Failure Behavior in Mechanical Testing of Two Plywood Products Distributed in Korea

In-Hwan Lee, Min Lee,* Eun-Chang Kang, Yonggun Park, and Sang-Min Lee *

The structural performance was tested for two plywood products distributed in South Korea: Plywood for roof (RP) and plywood for concrete form (CP), in accordance with ASTM standards. The evaluation included tests for tensile-shear strength under wet conditions, bending performance, compressive strength, and rolling shear strength. Results indicated that the CP specimens exhibited a compressive strength of 37 MPa, surpassing that of structural cross-laminated timber (CLT) with comparable specific gravity. The bending performance of CP plywood was also notable, with a modulus of rupture of 56.8 MPa and a modulus of elasticity of 12 GPa. The rolling shear strength was measured at 2.4 MPa, which is favorable compared to the rolling shear strengths of European structural wood species. Notably, the failure pattern was ideal. Furthermore, the CP specimens demonstrated excellent adhesive strength in the tensile-shear test after cyclic boiling, both meeting and exceeding the Korean standards for structural plywood in all evaluated aspects. In contrast, the RP specimens did not fully meet some of the Korean standards, indicating areas for improvement in structural applications.

DOI: 10.15376/biores.20.1.413-425

Keywords: Bending performance; Compressive strength; MOR; MOE; Shear strength; Plywood for concrete form; Plywood for roof; Rolling shear strength

*Contact information: Wood Engineering Division, Forest Products and Industry Department, National Institute of Forest Science, 57 Hoegi-ro, Dongdaemun-gu, Seoul 02455, Republic of Korea; *Corresponding authors: mlee81@korea.kr, sml5@korea.kr*

INTRODUCTION

Plywood plays a pivotal role in the design and construction of buildings and various structures, and its applications and performances are subjects of ongoing research (Hrázský and Král 2005; Kang *et al*. 2017; Laccone *et al*. 2020; Park and Jo 2020; Wen *et al*. 2020; Fekiač *et al*. 2021; Liu *et al*. 2021; Santarbárbara *et al*. 2022). Plywood is generally categorized into structural and non-structural types, each serving distinct applications with specific performance characteristics.

Structural plywood is engineered for load-bearing applications in construction, such as beams, hoardings, roof bracing, walls, and flooring (Suh *et al*. 2012). It is specifically designed for environments requiring high durability and strength, with enhanced resistance to climatic variations and moisture exposure. In contrast, non-structural plywood is not intended for load-bearing purposes and is more susceptible to damage from extreme temperatures and humidity fluctuations, rendering it unsuitable for structural applications or outdoor use. Non-structural plywood is primarily utilized for interior decoration or temporary applications and is generally more cost-effective and readily available than its structural counterpart.

The plywood predominantly produced in South Korea are generally categorized as plywood for roof (RP) and plywood for concrete form (CP). These two types of plywood materials are made for special purposes, with enhanced durability and water resistance compared to non-structural plywood. The RP material is used in the construction of building roofs, where resistance to climatic changes, long-term durability, and structural stability are essential (Lee *et al*. 2000). In contrast, the CP is employed to support concrete forms and must withstand high moisture levels and pressure during the concreting process. Consequently, CP must exhibit robust structural stability, moisture resistance, and durability for repeated use, as these properties directly influence the quality and longevity of the resulting concrete structures.

The assessment of RP and CP types of plywood is critical to ensure their suitability for structural applications, particularly in environments that demand high performance and reliability under varying environmental conditions. The tensile-shear strength test after cyclic boiling evaluates the plywood’s resistance to shear forces under moisture exposure, offering critical insights into its structural stability under practical environmental conditions. The bending performance test assesses the load-bearing capacity of plywood, which is fundamental for determining its overall strength and durability in structural applications. The compressive strength evaluation investigates the plywood's suitability for use in columns or wall applications by evaluating its ability to withstand compressive loads, while the rolling shear strength test measures the internal shear stresses within the plywood, providing an understanding of its capacity to resist shear forces (Oh 2018).

This study aimed to objectively assess the performance of commercially available plywood in South Korea, where evaluations based on material properties and failure patterns have been limited. Specifically, it examined the compliance of these plywood products with Korean standards for structural plywood required in construction and structural applications. The findings are expected to provide valuable insights into the suitability of plywood for various structural applications and offer recommendations for its optimal use in building and structural design. Ultimately, this research supports more reliable material selection and performance evaluation in designs incorporating plywood, thereby contributing to enhanced structural reliability and integrity.

