Properties of Engineered Wood Flooring with Cold-pressing and Emulsion Polymer Isocyanate Adhesive

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For the sake of improving the product quality and economy, a series of cold-pressing experiments were carried out to investigate the material properties of engineered wood flooring with emulsion polymer isocyanate adhesive. Effect of pressing time, pressure, and adhesive spreading rate on modulus of elasticity (MOE) and modulus of rupture (MOR) was analyzed based on orthogonal experimental design. According to the results, both the MOE and MOR were positively correlated with pressing pressure and adhesive spreading rate. The MOE first increased and then decreased with the increase of pressing time, and MOR showed an increasing trend with the pressing time. Meanwhile, pressing time had the greatest effect on the MOE, followed by adhesive spreading rate, and pressing pressure. However, adhesive spreading rate had the greatest influence on the MOE, followed by pressing time and pressure. Furthermore, pressing time had a significant contribution to both MOE and MOR, and adhesive spread rate had a significant effect on only the MOR. Finally, the optimal cold-pressing condition was determined as 18 s pressing time, 1.25 MPa pressure, and 200 g/m^3 adhesive spreading rate, and it is proposed for application in the industrial cold pressing of engineered wood flooring for the highest MOE, MOR, and production benefit.

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Keywords: Cold-pressing; Wood-based material; Material property; ANOVA; Optimization

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INTRODUCTION

With improvement in living standards, engineered wood flooring has become a leading product for flooring in terms of its natural texture, high comfort, and good stability (Bouffard and Blanchet 2009). Engineered wood flooring generally has a four-layer structure (Sepliarsky *et al*. 2022), including a wear-resistant layer, a decorative layer, a substrate layer, and a bottom layer. The functions of these four layers are different. The wear-resistant layer mainly plays a protective role on the surface, making the floor more durable. The decorative layer is generally used to imitate the texture of solid wood, making the floor look more beautiful. The base material layer is the main component of the composite floor, which is main made of the solid wood panel. The important role of the bottom layer is to prevent moisture uptake (Blanchet *et al*. 2003; Zhou *et al*. 2019; Sun *et al*. 2022). According to the statistics of the China National Forest Products Industry Association, the sales of engineered wood flooring in China reached 128 million m^2. Thus, how to improve the properties of flooring has been a hot topic in the research field of wood composite materials.

According to the reports about properties of wood-based products, the modulus of elasticity (MOE) and modulus of rupture (MOR) are two crucial evaluating indicators (Tiryaki and Hamzacebi 2014; Jatau *et al*. 2022). The MOE is also called Young's modulus; it describes the relationship between the stress and strain of a material with elastic deformation when loads are applied (Kacikova *et al*. 2013). The MOR is the ratio of bending moment to flexural section modulus under the maximum loading, *i.e.*, the pressure intensity that a material can withstand when subjected to bending to fracture (Chung *et al*. 2017). The effect of the stress-grade of the timber boards with polyurethane adhesive on the MOE and MOR was investigated by Pangh *et al*. (2019). The results revealed that the average MOE and MOR of the panels were significantly affected by the stress-grade of the boards in the top and bottom layers of the panels. Wei *et al*. (2013) used the six-cycle artificial accelerated aging method of ASTM D1037-12 (2012) to evaluate the aging performance of bamboo and wood container floors processed by diphenylmethane diisocyanate adhesive. The results showed that both the bending strength and MOE decreased after aging. Meanwhile, a series of tests conducted by Mihailović's team to explore the distribution of small clear beech specimens at three loading rates (Mihailović *et al.* 2022). The results showed that the loading rate influences the shape of the empirical distributions of MOE and MOR and therefore the choice of the theoretical distribution. In the related study, effects of strand density, resin content, hot pressing time, and orientation angle on MOR and MOE of plastic oriented strand board with thin and long strands from fast-growing poplar were investigated by Lian *et al.* (2008). The effect of moisture and temperature on beech wood static MOE, MOR, and stress at proportional limit in bending was tested by Popović *et al*. (2006). The MOE proved to be functionally linear with respect to the hygroscopic moisture of the wood and the temperature of the moist wood. Furthermore, to determine the MOE and MOR values for particleboard when processed by urea formaldehyde adhesive, a model based on a fuzzy logic classifier was developed by Yapici *et al*. (2009). With this system, for the manufacture of wood-composite materials, the most appropriate chip mixture amount required by the manufacturer could be determined.

