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Original Article

A Study on the Evaluation and Improvement of Permeability in Radial and Tangential Section of Domestic Softwoods[1]

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ABSTRACT

The purpose of this research was to evaluate the vapor permeability of nine different species of domestic softwood and the vapor permeability evaluation through the production of small wall structures for the developing applications, utilizing the vapor permeability of wood. In addition, the permeability evaluation was attempted by means of the production of a small wall structure injected with a waste material, bottom ash, as a moisture absorbent for improving the permeability. Consequently, the results of the vapor permeability evaluation by means of S_d value are as follows: (1) It was observed that *Abies holiphylla*, *Picea jezoensis*, *Ginkgo biloba*, *Pinus koraiensis* and *Pinus rigida* are permeable to moisture among 9 species of domestic softwood in Korea. (2) By means of this, semi-permeability efficiency was evaluated when producing a small wall structure. (3) Besides, improved effects of permeability were evaluated when producing a small wall structure inserted with bottom ash. As a result, it was confirmed that the S_d value of *Pinus koraiensis* turned out to be 1.63, which is superior to other 8 tree species.

Keywords: permeability, S_d value, bottom ash, moisture transport

1. INTRODUCTION

Indoor air quality is deteriorated by harmful chemicals such as formaldehyde and volatile organic compounds (VOCs) emitted from indoor building materials and household goods (Kim *et al*., 2011). Harmful chemicals released indoor are not enough to threaten the lives of indoor residents who spend most of their day, but long-term lifestyles have many effects on health, such as decreased immunity (Yoo *et al*., 2011). As interest in indoor air quality hazardous substances and interest in eco-friendly materials increase, the case of interior design using wood, which is a natural material has increased (Park *et al*., 2015).

Wood is a material excellent in humidity control, heat insulation, electrical resistance, sound insulation, impact resistance, and abrasion resistance, and provides a comfortable interior by controlling the temperature and humidity of the room (Kim *et al*., 2004; Lee *et al*., 2014; Yang *et al*., 2020; Yang *et al*., 2020).

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Among the characteristics of wood, heat insulation and humidity control are related to anatomical characteristics such as micropores and pit of wood. The moisture movement through the micropores caused by the differences of humidity conditions and water vapor pressure is defined as wood vapor permeability (Lim *et al*., 2006). Moisture permeability can be controlled indoor humidity due to the difference in water vapor pressure by moisture absorption in the high water vapor pressure and dehumidification in the low water vapor pressure (Lee, 1996).

However, the moisture permeability of wood differs depending on the species, density, sapwood and core, and the shape of the pitting, and the moisture permeability differs in the order of three sections of wood: cross section, radial section, and tangential section (Siau, 1984).

In particular, the flow of material is more advantageous in softwoods than in hardwoods, and more advantageous between the bordered pit of the axial trachied in tangential direction. It depends on the capillary structure of the axial trachied and pit structure in axial direction and the ray parenchyma help the horizontal flow. Air flow in the tangential direction is about 130 times less than the axial flow (Petty, 1970; Flynn, 1995). Radial direction liquid penetration is moved by the ray parenchyma and connected to the conduit ray-vessel tissue inter-wall to facilitate the radial direction of the liquid movement (Chun, 2017).

Recent government policy has increased interest in wooden buildings with low thermal conductivity compared to other architectural materials due to the strengthening of the thermal perfusion rate of buildings. In particular, the wooden structure is constructed with a waterproof paper that makes it possible to prevent the penetration of moisture inside and outside the structure member wood and control humidity. As the construction case of high-rise wooden buildings has increased using a large wood panel, Cross Laminated Timber, the study of the permeability, permeability resistance evaluation and wall configuration for moisture has been conducted (Yoo *et al*., 2019; Jang *et al*., 2017). In order to improve the residential environment of the wooden building made of wood as porous material, moisture permeability is evaluated using moisture permeance, permeability rate, vapor resistance, and etc (Lee, 1992).

In addition, Bio Dryer Co., Ltd. in Japan, to minimize drying defects that occur during forced drying, a bio-dryer (Fig. 1) consisting of a wall made of wood is being developed and sold. The principle of the bio-dryer assumes that the dryer is a single large cell, and moisture transfers from the green wood put in the dryer to the outside so that it can be dried to less than 10% without drying defects of the wood. Mostly, tree species such as hard maple, which is difficult to dry, such as wood for repair of cultural properties and musical instruments, are dried at 35°C for 1 month to produce less than 8% dry wood (bio-drywood,

Fig. 1. Bio-dryer of Bio Dryer Co., Ltd. in Japan.

2018). However, in the domestic situation, studies on the use of broadleaf trees are being conducted as the accumulation of broadleaf trees in the country increases, but due to drying defects such as torsion and internal splitting during forced drying of hardwood, the sawn yield of oyster oak is as low as 30-40% (Jang *et al*., 2017).

In this study, in order to localize the bio dryer used in Japan, the evaluation of the moisture permeability of domestic softwood was conducted. In addition, in order to promote the movement of moisture generated in the wood drying process to the outside and improve the moisture permeability, the evaluation of the moisture permeability of a small wall filled with bottom ash, which is a coal ash emitted after coal combustion in a thermal power plant, was conducted. Through this, it is intended to improve the moisture permeability of wood by selecting the optimal species and using absrobent.

Bottom ash used in this study is classified into fly ash and bottom ash according to the specific gravity of the remaining ash from coal burned in the thermal power plant ad bottom ash a coal ash that is collected in the boiler lower reservoir (Maeng *et al*., 2014). Bottom ash is generated as little as about 15-20% of the total ash generated and difficult to recycle (Kim *et al*., 2009). It contains compounds such as SiO_2 and Al_2O_3 which is as remarkable in moisture absorption ability as diatomite and when bottom ash consisting of 50% SiO_2 is in contact with moisture, a small amount of SiO_2 gets rehydrated with CaO, which forms a hydrate on the surface to be used in where required adsorption adsorption performance is required (Moon *et al*., 2012).