EXPERIMENTAL

Materials

The materials under investigation included plywood for roof (RP) and plywood for concrete form (CP), both manufactured by Company E in South Korea. The species of RP used in this study was radiata pine (*Pinus radiata*) from Chile, aged over 20 years. The average specific gravity of this wood was 0.53. The RP plywood was composed of five veneers, each with a thickness of 2.3 mm, resulting in a total average thickness of 11.5 mm. The CP used in this study was a 7-ply composite, featuring a core layer composed of five plies of radiata pine (*Pinus radiata*) from Chile. The face and back layers were composed of mixed species imported from China under the name mixed light hardwood (MLH). The core veneers had an average thickness of 2.35 mm, while the face and back layers had an average thickness of 0.35 mm, leading to a total average thickness of 12.5 mm. The CP also had an average specific gravity of 0.53. The adhesive used in both plywood types was a melamine-urea-formaldehyde (MUF) resin, supplied by Company A, with a melamine content of 20%.

Tensile-Shear Strength Test of Plywood after Cyclic Boiling

The tensile-shear strength test was conducted according to the KS F 3101 (2016) Korean standard, with test specimens prepared accordingly. The test specimens were categorized based on the glued line, and tests were performed with 20 specimens for each category. The plywood specimens were immersed in boiling water for 4 h, then allowed to dry for 20 h, and subsequently re-immersed in boiling water for another 4 h. After that, they were cooled in room-temperature water for 1.0 h before conducting the test while still wet. The test, as shown in Fig. 1 - a, was designed to apply shear loads to the adhesive layers. The test was performed using a universal testing machine (UTM; 50ST, Tinius Olsen, Kongsberg, Norway) at a speed of 0.5 mm/min. The adhesion strength was calculated according to Eq. 1, providing a quantitative assessment of the adhesive bond strength under the specified conditions.

This methodology aimed to simulate the effects of cyclic moisture exposure on the adhesive performance of plywood, offering insights into its structural integrity and suitability for practical applications. The bonding strength is given by Eq. 1,

$$\text{Bonding strength (MPa)} = P\text{max} / (b \times h) \qquad (1)$$

where P_{max} is maximum load (N), b is the width of the panel (mm), h is the thickness of the panel (mm).

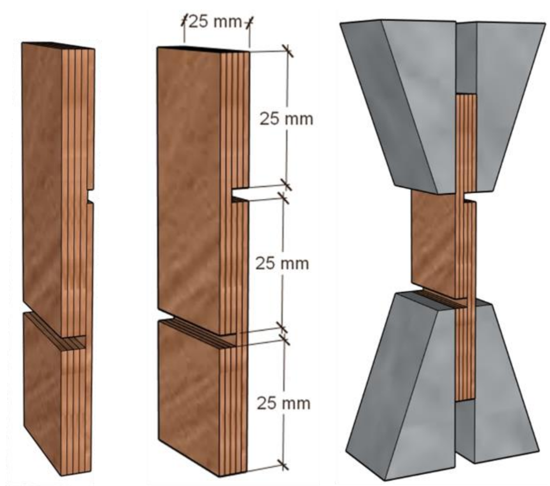

Fig. 1. Shape of tensile-shear strength specimen (a: 1-layer bonding line specimen, b: 2-layer bonding line specimen, c: shape of testing specimen)

Compressive Strength Test

The compressive strength test was conducted in accordance with ASTM D3501-05 (2018) standards. The compressive specimens were categorized based on the type of plywood and the direction of the fibers, with 10 specimens tested for each category. Specimens were prepared with dimensions of 200 mm by 300 mm, and the test setup is illustrated in Fig. 2. The specimens were supported to prevent bucking effects in the front and back directions. The test was conducted at a constant loading rate of 2 mm/min until specimen failure. During the test, load measurements were obtained using a 200 kN load cell positioned above the specimen, and deformation was precisely monitored using a 25 mm Linear Variable Differential Transducer (LVDT; CDP-25, TML, Tokyo, Japan) mounted at the center of the specimen on a UTM (Instron 5585, Instron, Norwood, MA, USA). The compressive modulus of elasticity (MOE) was calculated using Eq. 2, while the compressive strength was determined using Eq. 3, as specified by ASTM D3501-05 (2018). This testing protocol was designed to provide accurate assessments of the compressive properties of the plywood, including its load-bearing capacity and deformation characteristics under compressive loads, which are critical for evaluating its structural performance in practical applications.

$$E_c = (P/d) \cdot (L)/A \tag{2}$$

where E_c is compressive modulus of elasticity (MPa), P/d is slop of the linear portion of load-deformation curve (N/mm), L is deformation gage length (mm), and A is cross-sectional area (mm^2). The compressive strength (MPa) was calculated using Eq. 3,

$$F_c = P_{max}/A \tag{3}$$

where P_{max} is the maximum load (N).

