Manufacture and Properties of *Metasequoia*-Based Three-Layer Parquet Flooring

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Abstract

Metasequoia-based three-layer parquet flooring (MPF) was prepared under the following conditions: hot-pressing temperature of 95°C, hot-pressing time of 7 minutes, hot-pressing pressure of 9 $kg{\cdot}cm^{-2}$, and addition of 200 $g{\cdot}m^{-2}$ urea-formaldehyde resin adhesive. The results showed that the moisture content, density, formaldehyde emission, static bending strength, and elastic modulus of the three kinds of parquet flooring were not much different than poplar-based multilayer parquet flooring (PPF) or fir-based three-layer parquet flooring (FPF) on the market. The thermal conductivity of the MPF was 0.195 $W{\cdot}m^{-1}{\cdot}K^{-1}$, which was the lowest among the three kinds of parquet flooring. The sound absorption coefficient of MPF under 11 frequency conditions in the range of 0.2 to 2 kHz was higher than that of PPF and FPF under the same frequency condition. The research results provide a reference value for the efficient use of low-quality *M. glyptostroboides* wood.

The dawn redwood (*Metasequoia glyptostroboides* (Hu et Cheng)) is a member of the Cupressaceae family, to which juniper and red cedar also belong. *Metasequoia* is referred to as a ''living fossil'' and is a unique tree species in China that has not evolved; its growth process has not diverged (Bartholomew et al., 1983; Ma and Shao, 2003). *M. glyptostroboides* is a giant redwood that grows in a conical shape to 120 feet tall. The trees' branches, which stretch up and out with a gradual slope, can reach as far as 30 feet. The largest dawn redwood has a base diameter of approximately 6 feet. Since the 1940s, *Metasequoia* has been discovered and widely introduced around the world (Ma, 2007; Zhang et al., 2020). *Metasequoia* in many areas have become forests and timbers and have a wide range of adaptability (Li et al., 2005). The logging potential of the dawn redwood was evaluated in 1948 and found to be unpromising. Few other commercial uses for these trees exist, although it is an important tree for scientific inquiry due to its nature as a relic of the Late Cretaceous (Wang et al., 2019; Sanmartín and Isabel, 2012). Owing to the light and soft material, loose structure, and low strength of *Metasequoia*, its development and application are restricted. How to achieve high-quality use of *M. glyptostroboides*, which is considered a low-quality wood, is a subject that scholars have researched. There have been many studies on high-quality use of *M. glyptostroboides* from the processing and use of wood boards, forestry chemicals, pulp and papermaking, etc. (Honglu and Tiejun, 2006; Wang et al., 2019). Some studies have shown that the extract of *M. glyptostroboides* was subjected to a column chromatographic analysis that caused the isolation of an abietane-type diterpenoid, taxodone. Furthermore, taxodone showed potential antibacterial effects as diameters of zones of inhibition against foodborne pathogenic bacteria (Bajpai and Kang, 2010). Wood liquefaction refers to turning timber into a hot chemical of liquid sticky fluid with the function of

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organic matter, such as acid and phenol. The liquefaction of wood (*M. glyptostroboides*) was achieved using allyl alkyl imidazolium ionic liquids as liquefaction reagents at low temperatures. Ionic liquids with acidic anionic groups, such as [Cl/$AlCl_3$], possess high liquefaction efficiency under these conditions (Xie and Shi, 2010). Scholars have investigated the high-value use of *M. glyptostroboides* from various angles. By analyzing the growth characteristics and wood properties of *M. glyptostroboides* (Nelson, 1998), some scholars have explored the comprehensive use methods and potential use value of *M. glyptostroboides*, e.g., oriented strand board, blockboard core material, etc., to determine the direction of forest cultivation and forest products processing and use (Wang et al., 1998). In recent years, parquet flooring has gained market share among flooring types, in part because it is favored by naturalists. Parquet flooring has high dimensional stability because it overcomes the shortcomings of solid wood flooring: monomer shrinkage, warping, and cracking (Pierre et al., 2013). In addition, features such as the same elegant natural appearance as solid wood flooring, satisfactory thermal insulation performance, and user experience increase its popularity (Blumer et al., 2009). *M. glyptostroboides*, as an ecological greening tree species, not only improves the environment but also has a wide range of uses for its finished products. The best use method can be selected according to the changes in market conditions. In this study, because the light and soft material, loose structure, and price of *M. glyptostroboides* is low, it was selected as the core layer of parquet flooring. Parquet flooring has a higher added value than other wood-based panel products. To address the case of a limited supply of timber resources, we will continue to expand the methods for using wood raw materials and fine native tree species in the southern region of China. This expansion will help alleviate the contradiction between the supply of and demand for domestic resources and reduce the need for foreign timber.