2. MATERIALS and METHODS

2.1. Testing materials

2.1.1. Tree species

According to the pit structure of the domestic softwood in Korea, nine tree species that has such types of pit as piceoid, window-like, taxodioid, cupressoid, pinoid were selected as an testing tree species. Selected species are *Larix kaempferi*, *Pinus densiflora*, *Abies holophylla*, *chamaecyparis obtusa*, *picea jezoensis*, *Cryptomeria japonica*, *Ginkgo biloba*, *Pinus koraiensis*, *Pinus rigida* and the form of pit shape of the species and the distinction between the heartwood and the sapwood is shown as Table 1.

Table 1. Each species density and classified heartwood, sapwood

Species	Pit shape	Heartwood(H)/Sapwood(S)	
		Radial section	Tangential section
Abies holophylla	Taxodioid	H	H
Pinus koraiensis	Window-like	H	H
Picea jezoensis	Piceoid	H	H
Pinus rigida	Pinoid	H	H
Ginkgo biloba	Cupressoid	H	H
Pinus densiflora	Window-like	H	H
Cryptomeria japonica	Taxodioid	S(21.7%)+H(78.3%)	S(24.3%)+H(75.7%)
Larix kaempferi	Piceoid, Cupressoid	H	H
Chamaecyparis obtusa	Cupressoid	S(35.3%)+H(64.7%)	S(44%)+H(56%)

Table 2. Particle size and composition components of bottom ash

Particle size	Composition components					
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO
5-10 mm	55.9 %	24.17 %	7.77 %	1.01 %	1.34 %	1.53 %

Used specimen was cut down in YoungDong research forest, Chungnam Univ. and its surface was processed and tailored in the size of 100 mm (W) × 100 mm (L) × 15 mm (T) to make radial section and tangential section be large section. The specimen in air-dry condition with the percentage of moisture content, 11±0.3% was apportioned. The tailored specimen was used to measure its curing and weight until the temperature and humidity conditions reach the order of 24-hour period for moisture uniformization of the specimen in 35°C and 55% temperature and humidity conditions. Pre-treatment of it was completed at the point of reaching the constant weight and it was used as an testing material for measuring permeability resistance.

2.1.2. Bottom ash

Bottom ash was selected as a material for improving the effect of the permeability of the testing material. The bottom ash used at this time was used after drying until the time to reach the amount using a forced air dryer of 100±5°C with the water content 31.5%. The component and particle size of the bottom ash is shown as Table 2.

2.2. Test method

2.2.1. Wet cup test

For evaluating the performance of permeability of moisture generated inside to the outside, the permeability evaluation was processed according to types of species and cross section based on wet cup test, 「ISO 12572 Hydrothermal performance of building materials and products–Determination of water vapour transmission properties (ISO, 2001)」.

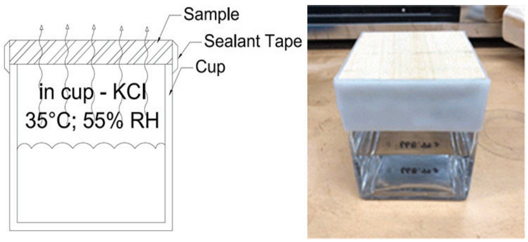

Fig. 2. Wet-cup test set-up model.

Specimens were prepared to dissolve the concentration of KCl (potassium chloride) aqueous solution to 85% and each 300 g of them was added to the glass cup. For comparing the permeability of the exposed section per species, the test sample was placed on a glass cup as shown Fig. 2 and sealed with moisture-proof tape in the area where the side of the specimen and the glass cup are attached. Moisture through the wood specimen was allowed to move in only one direction, and vapor generated inside the cup did not leak to the outside. The weight of the cup in a 24-hour period was measured while maintaining the condition of temperature 35°C and relative humidity 55% and the moment when the weight was changed by 5% than the initial was set as the moment to end the experiment, and the experiment was repeated three times.

2.2.2. Small wall test

For the application of domestic wood to bio-dryer walls, the top five species of test results in 2.2.1 were used to construct a small wall structure in the size of 100 mm (W) × 100 mm (L) × 50 mm (T) with interior space of 80 mm × 80 mm × 30 mm to measure the permeability of each species (Toyoshima and Suzuki, 2013).

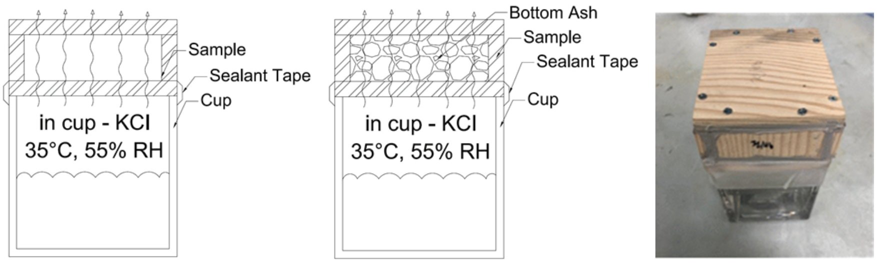

Fig. 3. Modified mock wall wet-cup test model.

If the moisture in the wall is not discharged easily to the outside in the process of wood drying of green wood condition, the moisture is condensed in the wall, which causes microorganisms such as mold in the bio-dryer wall to be propagated. By putting bottom ash into the internal space as a way to increase the discharge rate of moisture, changes in the permeability was measured. By applying the specifications of ISO-12572 used in experiment, 2.2.1, the test in regard with temperature, humidity, saturated aqueous solution was conducted in the same way.

The weight of the cup in a 24-hour period was measured while maintaining the condition of temperature 35°C and relative humidity 55% and the moment when the weight was changed by 5% than the initial was set as the moment to end the experiment, and the experiment was repeated three times.