Investigating the mechanical properties of hybrid cross-laminated timber (HCLT) with plywood is the key to improve its application in wooden houses. Choi *et al*. (2015) determined the MOE, MOR, and dimensional stability of HCLT based on the composition and lamination orientation of the plywood. Meanwhile, the influence of temperature on the bending strength (MOR) and the MOE of eight different wooden materials was tested at temperatures between -20 ℃ and +60 ℃. Sonderegger and Niemz (2006) found a maximum increase in MOR of 48% and a maximum decrease in MOE of 31%. Only fibre oriented solid wood panels showed a 6% decrease in MOE. For maximum loads, the work varied between a 19% reduction and a 10% increase. Meanwhile, Zhao *et al*. (2015) analyzed the MOR and MOE of birch at five different moisture content levels by cryogenic scanning electron microscopy at temperatures ranging from 0 °C to -196°C. The results show that very low temperatures have an important effect on the properties of wood with various MC.

In traditional processing of engineered wood flooring, hot pressing was mostly used. Although this production process was simple, there were many problems such as energy waste, temperature gradients that lead to high product costs and low flooring quality (Chen *et al*. 2007). With the rapid development of preparation technology, cold pressing technology has been used in more applications in the preparation of engineered wood flooring (Huang *et al*. 2018). Furthermore, emulsion polymer isocyanate adhesive (EPI) is a type of adhesive that consists of a polymer dispersed in water and contains isocyanate groups. It offers several advantages, including excellent bonding strength, high durability, and resistance to temperature and moisture. Nowadays, EPI adhesive is commonly used in various products, such as bonding laminates, veneers, and composite materials. Based on the above literature and field survey, pressing time, pressure, and adhesive spread have great impact on the properties of engineered wood flooring, especially for the MOE and MOR (Wang *et al*. 2017). Thus, in the industrial cold pressing of engineered wood flooring with EPI adhesive, how to choose the reasonable pressing time, pressure, and adhesive spread is the key to improving product quality, and it is also an urgent issue for enterprises to solve.

To this end, this work aims to improve the properties of engineered wood flooring processed by cold-pressing with EPI adhesive, main attention was given to effects of pressing time, pressure, and adhesive spread rate on the MOE and MOR. The optimal processing parameters were determined for high quality and low cost, and it is hope to provide scientific support for the industrial processing of engineered wood flooring.

EXPERIMENTAL

Materials

As displayed in Table 1 and Fig. 1, Oak wood (*Quercus robur* L.) was used for the surface board. Poplar (*Populus* sp.) was adopted as the substrate material. The board pieces were manufactured by the Dongsheng Timber Co., Ltd. (Langfang, China), and their average moisture contents were obtained based on six samples. Furthermore, EPI adhesive (Youyang New Material Co., Ltd., Guangdong, China) with solid mass fraction of 100% was applied during the preparation process of engineered wood flooring, and its melting temperature is between 140 and 180 °C.

Table 1. Dimensions and Moisture Content of Oak and Poplar

Materials	Length (mm)	Width (mm)	Thickness (mm)	Moisture Content
Oak	950	150	3.5	8.1%
Poplar A	950	150	1	8.2%
Poplar B	950	150	2	8.2%