Materials and Methods

Experimental material and equipment

M. glyptostroboides, which is 25 years old, was obtained from the forest products market in Guiyang, China. The adhesive has the following properties: modified urea-formaldehyde resin, solid content of 60 percent, and viscosity of 230 mPa·s. For the *Metasequoia*-based three-layered parquet flooring (MPF), the surface board was oak wood, the thickness was 5 mm, and the moisture content was 8.5 percent. The core board was *M. glyptostroboides* with a thickness of 10 mm and a moisture content of 9.5 percent; the bottom board was poplar with a thickness of 3 mm and a moisture content of 7 percent. For poplar-based multilayer parquet flooring (PPF), the surface board was oak wood, the bottom board was poplar wood, and the core layer was a multilayer plywood made of poplar wood and eucalyptus wood. For fir-based three-layer parquet flooring (FPF), the surface board was oak wood, the bottom board was poplar wood, and the core layer was spliced by short Chinese fir wood strips. PPF and FPF were purchased from the Guiyang forest products market.

Hot-pressing equipment (model, BY214×8/60(8) ZRC; total pressure, 6000 kN; and hot press board format, 1370 by 2700 mm) was manufactured by Shanghai Qiulin Machinery Co., Ltd. A universal mechanical testing machine (model, MTS/CMT) was produced by Meister Testing Machine Co., Ltd. A sound absorption coefficient measuring instrument (model, AWA6290Z) was produced by Shanghai Heyi Instrument Co., Ltd. A thermal conductivity tester (model, TC-3001) was produced by Shanghai Yiyang Industrial Co., Ltd.

Preparation of *Metasequoia*-based three-layered parquet flooring

The urea-formaldehyde resin was evenly applied to the surface of the veneer with a glue roller. The veneer's single-sided glue amount was 200 $g \cdot m^{-2}$, and the veneer was brushed twice. The materials of the surface board and bottom board were oak wood and poplar, respectively. The core layer was *M. glyptostroboides*, and the specification after processing and splicing was 800 by 90 by 10 mm (length by width by thickness). Five-layer plywood was used for the tongue and groove structure for the connection between the floors. The hot-pressing temperature, hot-pressing time, and hot-pressing pressure were set to 95°C, 7 minutes, and 9 $kg \cdot cm^{-2}$, respectively. The final product specification was 900 by 125 by 15 mm (length by width by thickness). The structure of MPF is shown in Figure 1.

Performance test

The detection and analysis of the physical and chemical properties of MPF, PPF, and FPF were based on Chinese national standards GB/T 18103-2013 (Parquet), GB 18580-2017 (Indoor decorating and refurbishing materials, limit of formaldehyde emission of wood-based panels and finishing products), and GB/T 17657-2013 (Test methods of evaluating the properties of wood-based panels and surface decorated wood-based panels).

For the thermal conductivity test, the heat flux density was calculated using Equation 1:

$$q_c = \frac{IV}{F} \tag{1}$$

where q_c = heat flux density ($W \cdot m^{-2}$); I = heater current (A); V = heater voltage (V); and F = section size of specimen (m^2).

The thermal conductivity was calculated using Equation 2:

$$\lambda = \frac{q_c \delta}{4 \Delta t} \tag{2}$$

where λ = thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$), δ = specimen thickness (m), and Δt = temperature difference of a hot surface and a cold surface when quasi-steady state (K^{-1}).

In the range of 0.2 to 2 kHz, there were 11 frequencies, 0.2, 0.25, 0.315, 0.4, 0.5, 0.63, 0.8, 1, 1.25, 1.6, and 2 kHz, to obtain the maximum and minimum values of the sound

Figure 1.—The construction of Metasequoia*-based three-layer parquet flooring.*

pressure level. The difference was *Lp*. According to the relationship between sound pressure and sound pressure level, the sound absorption coefficient was calculated using Equation 3:

$$\alpha_0 = \frac{4 \times 10^{(Lp/20)}}{\left(1 + 10^{(Lp/20)}\right)^2} \tag{3}$$

where α_0 is the sound absorption coefficient of the measured material and *Lp* is the extreme difference in sound pressure (dB; maximum value of the sound pressure level minus the minimum value).