2.2.3. Moisture-permeability calculation of the permeable air layer and a permeable resistance factor

For analysis on experiment results, the calculation formula specified in the ISO 12572 specification was utilized. Through the mass change rate of each permeable cup, a permeability resistance factor (μ, water vapor resistance factor) was calculated according to the tree species and cross-section. The formula for the calculation of permeability resistance factor is shown as in the equation (1). At this time, δ_α is humidity penetrability in the air 5°C, which is applied to by a constant, $\frac{1}{1.5\times10^6}$.

$$\mu = \frac{\delta_a}{\delta} \tag{1}$$

μ : Water vapour resistance factor (-)
δ_a : Water vapour permeability of air (kg/m·s㎩)
δ : Water vapour permeability of sample (kg/m·s㎩)

The moisture penetrability of the measuring material, δ was calculated using the equation (2) for the humidity penetrability of the equivalent air layer according to the saturated water vapor pressure (5,630 Pa) of the temperature condition satiated 35°C.

$$\delta = \frac{G \bullet d}{A \bullet \triangle p_a} \tag{2}$$

G : Mass change rate (kg/s)
A : Exposed area of sample (㎡)
$\triangle p_v$: Water vapour pressure difference across sample (㎩)
d : Thickness of sample (m)

The initial G (mass change rate) and the one after moisture absorption were calculated through the equation shown in (3) with the time (t_2-t_1) that takes up to a difference of weight (m_2-m_1) and a 5% increase in weight.

$$G = \frac{m_2 - m_1}{t_2 - t_1} \quad (3)$$

m_1 : Mass of sample at time, t_1 (kg)
m_2 : Mass of sample at time, t_2 (kg)
t_1, t_2 : time taken to change to 5% weight (s)

Water vapor pressure difference inside and outside the wood test specimen (Water vapor pressure difference across sample) was calculated in the condition of the experimental temperature and humidity (35°C, 55%) and through the equation (4).

$$\triangle p_v = \frac{\varphi}{100} \times 610.5 \times e^{\frac{17.269 \times \theta}{237.3 + \theta}} \quad (4)$$

φ : relative humidity (%)
θ : temperature (°C)

The permeable resistance coefficient value derived through the equation above is the value relatively compared to the permeability resistance of the floating air layer of the same thickness at the same temperature and the degree of permeability of each material was evaluated with S_d (equivalent air layer thickness) value, which multiplies the thickness of the specimen used in the test to μ value.

In this study, according to 「KS F 2607 : 2007 permeability measuring methods of building materials」 revised since 2007 based on the local circumstances, S_d value was calculated with the equation (5) and the permeability of materials was evaluated with three standards, Permeable, Semi-peremable, Impermeable. It is determined that the smaller S_d value as the resistance value is, the greater the permeability is and vice versa.

$$S_d = \mu \cdot d \quad (5)$$

μ: *Water vapour resistance factor* $(-)$
d: *Thickness of sample* (m)

3. RESULTS and DISCUSSION

In this study, in order to localize the bio-dryer that is used in Japan, through evaluation on the vapor permeability of domestic softwood in Korea and the permeability of a small wall discharged with bottom ash, improvement of vapor permeability of wood is attempted to improve by selecting the optimal tree species and using absorbent.

3.1. Comparison of permeability according to radial section and tangential section per species

The result of analysis on permeability by classifying into radial section and tangential section per species is found in Table 3, Fig. 4, and Fig. 5. *Abies holophylla*, *Picea jezoensis*, *Ginkgo biloba*, *Pinus densiflora*, and *Pinus rigida* whose S_d value is 1 or less than 1 showed as permeability and *Larix kaempferi*, *Cryptomeria japonica*, *Chamaecyparis obtusa* with a S_d value of 1 or more than 1 showed semi-permeability. In the case of *Pinus koraiensis*, S_d value of its radial section showed permeability and its tangential section showed are S_d value radiation cross-section is permeable, tangential cross-section showed semi-permeability. In the case of two species, *Ginkgo biloba* and *Cryptomeria japonica*, it was shown that their tangential section was more permeable than their radial section. In general, the radial section is known to be superior in permeability than the tangential section, but the permeability varies depending on the density of the wood, the ratio of the heartwood and the sapwood, the closure of the pit due to changing heartwood. The permeability of the wood varies depending on the density and water content of the wood, the composition of springwood and latewood. In the case of *Chamaecyparis obtusa*, the permeability rate of portion of the springwood and the latewood shows three times more than usual (Lee and Kim, 1992). The

Table 3. Each section of species permeability (μ) and S_d value

Species	Radial Section			Tangential Section		
	Density (g/㎤)	μ	S_d	Density (g/㎤)	μ	S_d
Abies holophylla	0.379±0.002	19.31	0.29	0.388±0.003	36.61	0.55
Pinus koraiensis	0.438±0.002	29.29	0.44	0.552±0.009	70.29	1.05
Picea jezoensis	0.417±0.002	34.45	0.52	0.470±0.003	38.2	0.57
Pinus rigida	0.474±0.001	46.24	0.69	0.472±0.001	40.86	0.61
Ginkgo biloba	0.439±0.001	56.68	0.85	0.445±0.002	28.81	0.43
Pinus densiflora	0.456±0.001	60.59	0.91	0.555±0.004	62.76	0.94
Cryptomeria japonica	0.381±0.001	92.48	1.39	0.400±0.001	109.82	1.65
Larix kaempferi	0.521±0.002	103.36	1.55	0.445±0.002	351.44	5.27
Chamaecyparis obtusa	0.497±0.002	292.86	4.39	0.479±0.001	73.22	1.1

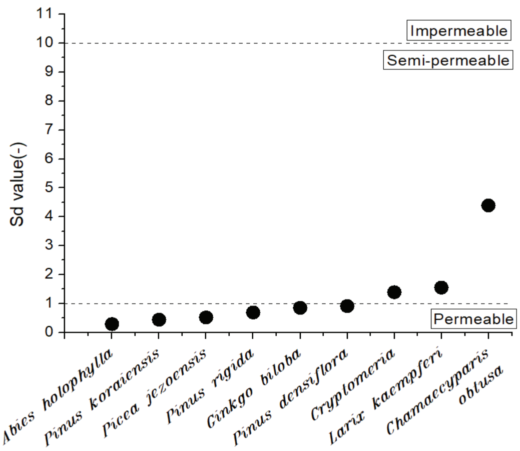

Fig. 4. Radial section of S_d value.

