layers near the board surfaces, whereas the boards with PCTs > 100 s had low-density regions in the face layer, and the PDs were not much higher than the mean density. The differences in LE might correspond to the differences in the density profiles shown in Fig. 5. For particleboard, it has been reported that the LE of the whole board can be determined as a result of the interaction of the LEs of each layer, which differ as a result of density differences.[14] Fujimoto et al.[19] found that the interactive restraint between the two faces and the core of the particleboard was sensitive to changes in humidity. Considering the board made with a

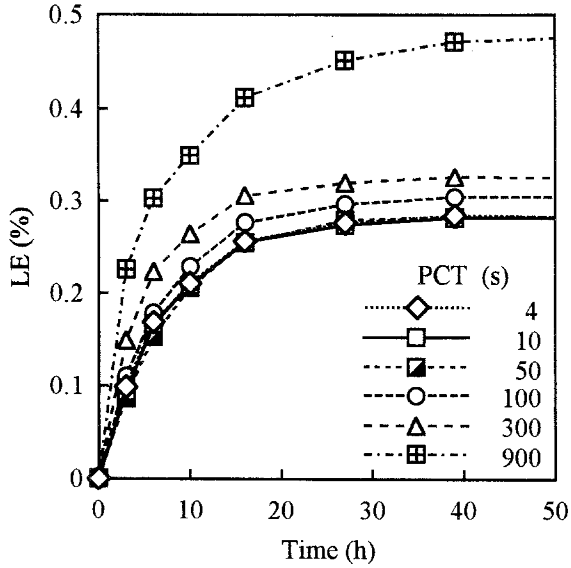

Fig. 7. Linear expansion (*LE*) behavior of particleboard at various PCTs

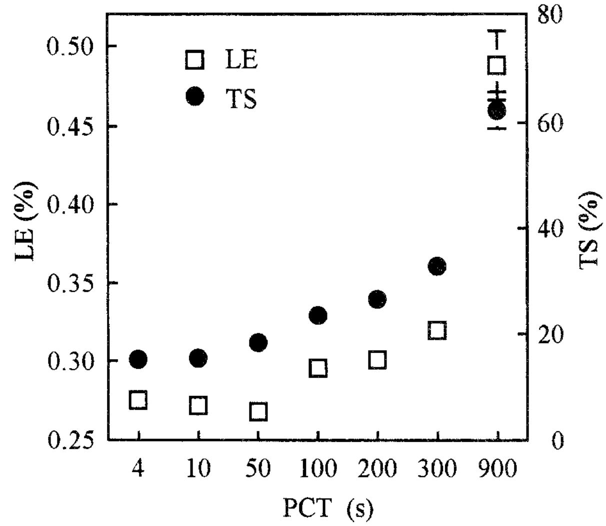

Fig. 8. Effect of PCT on the LE and thickness swelling (*TS*) of particleboard after high relative humidity (RH) treatment at 40°C and 90% RH

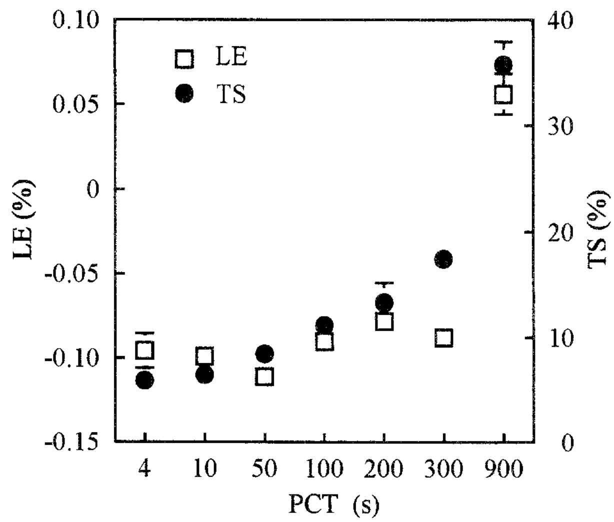

Fig. 9. Effect of PCT on the LE and TS of particleboard after high relative humidity treatment followed by drying treatment at 60°C

PCT of 300 s, its core layer had good bonding property, as shown in the IB test results in Fig. 6. However, the outer layers of the board, which were about 3 mm thick, had quite a low density. It was thought that the low-density region of the board surface affected the LE of this board. Figure 8 shows the effect of the PCT on LE and TS after humidity treatment for about 200 h. No significant differences were seen among the boards with PCTs of 4, 10, or 50 s; and the LE increased with increasing PCT when PCT exceeded 100 s, as mentioned above. On the other hand, TS seemed to increase with increasing PCT. The TS was 15% and 62% for boards with PCTs of 4 and 900 s, respectively. It is thought that the density distribution across the board thickness and the bonding efficiencies of both the face and core layers affect the TS of the board.

After the high relative humidity treatment, the specimens were dried at 60°C until equilibrium was reached. Figure 9 shows the effect of the PCT on LE and TS after this treatment. Plotting TS against PCT showed a tendency similar to that shown in Fig. 8. The TS in Fig. 9 was regarded as an irrecoverable thickness change caused by these treatments. The recoverable TS of the board with a PCT of 4 s was 6% of the original thickness, and its ratio to the total TS under the wet conditions shown in Fig. 8 was about 0.6. This recoverable/total TS ratio decreased with increasing PCT; it was approximately 0.4 for the board with a PCT of 900 s.

After the treatments, the LE values were around −0.1%, except that for a PCT of 900 s. The negative value indicates that the specimens were shorter after the treatments. We do not have any rational explanation for this finding that relates to the experimental results for the density profiles, temperature, and pressure behaviors during pressing or the mechanical properties. It may be due to a Poisson effect corresponding to the irrecoverable TSs shown in Fig. 9.

Conclusions

The effects of PCT on mat consolidation behavior and dimensional stability of particleboards were investigated using laboratory-made boards. The results obtained are summarized as follows.

The core temperature at the plateau stage during pressing was affected by the PCT. It decreased with increasing PCT. The core temperature did not rise before the platen distance equaled the target thickness of the board in the PCT range of 4–50 s. There was a linear relation between the logarithm of PCT and the maximum press pressure during pressing. The shape of the density profile across board thickness was strongly affected by the PCT. When PCT increased, the peak density moved toward the core layer from the face layer and decreased, and the core density increased slightly.

There was no difference in LE behavior in the PCT range 4–50 s, although LE increased with increasing PCT when the PCT was >100 s. LE seemed to be affected by the layer structure of the board, as characterized by its density profile and the IB strength of the core layer.

Although the irrecoverable TS after high relative humidity treatment followed by drying treatment was strongly affected by PCT, the LE after these treatments had a negative value of around −0.1%. This means that the specimens became slightly shorter.

Acknowledgments The authors thank Dr. Sobue and Mr. Ikeda, Shizuoka University, for their suggestions and help during this study.

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