Statistical analysis

The Pearson correlation coefficient for floor performance was evaluated using SPSS 22.0 statistical software. The R package function heatmap.2 was employed to draw a heatmap. Other graphs were constructed using Origin 9.1 (Origin Lab, Northampton, MA, USA).

Results and Discussion

Measurement results and analysis of physical and chemical properties

The experiment measured the moisture content, density, formaldehyde emission, immersion peeling, static bending strength (modulus of rupture, MOR), elastic modulus (modulus of elasticity, MOE), thermal conductivity, and sound absorption coefficient of three kinds of parquet flooring (Yildiz et al., 2004; Anders and Terje, 2018). These results are shown in Table 1.

The measurement results of physical and chemical properties showed that the final moisture content and density of MPF were 10.7 percent and 0.52 $g \cdot cm^{-3}$, respectively, and the impregnation stripping performance of MPF, PPF, and FPF were acceptable. The surface board and bottom board of the three kinds of parquet flooring were made from the same materials; the total thickness was the same; but the core materials were different. The core material of the MPF was made of *M. glyptostroboides*. Compared with PPF and FPF, the density of the core material of MPF was lower. The formaldehyde emission of the MPF was 0.112 $mg \cdot m^{-3}$, and there was minimal difference between the formaldehyde emission of 0.104 $mg \cdot m^{-3}$ for PPF and the formaldehyde emission of 0.092 $mg \cdot m^{-3}$ for FPF. The standard limit of all parquet flooring was less than the national standard limit of 0.124 $mg \cdot m^{-3}$. The MOR and MOE of the three kinds of parquet flooring meet the national standards of $\geq$30 MPa and $\geq$4000 MPa, respectively.

Thermal conductivity detection

Although numerous related studies investigate the detection and analysis of conventional indicators such as formaldehyde emissions, abrasion resistance, and acid and alkali resistance, few studies address thermal conductivity testing and analysis to determine the comfort of wood flooring (Berger et al., 2006). Therefore, the thermal conductivity of three kinds of parquet flooring was tested; the results are shown in Table 2.

Materials with thermal conductivity less than 0.3 $W \cdot m^{-1} \cdot K^{-1}$ are referred to as thermal insulation materials, which can be used for heat preservation and heat insulation (Zoltán et al., 2015). The thermal conductivity of wood flooring is the key to thermal insulation, and the main influencing factors of the thermal conductivity of wood are density and humidity (Wang et al., 2000). In addition to these factors, which significantly impact the thermal conductivity of wood flooring, the temperature conditions, even the directionality of the wood, and the structural composition also have a certain impact. Under natural conditions, wood contains different degrees of moisture, and the moisture content indicates that the moisture in the wood occupies a certain volume of pores (Abdou and Budaiwi, 2005). The greater the moisture content is, the more volume the moisture occupies, and the thermal conductivity of water is approximately 20 times higher than that of air (Montgomery, 1947). Therefore, the increase in wood moisture content inevitably increases the thermal conductivity value. The moisture contents of the three kinds of parquet flooring used in the study are 10.2, 11.1, and 10.7 percent, and the detection results of the thermal conductivity were relatively comparable. The majority of the differences among the MPF, PPF, and FPF pertained to the structure and materials of the core layer. The thermal conductivity of parquet flooring was attributable to the comprehensive effect of each component's thermal conductivity.

The thermal conductivities of the PPF, FPF, and MPF were 0.292, 0.216, and 0.195 $W \cdot m^{-1} \cdot K^{-1}$, respectively. Among these materials, MPF had the lowest thermal conductivity and was a suitable thermal insulation material. The excellent thermal insulation performance of MPF was mainly due to the loose structure and low density of *M. glyptostroboides* in the core layer, which yields low thermal conductivity (Caniato et al., 2013).

Sound absorption coefficient detection

People have increasingly higher requirements for the comfort of their living environments, and the acoustic performance of wood flooring directly affects the acoustic environment of a room (Ahnert et al., 2015). The sound absorption performance of flooring, which is an interior

Table 1.—Measurement results for three kinds of parquet flooring.[a]

Samples	Indicators: Moisture content (%)	Density ($g \cdot cm^{-3}$)	Formaldehyde emission ($mg \cdot m^{-3}$)	Impregnation stripping	MOR (MPa)	MOE (MPa)
Poplar-based multilayer parquet flooring	10.2	0.65	0.104	—	80.6	6244
Fir-based three-layer parquet flooring	11.1	0.57	0.092	—	82.8	6371
Metasequoia-based three-layer parquet flooring	10.7	0.52	0.112	—	74.3	5843

[a] Note: All data presented are the means of three replicates.