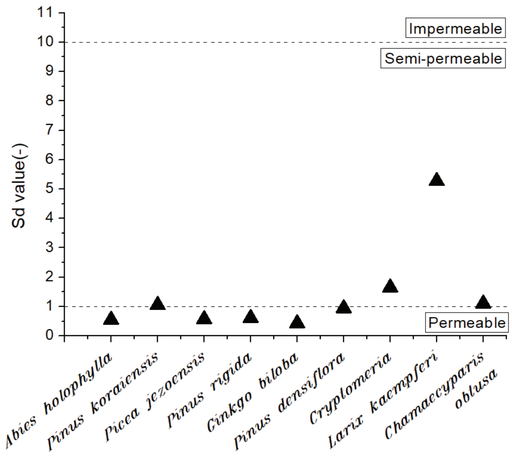

Fig. 5. Tangential section of S_d value.

bordered pit pair of sapwood portion serves as a channel for moisture, but the pit of the heartwood portion doesn't make the movement of moisture smooth due to the displacement of the torus (Kang *et al*., 2008).

The increase in the heartwood ratio among heartwood and sapwood ratio (Table 2) of the specimen makes difference in permeability despite the same tree species, and it is determined that in the case of using a bio-dryer wall, methods of sawing and the composition ratio of heartwood and sapwood should be considered.

3.2. Permeability results of small walls

3.2.1. Small walls per species

The walls of bio-dryer actually are manufactured for a wall structure made of the outer wall and the inner wall, and the permeability of the small wall was evaluated to compare the difference between the species according to the inner air layer. For smooth discharge of water vapor inside the dryer, the moisture permeability of small walls was evaluated with five species of high moisture *Abies holophylla*, *Picea jezoensis*,

Table 4. Each mock wall permeability (μ) and S_d value

Species	Radial Section		Tangential Section	
	μ	S_d	μ	S_d
Abies holophylla	52.72	2.64±0.35	97.9	4.89±0.2
Picea jezoensis	84.62	3.61±0.25	146	6.2±0.06
Pinus koraiensis	89.32	3.81±0.67	76.1	5.27±0.61
Pinus rigida	91.37	4.57±0.38	85.7	9.79±0.13
Ginkgo biloba	80.39	3.43±0.12	39.2	1.67±0.14

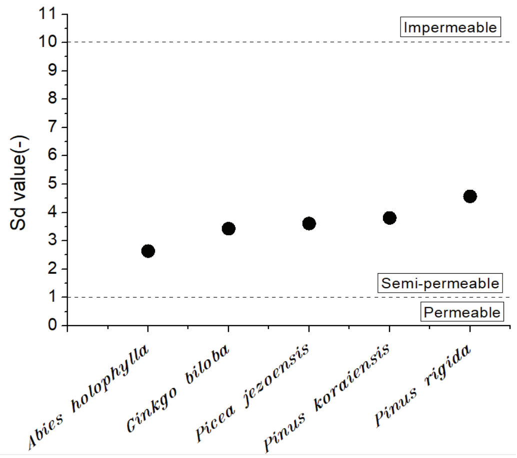

Fig. 6. Radial section S_d value of Mock wall.

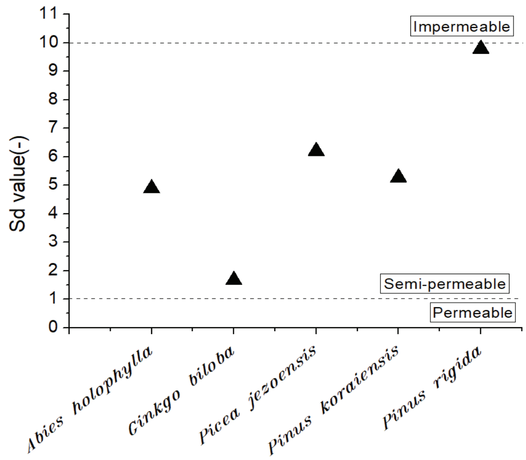

Fig. 7. Tangential section S_d value of Mock wall.

Pinus koraiensis, *Pinus rigida*, *Ginkgo biloba* through the moisture permeability evaluation result according to the previous wood species. The results are shown in Table 4, same as Fig. 6 and 7. Small wall manufactured for the wall structure showed the decrease of permeability regarding 5 tree species due to the increase in wood thickness as the wall structure, although the air layer inside did not affect the permeability resistance. Wall structure consisting of radial section rather than tangential section made it easy for the moisture to move and showed the permeability of tangential section turned out to be about twice higher than that of radial section. High permeability of radial section was shown in the order of *Abies holophylla*, *Ginkgo biloba*, *Picea jezoensis*, *Pinus koraiensis*, *Pinus rigida*. High permeability of tangential section was shown in the order of *Ginkgo biloba*, *Abies holophylla*, *Pinus koraiensis*, *Piecea jezoensis*, *Pinus rigida.*

Among them, *Ginkgo biloba* showed higher moisture permeability in the tangential direction than in the radial direction, and it was believed that it was due to the mixing of the radial section and the imbalance of the wood material during the sawing.

3.2.2. Bottom ash filling wall for improving permeability

Through the small wall test, the moisture permeability decreased due to the increase in the thickness of the wood and the moisture permeability was evaluated by filling 100% of the bottom ash inside the

Table 5. Each mock wall permeability (μ) and S_d value added bottom ash

Species	Radial Section		Tangential Section	
	μ	S_d	μ	S_d
Pinus koraiensis	1.14	1.63±0.21	44.21	2.21±0.48
Picea jezoensis	1.63	1.9±0.18	38.07	1.9±0.61
Abies holophylla	2.28	2.21±0.34	50.76	2.54±0.22
Ginkgo biloba	2.98	2.54±0.65	32.63	1.63±0.12
Pinus rigida	5.71	2.98±0.53	59.59	2.98±0.24

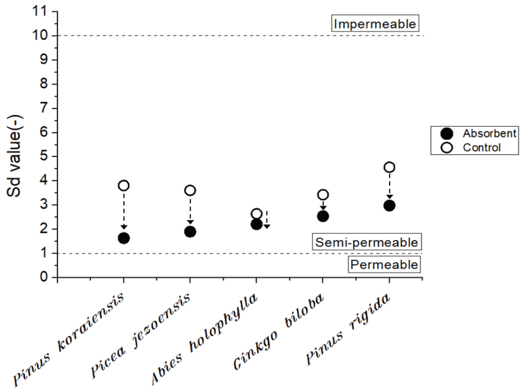

Fig. 8. Radial section S_d value of Mock wall added Bottom ash.