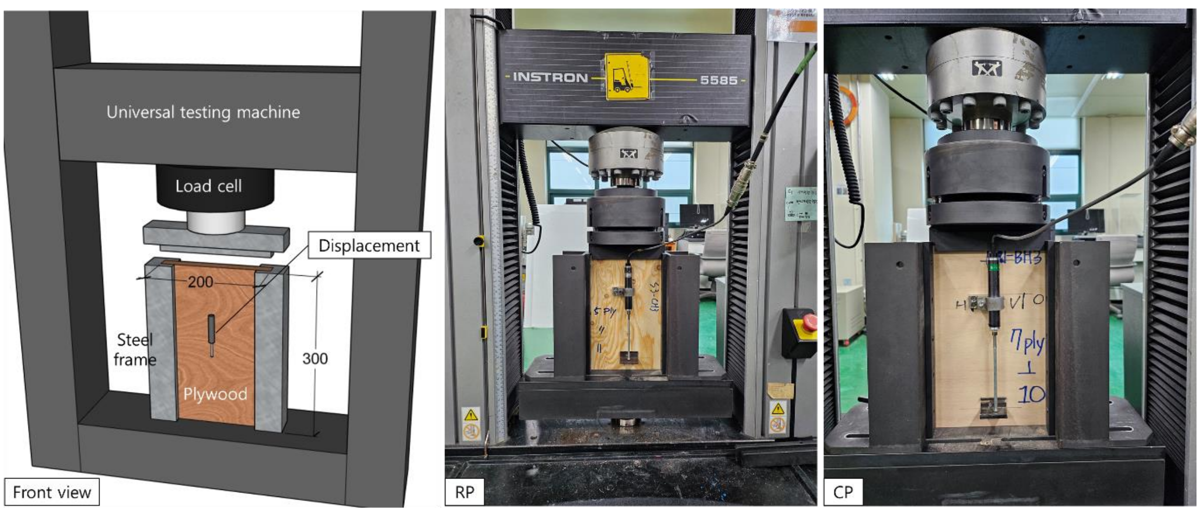

Fig. 2. Shape and photograph of compressive test for plywood specimens

Bending Performance Test

A bending test was conducted in accordance with ASTM D3043 (2005)-Method B to evaluate the mechanical properties of the specimens. The test specimens were prepared in a rectangular shape with dimensions of 300 mm in width and 800 mm in length. The bending specimens were categorized based on the type of plywood and the direction of the fibers, with 10 specimens tested for each category. The bending test utilized a span length of 780 mm with a four-point loading configuration, where the load spacing was set at 300 mm. Testing was performed using a UTM (Instron, Norwood, MA, USA) equipped with a 200 kN load cell. The crosshead speed was maintained at 5 mm/min, and the test continued until the maximum load capacity of the specimen was reached. Deformation was monitored using a LVDT (CDP-25, TML, Tokyo, Japan) positioned at the center of the specimen's bottom surface, while load measurements were recorded *via* the 200 kN load cell of the UTM. The modulus of elasticity (MOE) and modulus of rupture (MOR) for the panel specimens were subsequently calculated using the specified Eqs. 4 and 5,

$$\mathrm{MOE} = (\Delta P l^3)/(4 \Delta Y b h^3) \tag{4}$$

$$\mathrm{MOR} = (3P_{max}(l - s))/(2bh^2) \quad (5)$$

where $P_{\max}$ is maximum load (N), ΔP is the difference between the upper and lower loading limits in the proportional limit region (N), ΔY is the deformation with respect to ΔP (mm), l is span (mm), b is the width of the panel (mm), h is the thickness of the panel (mm), and s is span between load points (mm).