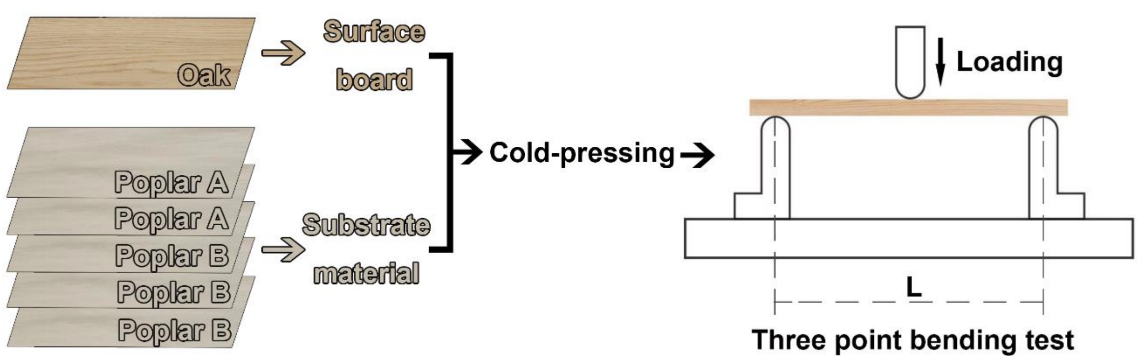

Fig. 1. Preparation and properties measurement of engineered wood flooring

Methods

In this work, the engineered wood flooring was manufactured by 6 layers of board, including 1 layer of Oak board and 5 layer of poplar boards (Table 1 and Fig. 1), and it was conducted on a cold press machine (FDS22, Chunju Machinery Co., Ltd., Shandong, China). Fast infrared heating technology was used to heat the EPI adhesive, and its heating time was 14 s (Huang *et al.* 2018). The adhesive was evenly applied to the surface of the board by roller coating processes (Huang *et al.* 2018). The properties of engineered wood flooring were measured by a wood mechanics testing machine (GJ212, Qingji Instrument Technology Co., Ltd., Shanghai, China) at different processing conditions of pressing time, pressure, and adhesive spread. As shown in Fig. 1, based on the measuring standard of GB/T 18103 (2013), the sample dimension was 350 mm (length) × 50 mm (width), and the values of MOE and MOR were measured by three-point bending method and calculated based on Eqs. 1 and 2 (Ji 2022) by using the Jinhui software (GJ212, Qingji Instrument Technology Co., Ltd., Shanghai, China).

$$E = \frac{\Delta P L^3}{4 \Delta Y w t^3} \tag{1}$$

In Eq. 1, E stands for the MOE in MPa, ΔP is the difference of the higher-lower limit load in N, L denotes the distance between two supports in mm, ΔY is the deformation value with higher-lower limit load, and w and t stand for the width and thickness of sample in mm, respectively. The MOR is given by Eq. 2,

$$\sigma = \frac{3P_{max}L}{2wt^2} \tag{2}$$

where σ denotes the MOR in MPa, and $P_{\max}$ is the failure load in N.

In this work, orthogonal experimental design (Jin and Wei 2021) was adopted. It utilizes orthogonal arrays to ensure that each factor level is combined with every other level equally. This achieves orthogonality, enabling independent assessment of factor effects and accurate estimation of interactions. Orthogonal design efficiently identifies influential factors and their optimal levels, leading to effective experimental optimization. As shown in Table 2, the levels of pressing time, pressure, and adhesive spread were selected based on the related reports (Guo *et al*. 2017; Huang *et al.* 2018) and industrial processing of engineered wood flooring. Meanwhile, each combination of processing parameters was repeated five times, and the average values of MOE and MOR was used for further analysis.

Table 2. Orthogonal Experimental Design

Runs	Pressing Time (s)	Pressing Pressure (MPa)	Adhesive Spreading Rate (g/m^2)
1	12	1	150
2	12	1.25	175
3	12	1.5	200
4	18	1	175
5	18	1.25	200
6	18	1.5	150
7	24	1	200
8	24	1.25	150
9	24	1.5	175

RESULTS AND DISCUSSION

Range Analysis on the Modulus of Elastic

Figure 2a shows the changes in MOE of engineered wood flooring at different pressing time, where the MOE increased first and then decreased with the increase of pressing time. According to related work (Wang *et al.* 2017), the surface board and substrate are bonded with adhesive, when the cold pressing time is short, and the adhesive has not yet fully contacted the surface of substrate. In other words, it did not form a continuous adhesive layer between the surface board and substrate, which led to the lower level of MOE. With increased pressing time, the adhesive has enough time to penetrate, and a continuous and durable adhesive layer was formed, which resulted in the higher level of MOE. However, as pressing time continued to increase, the temperature of the infrared heated adhesive layer decreased, thereby affecting the penetration of the adhesive and reducing the MOE. Therefore, with the increase of pressing time, MOE first increased and then declined.