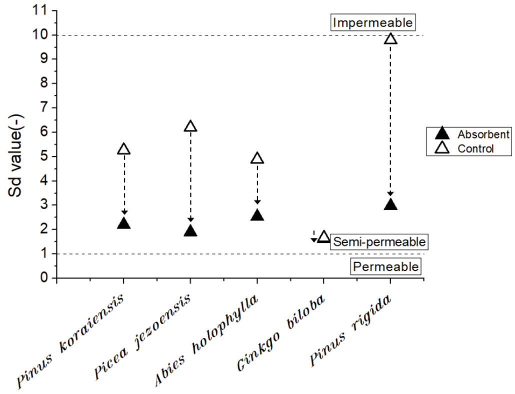

Fig. 9. Tangential section S_d value of Mock wall added Bottom ash.

small wall for smooth discharge of vapor inside the dryer. The results are shown in Table 5, Fig. 8 and Fig. 9. The permeability of the radial section was improved by 36.4% on average and in particular, the permeability of *Picea jezoensis* was improved by 54.8%, and that of *Pinus koraiensis* was improved by 50.1%. The permeability of the tangential section was excluded as the improvement effect of the *Ginkgo biloba* wall is as small as 2.4%, the permeability of four species was by 61.5% on average. Tangential section is known to make the moisture movement inefficient, but the fluid adsorption force of bottom ash as moisture absorbent is greater than the internal water vapor pressure by the wood anatomical structure. Particularly, the permeability of tangential section was improved, which is why it is determined to show the similar results as the radial section.

4. CONCLUSION

In this study, in order to localize the bio-dryer that is used in Japan, through evaluation on the vapor permeability of domestic softwood in Korea and evaluation on the permeability of a small wall discharged with bottom ash, it was attempted to select the optimal tree species and the results are as follows.

1. *Abies holophylla*, *Piecea jezoensis*, *Ginkgo biloba*, *Pinus densiflora*, *Pinus rigida* whose S_d value is 1 or less than 1 out of nine domestic softwoods in Korea showed permeability and *Larix kaempferi*, *Cryptomeria japonica*, *Chamaecyparis obtusa* with a S_d value of 1 or more than 1 showed semi-permeability.
2. In an attempt to make the discharge of water vapor inside the dryer easy, the small walls were

evaluated using 5 wood species that showed permeability. As a result, the increase of the thickness of wood due to the wall structure showed semi-permeability and in order to improve the vapor permeability, it was attempted to put bottom ash in, which resulted in the improvement for radial section, 36.4% on average and tangential section, 61.5% on average (except for *ginkgo biloba*).

Through evaluation on the permeability of the same thickness of wood, small wall, moisture absorbent with small wall, and through the improvement effect by means of permeability per species and moisture absorbent, *Pinus koraiensis* and *Picea jezoensis* were derived as the optimum species for the wall of bio-dryer.

Sawn lumber produced in Korea is mostly for flat sawn with high yield rate because of the issue of yield problems resulted from types of sawing and sawn as flat sawn and quarter sawn. In order for flat sawn to be applied for bio-dryer, it is determined that optimization studies on the elements such as moisture absorbent type and input ratio, wall thickness for the permeability improvement are needed.

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APPENDIX

(Korean Version)

국산 침엽수의 방사, 접선단면의 투습성 평가와 개선방안에 관한 연구

초록 : 본 연구는 목재의 투습성을 활용한 용도개발을 위해 국산 침엽수 9개 수종에 대한 투습성 평가와 소형 벽체 구조 제작을 통한 투습성 평가를 하고자 하였다. 또한, 투습성 개선을 위해 폐자재인 bottom ash를 흡습제로 투입한 소형 벽체를 제작하여 투습성을 평가하였다. 그 결과, S_d 값에 의한 투습성 평가 결과는 다음과 같다. ① 국산 침엽수 9개 수종 중 *Abies holiphylla*(잣나무), *Picea jezoensis*(가문비나무), *Ginkgo biloba*(은행나무), *Pinus koraiensis*(잣나무) *and Pinus rigida*(리기다 소나무)는 투습 성능을 나타내는 것을 확인하였다. ② 이를 이용하여 벽체 구조 제작 시 반투습 성능을 나타냄을 평가하였다. ③ 또한, Bottom ash를 투입한 소형 벽체 구조를 제작하여 투습성 개선 효과를 평가한 결과, *Pinus koraiensis*(잣나무)의 S_d 값이 1.63으로 나타나, 8개 타 수종보다 우수함을 확인하였다.

1. 서 론

실내의 건축자재 및 생활용품으로부터 방출되는 포름알데히드나 휘발성 유기화합물(VOCs) 등과 같은 유해화학물질에 의해 실내공기질이 악화된다(Kim *et al*., 2011). 실내에 발생되는 유해화학물질은 하루 중 대부분 시간을 보내는 실내거주자들의 생명을 위협할 정도는 아니지만 장기간 생활하면 면역력 저하 등 건강에 많은 영향을 끼친다(Yoo *et al*., 2011). 실내공기질 유해물질에 대한 관심도가 높아지면서 친환경 소재에 대한 관심도가 높아지고 있으며 천연 재료인 목재를 이용한 실내 인테리어 사용 사례가 증가하고 있다(Park *et al*., 2015). 목재는 조습성, 단열성, 전기저항성, 차음성, 내충격성, 내마모성 등이 우수한 재료이며 실내의 온·습도 조절을 통하여 쾌적한 실내를 제공한다(Kim *et al*., 2004; Lee *et al*., 2014; Yang *et al*., 2020; Yang *et al*., 2020). 목재의 특성 중 단열성과 조습성은 목재의 미세공극, 벽공 등과 같은 해부학적 특성과 관련 있다. 온·습도 조건과 수증기압 차이로 인해 발생하는 미세공극을 통한 수분 이동을 목재 투습성이라 정의한다(Lim *et al*., 2006). 투습성은 수증기압 차이에 의해 수증기압이 높은 쪽에서는 흡습 현상, 낮은 쪽에서는 탈습현상으로 실내 습도조절이 가능하다(Lee, 1996).