Table 2.—Heat flux density and thermal conductivity of parquet flooring.[a]

Samples	Indicators				
	Current I (A)	Voltage V (V)	Temperature difference Δt (°C)	Heat flux density q_c ($W \cdot m^{-2}$)	Thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$)
Poplar-based multilayer parquet flooring	0.14	30	5.37	420.01	0.292
Fir-based three-layer parquet flooring	0.14	30	7.23	416.11	0.216
Metasequoia-based three-layer parquet flooring	0.14	30	8.00	418.62	0.195

[a] Note: All data presented are the means of three replicates.

decoration material, has a certain role in the control of indoor noise pollution. If parquet flooring with a high sound absorption coefficient is used indoors, it can absorb part of the reflected sound in a room and ultimately reduce the overall noise in the room. The sound absorption efficiency of wood is measured by its sound absorption coefficient for a specific frequency. The greater the sound absorption coefficient is, the better the sound absorption effect is (Magnusson, 2001). Wu et al. (2016) modified the acoustic properties of *Metasequoia* by thermal, ultrasonic, and combined thermal-ultrasound treatments. *Metasequoia* samples treated with ultrasonic power at 340 W for 9 minutes at a thermal temperature of 200°C were chosen as the optimal method. Changing the extracted chemical materials from the extractive solution was conducive to modifying the acoustic properties of *Metasequoia*. Research has shown that the acoustic performance of *Metasequoia* is related to many factors. According to the detection results in Figure 2, the sound absorption coefficient of MPF increased with an increase in sound frequency, and the sound absorption coefficient was better than that of PPF and FPF at the same frequency, but the difference was not significant. The sound absorption performance of PPF, FPF, and MPF was mainly attributed to their composite sound absorption structure, that is, the characteristics of both the porous sound absorption structure and the resonance sound absorption structure (Wassilieff, 1996). The sound absorption properties of the three kinds of parquet flooring were closely related to their microstructures (Hou et al., 2010). The wood structure is characterized by a large number of internal and external connected pores. When sound waves are incident, micropores can cause friction and viscous air consumption and convert sound energy into heat energy. Its sound absorption frequency characteristics have a greater impact on the mid- and high-frequency sound absorption coefficient than on the low-frequency sound absorption coefficient (Okudaira et al., 1998). Influencing factors include material porosity, thickness, density, and humidity. Based on an analysis of density and void characteristics of the core materials in the three kinds of parquet flooring, MPF has the smallest density of the three kinds of parquet flooring, and the porosity of *M. glyptostroboides* was higher than that of the multilayer plywood and Chinese fir (Williams et al., 2003; Ji et al., 2018). Therefore, the average sound absorption coefficient of MPF is larger, which renders the overall sound absorption effect of the MPF better than PPF and FPF. The moisture contents of the three kinds of parquet flooring were not much different, but after moisture absorption, the air in the gaps and small holes of the wood would be replaced by moisture, which reduced the porosity and reduced the sound