The effect of pressing pressure on the MOE is given in Fig. 2b. The MOE of engineered wood flooring showed an increasing trend with the increase of pressing pressure. The low pressing pressure led to the lack or accumulation of glue, which is not conducive to bonding. As the pressing pressure increased, the higher pressure reduced the gaps in the adhesive layer, increasing the cohesion of the adhesive layer molecules, and improving the mechanical properties of the board. Thus, the higher pressure improved the MOE of engineered wood flooring. Furthermore, the MOE of engineered wood flooring also showed an increasing trend with the adhesive spreading rate. Based on relevant research about adhesive spreading rate, it has great impact of the material properties. With the increase of adhesive spreading rate, it promoted the formation of the adhesive layer, which improved adhesion between boards, thereby leading to the improvement for MOE of engineered wood flooring.

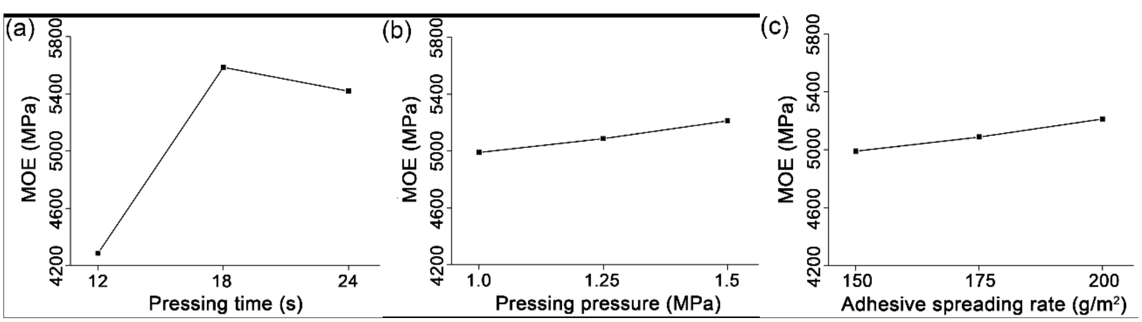

Fig. 2. Effects of (a) pressing time, (b) pressure, and (c) adhesive spreading rate on MOE

Table 3 displays the range values of MOE, and the R_{MOE} denotes the difference between the highest and lowest values of K_{MOE}. The higher value of R_{MOE} means the greater impact on the results (Jiang *et al*. 2022; Song *et al*. 2023). The K_{MOE} of pressing time was equal to 1299.68, which was higher than adhesive spreading rate (505.52) and pressing pressure (222.37). Thus, it can be obtained that the pressing time had the greatest impact on the MOE, followed by adhesive spreading rate and pressing pressure.

Furthermore, in the industrial processing of engineered wood flooring, the higher MOE means the stabler quality with high rigidity. The highest MOE was adopted as the objective, which can be obtained by selecting the optimal combination of processing conditions. According to the values of K_{MOE}, the highest MOE can be concluded at the optimal combination of processing conditions as pressing time of 18 s, pressure of 1.5 MPa, and adhesive spreading rate of 200 g/m^3.

Table 3. Experimental Results of MOE

Runs	Processing Parameters			Results
	Pressing Time (s)	Pressing pressure (MPa)	Adhesive Spreading Rate (g/m^2)	MOE (MPa)
1	12	1	150	4027.67
2	12	1.25	175	4142.91
3	12	1.5	200	4686.41
4	18	1	175	5569.41
5	18	1.25	200	5930.19
6	18	1.5	150	5256.41
7	24	1	200	5373.72
8	24	1.25	150	5189.68
9	24	1.5	175	5695.11
K_{MOE1} (MPa)	4285.66	4990.27	4824.59	/
K_{MOE2} (MPa)	5585.34	5087.59	5135.81	/
K_{MOE3} (MPa)	5419.50	5212.64	5330.11	/
R_{MOE} (MPa)	1299.68	222.37	505.52	/

Variance Analysis on the Modulus of Elastic

To explore the prominence of each processing parameter on the MOE, analysis of variance (ANOVA) with a 95% confidence level (significance level of α = 0.05, $F_{0.05}$ = 19.00) (Zhu *et al*. 2020, 2022a; Zhang *et al*. 2021) was adopted, as shown in Table 4. If the F-value of a processing parameter is greater than that $F_{0.05}$ = 19.00, then it can be concluded that this processing parameter has significant contribution to the MOE; otherwise it is considered insignificant (Wu *et al*. 2022). As given in Table 3, the F-value of pressing time was equal to 21.28, which is higher than that of $F_{0.05}$. Thus, the pressing time had significant effect on the MOE. However, the F-values of pressing pressure (0.53) and adhesive spread rate (2.77) are all lower than that of $F_{0.05}$ = 19.00. Therefore, both pressing pressure and adhesive spread rate have an insignificant contribution to the MOE during the cold-pressing of engineered wood flooring.