그러나 목재의 투습성은 수종, 밀도, 변재와 심재, 벽공의 형태 등에 따라 다르며 목재 3단면인 횡단면, 방사단면, 접선단면 순으로 투습성이 다르다(Siau, 1984). 특히 활엽수보다 침엽수가 물질의 흐름이 유리하며 접선방향에서는 축방향가도관의 유연벽공 사이, 축 방향은 축방향가도관과 벽공 구조의 모세관 구조에 의존하며 방사유세포가 수평방향 흐름을 돕는다. 접선방향의 공기 흐름은 축 방향 흐름의 약 130배 정도 적다(Petty, 1970; Flynn, 1995). 방사방향 액체 침투는 방사유조직에 의해 이동되며 도관방사조직간 벽공과 연결되어 액체의 방사방향 이동을 용이하게 한다(Chun, 2017).

최근 정부 정책에 의하여 건축물의 열관류율 강화로 다른 건축소재에 비해 열전도도가 낮은 목조건축물에 대한 관심도가 증가하고 있다. 특히 목조건축물은 구조부재가 목재로 외부와 내부의 수분 침투를 막고 습도조절이 가능한 투습방수지 등을 함께 시공하고 있다. 고층목조건축물 시공사례가 증가하면서 대형목재패널인 Cross Laminated Timber를 이용하여 수분에 대한 투습성, 투습저항 평가 및 벽체 구성에 대한 연구가 진행된 바 있다(Yoo *et al*., 2019; Jang *et al*., 2017). 다공성 재료인 목재로 만들어진 목조 건축물의 주거환경 개선을 위하여 수분 투과성에 대해 투습계수, 투습률, 투습 저항 등을 이용하고 평가하고 있다(Lee, 1992).

또한 일본 불연목재에서는 강제건조 시 발생되는 건조결함을 최소화하기 위하여 목재를 이용하여 벽체가 구성된 바이오건조기(Fig. 1)를 개발 및 판매하고 있다. 바이오건조기 원리는 건조기를 하나의 큰 세포로 가정하여 건조기 내부에 투입된 생재 상태의 목재로부터 외부로 수분 이동시켜 목재의 건조결함 없이 10% 이하로 건조가 가능하다. 주로 문화재 보수용 목재, 악기 등 건조가 어려운 하드 메이플 같은 수종을 35℃에서 1개월 동안 건조하여 8% 이하 건조목재로 생산하고 있다(bio-drywood, 2018). 그러나 국내 상황은 국내 활엽수 임목 축적량 증가에 따라 활엽수의 용도개발에 대한 연구가 진행되고 있으나 활엽수 강제건조 시 비틀림, 내부할렬 등의 건조 결함으로 인하여 굴참나무의 경우 제재수율이 30-40% 정도로 낮다(Jang *et al*., 2017).

본 연구에서는 일본에서 사용되고 있는 바이오건조기를 국산화하기 위해 국산 침엽수종의 투습성 평가와 목재 건조 과정에서 발생되는 수분을 외부로 이동 촉진과 투습성 개선을 위해 화력발전소의 석탄 연소 후 배출되는 석탄회인 bottom ash를 충전한

소형벽체 투습성 평가를 통해 최적 수종을 선정과 흡습제를 이용하여 목재의 투습성을 개선하고자 한다.

본 연구에서 사용된 bottom ash(바텀애쉬)는 화력발전소에서 석탄을 태우고 남은 회분으로 비중에 따라 fly ash(플라이애쉬)와 bottom ash로 구분되며 bottom ash는 보일러 하부 저장조에서 포집되는 석탄회이다(Maeng *et al*., 2014). bottom ash는 전체 발생하는 회분의 15-20% 정도로 발생량이 적고 재활용이 어렵다(Kim *et al*., 2009). 흡습 능력이 뛰어난 규조토와 동일한 SiO_2와 Al_2O_3와 같은 화합물을 함유하고 있고 SiO_2가 50% 구성된 Bottom ash는 수분과 접촉 시 미량의 SiO_2가 CaO와 수화하여 표면에 수화물을 형성하여 흡착성능을 요구하는 곳에 사용되고 있다(Moon *et al*., 2012).

2. 재료 및 방법

2.1. 공시재료

2.1.1. 공시 수종

국산 침엽수종 중 벽공 구조에 따라 가문비형(piceoid), 창상형(window-like), 삼나무형(taxodioid), 편백형(cupressoid), 소나무형(pinoid) 벽공을 가진 9가지 수종을 공시 수종으로 선정하였다. 선정된 수종은 일본잎갈나무(*Larix kaempferi*), 소나무(*Pinus densiflora*), 전나무(*Abies holophylla*), 편백(*Chamaecyparis obtusa*), 가문비나무(*Picea jezoensis*), 삼나무(*Cryptomeria japonica*), 은행나무(*Ginkgo biloba*), 잣나무(*Pinus koraiensis*), 리기다소나무(*Pinus rigida*)로 수종의 벽공 형태와 심·변재 구분은 Table 1과 같다. 사용된 시험편은 충남대학교 영동학술림에서 벌채하여 표면 가공 및 100 mm (W) × 100 mm (L) × 15 mm (T) 크기로 방사단면과 접선단면이 넓은 단면이 되도록 재단하였으며 함수율 11±0.3%인 기건상태의 시험편 분양받았다. 재단된 시험편은 온습도 조건은 35℃, 55% 항온항습 조건에서 시험편의 수분 균일화를 위해 24시간 주기로 항량에 도달할 때 까지 양생 및 중량을 측정하였다. 항량에 도달하는 시점에서 전처리를 완료하고 투습저항 측정을 위한 공시재료로 사용하였다.