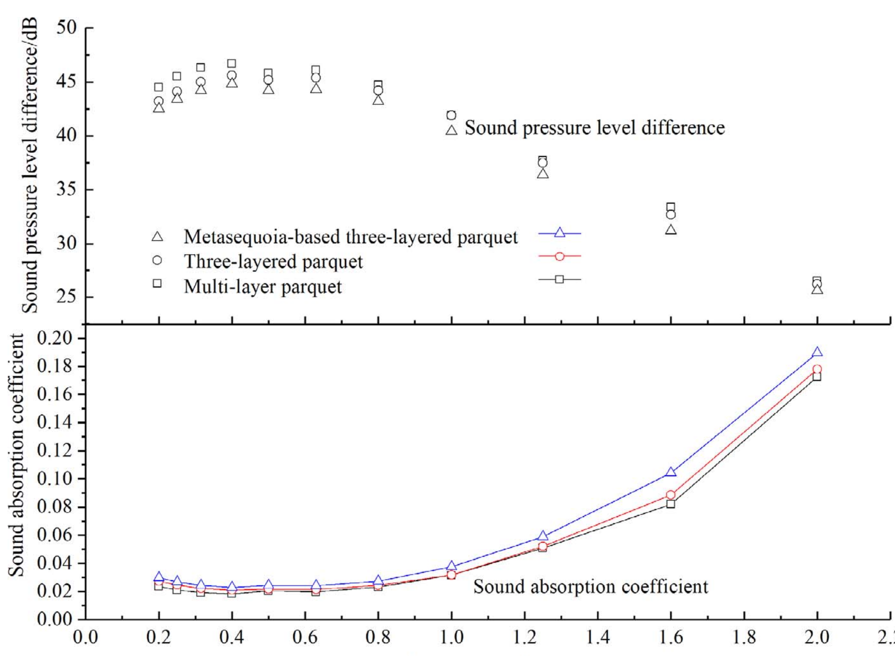

Figure 2.—Sound pressure level difference and sound absorption coefficient of three kinds of parquet flooring.

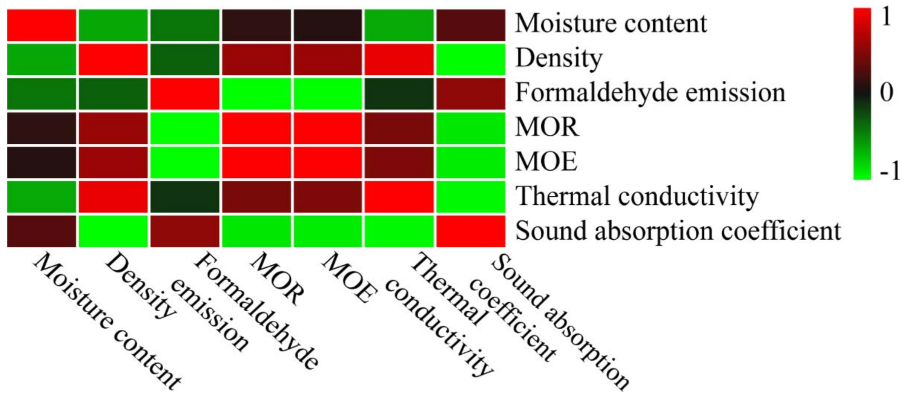

Figure 3.—Pearson correlation heatmap of floor properties.

absorption coefficient for medium and high frequencies (Yamamura and Ohta, 2015). Therefore, parquet flooring was not suitable for use in high humidity conditions. Increasing the thickness of parquet flooring could increase the absorption of mid- and low-frequency sound but had less effect on the sound absorption performance of high-frequency sound. When the thickness increased to a certain level, the effect on the sound absorption coefficient was not obvious. Cao et al. (2014) found that the sound absorption coefficient of wood improved with an increase in thickness, and tree species had a significant influence on the sound absorption coefficient of plywood within a specific range. Additionally, the surface film of parquet flooring made its surface poorly breathable and reduced its sound absorption coefficient. Wei et al. (2016) investigated the effect of paint film thickness on the sound absorption effect of spruce wood. The sound absorption coefficient increased with an increase in paint film thickness. The surface films of the three kinds of parquet flooring were unfavorable due to their sound absorption effect.

Some obvious correlations among the flooring properties were identified (Fig. 3). Density was significantly positively correlated with thermal conductivity ($R = 0.914^{**}$) and had a remarkably negative correlation with the sound absorption coefficient ($R = -0.893^{**}$). Formaldehyde emission was negatively and very significantly correlated with MOR ($R = -0.907^{**}$) and MOE ($R = -0.905^{**}$). However, there is a significant positive correlation between MOR and MOE ($R = 0.997^{**}$). The sound absorption coefficient showed a significantly negative correlation with MOR ($R = -0.815^{**}$), MOE ($R = -0.831^{**}$), and thermal conductivity ($R = -0.878^{**}$).

Conclusions

Comparing the moisture content, density, formaldehyde emission, MOR, MOE, and other parameters of MPF produced under hot pressing and glue application conditions with those of PPF and FPF purchased from the market revealed few differences in the physical and chemical properties of the three kinds of parquet flooring. The thermal conductivity of MPF was 0.195 $W{\cdot}m^{-1}{\cdot}K^{-1}$, which was lower than that of PPF and FPF. Therefore, MPFs are a better heat-insulating material among construction engineering materials. The sound absorption coefficient of MPF in the frequency range of 0.2 to 2 kHz was higher than that of PPF and FPF under the same frequency conditions. The sound absorption coefficient of parquet flooring increased with an increase in sound frequency.

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