Table 4. Results of ANOVA for MOE

Factor	Sum of Squares	Degrees of Freedom	F-Value	Prominence
Pressing time	3002244.61	2	21.28	*
Pressing pressure	74561.36	2	0.53	/
Adhesive spreading rate	390161.63	2	2.77	/
Error	141058.12	2	/	/

Range Analysis on the Modulus of Rupture

Changes in MOR of engineered wood flooring at different pressing time are displayed in Fig. 3, it can be found that the MOR is positively related to both the pressing time, pressure, and adhesive spread rate. As mentioned above, with the increase of pressing time, pressure, and adhesive spread rate, the adhesive fully contacted the surface of the board, allowing it to penetrate into the board and form a continuous adhesive layer. Thus, the higher pressing time, pressure, and adhesive spread rate led to the greater MOE of engineered wood flooring.

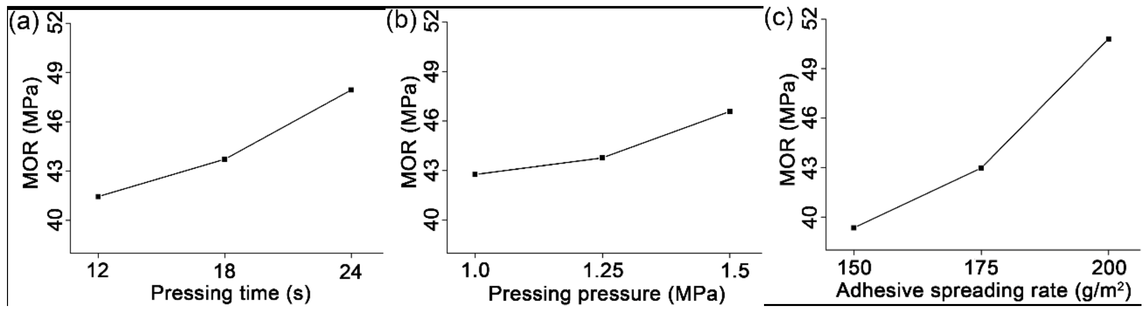

Fig. 3. Effects of (a) pressing time, (b) pressure and (c) adhesive spreading rate on MOR

The range analysis of MOR is tabulated in Table 5, and the R_{MOR} stands for the difference between the highest and lowest values of K_{MOR}. The K_{MOE} value of adhesive spreading rate was equal to 11.45, which is higher than those of pressing time (6.49) and pressure (3.82). Therefore, the adhesive spreading rate had the greatest impact on the MOE, followed by pressing time and pressure. Meanwhile, the greater value of MOR shows the samples have a stronger ability to withstand pressure. Based on the values of K_{MOE}, the greatest MOE can be obtained at the combination processing parameters as pressing time of 24 s, pressure of 1.5 MPa, and adhesive spreading rate of 200 g/m^3.

Table 5. Experimental Results of MOR

Runs	Processing Parameters			Results
	Pressing Time (s)	Pressing pressure (MPa)	Adhesive Spreading Rate (g/m^2)	MOR (MPa)
1	12	1	150	35.33
2	12	1.25	175	39.37
3	12	1.5	200	49.66
4	18	1	175	40.28
5	18	1.25	200	50.06
6	18	1.5	150	40.83
7	24	1	200	52.68
8	24	1.25	150	41.89
9	24	1.5	175	49.25
K_{MOR1} (MPa)	41.45	42.76	39.35	/
K_{MOR2} (MPa)	43.72	43.77	42.97	/
K_{MOR3} (MPa)	47.94	46.58	50.80	/
R_{MOR} (MPa)	6.49	3.82	11.45	/