2.1.2. bottom ash

공시재료의 투습성의 효과를 개선하기 위한 재료로 bottom ash를 선정하였다. 이때 사용된 bottom ash는 함수율 31.5%로 100±5°C의 강제송풍식 건조기를 이용하여 항량에 도달할 때 까지 건조 후 사용하였다. bottom ash의 성분 및 입자크기는 Table 2와 같다.

2.2. 실험 방법

2.2.1. Wet cup test

내부에서 발생한 수분을 외부로 투습하는 성능평가를 위해 「ISO 12572 Hygrothermal performance of building materials and products–Determination of water vapour transmission properties(ISO, 2001)」 Wet cup test 규정에 따라 수종별 및 단면별 투습성 평가를 진행하였다. 시편은 KCl(염화 칼륨) 수용액의 농도를 85%로 용해 제조하여 유리컵에 각 300g씩 투입하였다. 수종별 노출단면의 투습성 비교를 위해 Fig. 2와 같이 유리컵 위에 시험편을 올려놓고 시험편의 옆면과 유리컵이 만나는 부위를 방습테이프로 밀폐하였다. 목재 시편을 통한 수분이 한쪽 방향으로만 이동하게 하였으며 컵 내부에서 발생한 수증기가 외부로 새지 않도록 하였습니다. 온도 35°C, 상대습도 55% 항온항습 조건을 유지하여 24시간 주기로 컵의 중량을 측정하였으며 초기보다 중량이 5% 변화된 시점을 실험 종료 시점으로 설정하였으며 3회 반복하여 실험하였다.

2.2.2. 소형 벽체 실험

바이오 건조기 벽체에 국산 목재 적용을 위하여 2.2.1의 실험 결과의 상위 5개 수종을 이용하여 내부 공간 80 mm × 80 mm × 30 mm를 포함하는 100 mm (W) × 100 mm (L) × 50 mm (T) 규격의 소형 벽체구조를 제작하여 수종별 투습성을 측정하였다(Toyoshima and Suzuki, 2013). 생재상태의 목재 건조 과정에서 벽체에서 수분이 외부로 원활하게 배출되지 않으면 벽체 내부에 수분이 응결되어 바이오 건조기 벽체에 곰팡이 등의 미생물이 번식하게 된다. 수분의 배출 속도를 증가시키기 위한 방안으로 내부 공간에 Bottom ash를 투입하여 투습성의 변화를 측정하였다. 실험 2.2.1에서 이용한 ISO-12572의 규격을 응용하여 온도, 습도, 포화 수용액 등 시험 과정을 동일하게 진행하였다. 온도 35°C, 상대습도 55% 항온항습 조건을 유지하여 24시간 주기로 컵의 중량을 측정하였으며 초기보다 중량이 5% 변화된 시점을 실험 종료 시점으로 설정하였으며 3회 반복하여 실험하였다.

2.2.3. 투습저항계수 및 등가 공기층의 습기 투과성 산출

실험 결과 분석에는 ISO 12572 규격에 명시된 계산식을 활용하였다. 각 투습 컵의 질량 변화율을 통해 수종 및 단면에 따른 투습저항계수(μ, water vapor resistance factor)를 산출하였으며 투습 저항계수 산출을 위한 식은 식 (1)과 같다. 이때,

δ_α는 공기 5°C에서의 습기 투과성으로 $\frac{1}{1.5\times10^6}$ 상수를 적용한다.

$$\mu = \frac{\delta_a}{\delta} \tag{1}$$

μ : Water vapour resistance factor (-)
δ_a : Water vapour permeability of air (kg/m·s㎩)
δ : Water vapour permeability of sample (kg/m·s㎩)

δ은 측정재료의 습기투과성은 항온조건인 35℃의 포화수증기압(5,630㎩)에 따른 등가 공기층의 습기투과성은 식 (2)를 이용하여 계산하였다.

$$\delta = \frac{G \cdot d}{A \cdot \triangle p_a} \tag{2}$$

G : Mass change rate (kg/s)
A : Exposed area of sample (㎡)
$\triangle p_v$: Water vapour pressure difference across sample (㎩)
d : Thickness of sample (m)

G(mass change rate)는 초기와 흡습 후 중량의 차(m_2-m_1)와 중량 5% 증가까지 소요되는 시간(t_2-t_1)으로 다음 식 (3)을 통하여 계산하였다.

$$G = \frac{m_2 - m_1}{t_2 - t_1} \tag{3}$$

m_1 : Mass of sample at time, t_1 (kg)
m_2 : Mass of sample at time, t_2 (kg)
t_1, t_2 : time taken to change to 5% weight (s)

목재 시험편 내·외부의 수증기압 차이(water vapour pressure difference across sample)는 실험 온·습도 조건(35℃, 55%)과 식 (4)를 통해 계산하였다.

$$\triangle p_v = \frac{\varphi}{100} \times 610.5 \times e^{\frac{17.269\times\theta}{237.3+\theta}} \tag{4}$$

φ : relative humidity (%), θ : temperature (°C)

위 식을 통해 도출되는 투습저항계수 값은 같은 온도에서 같은 두께의 부동 공기층의 투습 저항과 상대 비교한 값으로서 μ 값에 시험에 사용된 시험편의 두께를 곱하여 S_d(등가 공기층 두께) 값으로 각 재료의 투습성의 정도를 평가하였다. 본 연구에서는 국내 실정에 맞추어 2007년 이후 개정된「KS F 2607 : 2007 건축 재료의 투습성 측정 방법」에 따라 식 (5)을 통해 S_d 값을 계산하여 투습(Permeable), 반투습(Semi-peremable), 불투습(Impermeable) 3가지 기준으로 재료의 투습성을 평가하였다. S_d 값은 저항값으로 작을수록 투습성이 높으며 클수록 투습성이 낮다고 판단할 수 있다.

$$S_d = \mu \cdot d \tag{5}$$

μ: *Water vapour resistance factor* $(-)$, d: *Thickness of sample* (m)

3. 결과 및 고찰

본 연구에서는 일본에서 사용되고 있는 바이오건조기를 국산화하기 위해 국산 침엽수종의 투습성 평가와 bottom ash를 충전한 소형벽체 투습성 평가를 통해 최적 수종을 선정과 흡습제를 이용하여 목재의 투습성 개선에 관한 연구를 하였다.