Variance Analysis on the Modulus of Rupture

Per the ANOVA, a significance level of $\alpha = 0.05$ ($F_{0.05} = 19.00$) (Zhu *et al*. 2022b) for MOR is displayed in Table 6. The F-values of pressing time and adhesive spread rate were equal to 48.37 and 152.94, respectively, which were all higher than that of $F_{0.05}$. Thus, the pressing time and adhesive spread rate had a significant impact on the MOR. However, only the F-value of pressing pressure (17.46) was less than $F_{0.05} = 19.00$. Therefore, it can be inferred that the pressing pressure had an insignificant influence on the MOR during the cold pressing of engineered wood flooring. This result is similar to the changes in the shear strength in the cold pressing of engineered wood flooring with EPI adhesive (Huang *et al*. 2018).

Table 6. Result of ANOVA for MOR

Factor	Sum of Squares	Degrees of Freedom	F Value	Prominence
Pressing time	65.01	2	48.37	*
Pressing pressure	23.46	2	17.46	/
Adhesive spreading rate	205.54	2	152.94	*
Error	1.34	2	/	/

Optimization and Validation

In the industrial cold-pressing of engineered wood flooring, the higher MOE and MOR indicate the greater quality of final products (Wang *et al*. 2001). Thus, this work aims to improve the product quality of engineered wood flooring in terms of the greatest MOE and MOR as possible. Based on the above range analysis on MOE and MOR, the greatest MOE could be obtained at the pressing time of 18 s, pressure of 1.5 MPa, and adhesive spreading rate of 200 g/m^3, and the highest MOR was observed at the pressing time of 24 s, pressure of 1.5 MPa, and adhesive spreading rate of 200 g/m^3. Meanwhile, according to the results of ANOVA for MOE and MOR, pressing time had significant impact on the MOR and MOE, adhesive spread rate had insignificant effect on the MOE and had significant influence on the MOR, more importantly the pressing pressure had an insignificant contribution to the MOE and MOR.

During actual cold-pressing of engineered wood flooring, pressing pressure is the key affecting energy consumption of the pressing machine, and the high pressing pressure may damage the wood structure. Meanwhile, the pressing time is the essential to improve production efficiency and cost. Thus, the pressing time and pressure can be appropriately reduced, and the proposed optimal processing parameters were determined as pressing time of 18 s, pressure of 1.25 MPa, and adhesive spreading rate of 200 g/m^3. In this combination of processing parameters, the values of MOE and MOR were equal to 5930.19 MPa and 50.06 MPa (Tables 3 and 5), respectively, and the MOE and MOR are meet the quality standard of engineered wood flooring as per GB/T 18103 (2013) (MOE $\geq$ 4000 MPa, MOR $\geq$ 30 MPa) (Guo *et al*. 2017). In general, the optimal cold-pressing conditions are as follows: pressing time of 18 s, pressure of 1.25 MPa, and adhesive spreading rate of 200 g/m^3, it is proposed to be applied in the industrial processing of engineered wood flooring in terms of greater MOE, MOR, production efficiency, and benefits.

CONCLUSIONS

In this work, orthogonal experimental design was adopted to investigate the modulus of elasticity (MOE) and modulus of rupture (MOR) of engineered wood flooring with cold pressing, and the main conclusions are as follows:

1. The higher pressing pressure and adhesive spreading rate can improve the MOE and MOR of the engineered wood flooring, and the greater pressing time positively affected the MOE of engineered wood flooring.

2. Based on the range analysis, pressing time had the greatest effect on the MOE, followed by adhesive spreading rate, and pressing pressure, while adhesive spreading rate had the greatest influence on the MOE, followed by pressing time and pressure.

3. According to the results of ANOVA, MOE and MOR were significantly affected by the pressing time, but insignificantly impacted by the pressing pressure. Meanwhile, adhesive spread rate had a significant contribution to the MOR, but insignificant influence on the MOE.

4. In the industrial cold-pressing of engineered wood flooring, pressing pressure had great impact on the energy consumption of pressing machine, and the high pressing pressure may damage the wood structure. With the multiple objectives of highest MOE, MOR, and production benefit, the optimal cold-pressing parameters were determined as pressing time of 18 s, pressure of 1.25 MPa, and adhesive spreading rate of 200 g/m^3. This combination of parameters was proposed to be applied in the manufacturing of engineered wood flooring with respect higher production quality and benefits.

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