3.1. 수종별 방사, 접선단면에 따른 투습성 비교

수종별 방사단면과 접선단면으로 구분하여 투습성을 분석한 결과는 Table 3과 Fig. 4, Fig. 5와 같다. S_d 값이 1 이하인 전나무, 가문비나무, 은행나무, 소나무, 리기다소나무는 투습, S_d 값이 1 이상인 일본잎갈나무, 편백, 삼나무는 반투습성을 나타냈다. 잣나무는 S_d값이 방사단면은 투습, 접선단면은 반투습의 결과를 나타냈으며 은행나무와 편백 2개 수종은 방사단면보다 접선단면의 투습성이 높게 나타났다. 일반적으로 방사단면이 접선단면 보다 투습성이 우수하다고 알려져 있으나 목재의 밀도, 심·변재 비율, 심재화로 인한 벽공의 폐쇄 여부에 따라 달라진다. 목재의 투습성은 목재 밀도와 함수율, 춘재부와 추재부 구성에 따라 투습율 다르다. 삼나무의 경우 춘재부와 추재부의 투습률은 약 3배 차이를 나타낸다(Lee and Kim, 1992). 변재부의 유연벽공대는 수분 통로의 역할을 하지만 심재부의 벽공은 토러스의 변위로 폐색벽공대화 되어 수분 이동이 원활하지 않다(Kang *et al*., 2008). 시험편의 심·변재 비율(Table 2) 중 심재 비율 증가는 폐색벽공의 증가로 인하여 동일 수종이라도 투습성의 차이를 나타낼 수 있으며 이는 바이오건조기 벽체로 사용 시 제재 방법과 심·변재 구성 비율도 고려하여야 할 것으로 판단된다.

3.2. 소형 벽체의 투습성 결과

3.2.1. 수종별 소형 벽체

실제 바이오 건조기 벽체는 외벽과 내벽이 존재하는 벽체구조로 제조되며 내부 공기층에 따라 수종 간 차이를 비교하고자 소형 벽체의 투습성을 평가하였다. 건조기 내부의 수증기의 원활한 배출을 위하여 앞선 목재 수종에 따른 투습성 평가 결과를 통해 투습성이 높은 전나무, 가문비나무, 리기다소나무, 잣나무, 은행나무의 5가지 수종으로 소형 벽체 투습성을 평가하였으며 그 결과는 Table 4, Fig. 6, 7과 같다.

벽체구조로 제조된 소형 벽체는 내부의 공기층은 투습저항 계수에 영향을 미치지 않지만 벽체구조로 목재 두께 증가로 인하여 5가지 수종에 대해서 투습성이 감소하였다. 접선단면보다 방사단면으로 구성된 벽체구조가 수분의 이동이 용이하며 투습성은 접선단면이 방사단면보다 약 2배 높은 결과를 나타냈다. 방사단면은 전나무, 은행나무, 가문비나무, 잣나무, 리기다소나무 순으로 접선단면은 은행나무, 전나무, 잣나무, 가문비나무, 리기다소나무 순서로 높은 투습성을 나타냈다. 이 중 은행나무에서 방사방향보다 접선방향에서 투습성이 높은 결과를 나타났으며 제재 시 방사단면의 혼합과 목재 재질의 불균형으로 인한 것으로 판단된다.

3.2.2. 투습성 개선을 위한 bottom ash 충진 벽체

소형 벽체 실험을 통하여 목재 두께 증가에 따른 투습성이 저하되었으며 건조기 내부의 수증기의 원활한 배출을 위하여 소형 벽체 내부에 bottom ash를 100% 충진하여 투습성을 평가하였으며 그 결과는 Table 5, Fig. 8, 9와 같다. 방사단면의 투습성이 평균 36.4% 개선되었으며 특히 가문비나무 54.8%, 잣나무 50.1% 투습성이 향상되었다. 접선단면의 투습성은 은행나무 벽체의 개선 효과가 2.4%로 작아 제외하였으며 4개 수종은 평균 61.5% 투습성이 향상되었다. 접선단면은 수분 이동이 용이하지 않다고 알려져 있으나 목재 해부학적 구조에 의한 내부 수증기압보다 흡습제인 bottom ash의 유체 흡착력이 커 특히 접선단면의 투습성이 개선되어 방사단면과 유사한 결과를 나타낸 것으로 판단된다.

4. 결 론

본 연구에서는 일본에서 사용되고 있는 바이오건조기를 국산화하기 위해 국산 침엽수종의 투습성 평가와 bottom ash를 충전한 소형벽체 투습성 평가를 통해 최적 수종을 선정하고자 하였으며 그 결과는 다음과 같다.

1. 국산 침엽수 수종 9종 중 전나무, 가문비나무, 은행나무, 소나무, 리기다소나무는 방사·접선 단면에서 S_d 값이 1 이하로 투습성을 이외 일본잎갈나무, 편백나무, 삼나무, 소나무는 S_d 값이 1 이상으로 반투습성을 나타냈다.
2. 건조기 내부의 수증기의 원활한 배출을 위하여 투습성을 나타낸 5개 수종을 이용하여 소형벽체를 평가하였으며 벽체구조로 인한 목재 두께 증가로 반투습을 나타냈고, 투습성 개선을 위하여 bottom ash를 투입한 결과 방사단면 평균 36.4%, 접선단면 평균 61.5%(은행나무 제외)의 개선 효과를 나타냈다.

동일한 두께의 목재, 소형 벽체, 흡습제 충진형 소형벽체의 투습성 평가를 통하여 수종별 투습성과 흡습제에 의한 투습성 개선 효과를 통하여 바이오 건조기용 벽체로는 잣나무와 가문비나무가 최적 수종으로 도출하였다. 국내 생산되는 제재목은 제재방식에 따른 수율 문제로 수율이 높은 판목 제재 위주이며 판목과 정·판목으로 제재된다. 판목을 바이오 건조기 벽체로 적용하기 위해서는 투습성 향상을 위한 흡습제 종류와 투입비율, 벽체 두께 등 요소에 관한 최적화 연구가 필요할 것으로 판단된다.