Rolling Shear Strength Test

The rolling shear strength of the specimens was evaluated following Method B of ASTM D2718 (2000). The rolling shear specimens were categorized based on the type of plywood and the direction of the fibers, with 10 specimens tested for each category. were sectioned into four parts and assessed at five distinct points using a UTM (50ST, Tinius Olsen, Kongsberg, Norway) equipped with a 10-ton capacity load cell. Each specimen had a length of 320 mm, with lower support points spaced 150 mm apart, and three upper support points were positioned at 150 mm intervals along the length of the specimen. Load and deformation data were captured through the load cell integrated with the universal testing machine. The rolling shear strength of the specimens was determined using Eq. 6,

$$Shear\ stress(MPa) = (33P)/(64bd) \quad (6)$$

where P is maximum load (N), b is the width of the panel (mm), h is the thickness of the panel (mm).

RESULTS AND DISCUSSION

Composition Ratio of Plywood

The veneer composition ratios of the plywood specimens are detailed in Table 1, with the specimens categorized into major and minor directions based on veneer orientation. The major direction is defined as the orientation with a higher proportion of veneers aligned parallel to both the load direction and fiber direction, while the minor direction, referred to as the S direction, is characterized by a higher proportion of veneers oriented perpendicular to the load and fiber directions.

Table 1. Veneer Composition Ratio of Plywood

Plywood type	Direction	thickness or ratio	Mean
RP	Major	*t*(mm)	7.42±0.15
		ratio	64±1.2
	Minor	*t*(mm)	4.19±0.24
		ratio	36±1.8
CP	Major	*t*(mm)	5.58±0.28
		ratio	54.3±2.3
	Minor	*t*(mm)	6.62±0.24
		ratio	45.7±2.4

For the RP specimens, the average long grain ratio was 64%, with the major direction corresponding to the long grain orientation on the plywood surface. The average short grain ratio for these specimens was 36%. Conversely, the CP specimens exhibited a long grain ratio of 45.8% and a short grain ratio of 54.2%, with the major direction aligned with the short grain orientation on the plywood surface. Notably, the CP specimens demonstrated relatively minor differences between the major and minor grain directions, which is attributed to the presence of thin hardwood veneer layers on the face and back of the plywood.

Tensile-shear Strength Results of Plywood after Cyclic Boiling

The results of the tensile-shear strength tests conducted after cyclic boiling of the plywood revealed average values of 0.74 MPa for the RP specimens and 0.75 MPa for the CP specimens. According to the KS F 3113 (2014) standard for structural plywood, the minimum requirement for adhesive strength in the tensile-shear bonding strength test is 0.7 MPa. Both the RP and CP specimens met this criterion, indicating that they possessed adequate bonding strength between veneer layers. Consequently, both the RP and CP plywood specimens were deemed suitable for use as structural plywood, as they conformed to the established adhesive strength standards.

Table 2. Results of Tensile Type Shear Strength Test for Plywood

Plywood type	Mean
RP	0.74±0.17
CP	0.75±0.25

Compression Test Results of Plywood

The compression test on plywood was performed in accordance with Method B of ASTM D3501-05 (2018). The results for the RP and CP specimens, prepared as specified, are summarized in Table 3. The RP major direction specimens exhibited a 22% higher compressive strength, and a 44% higher compressive MOE compared to the RP minor direction specimens.

Table 3. Results of Compressive Strength Test for Plywood

Plywood type	Direction	Compressive strength (MPa)	Mean
RP	Major	F_C	29.9±3.3
		E_C	16,264±4,965
	Minor	F_C	24.5±3.5
		E_C	11,284±3,693
CP	Major	F_C	37±8.2
		E_C	15,273±3,247
	Minor	F_C	28.5±2.4
		E_C	13,165±3,164

*F_C: Compressive strength, E_C: Compressive modulus of elasticity

Similarly, the CP major direction specimens showed a 30% increase in compressive strength and a 16% higher compressive MOE relative to the CP minor direction specimens. The failure modes observed during the compression tests are illustrated in Fig. 4, with wood failure identified as the primary mode, and minimal cohesive or interfacial failures between the veneers and adhesive layers observed. This failure behavior is likely attributed to the superior adhesion between the veneers in the plywood.

He *et al*. (2018) reported the compressive strength of lumber made from Canadian hemlock and construction-grade cross-laminated timber (CLT), noting an average compressive strength of 26.1 MPa for lumber with fibers oriented parallel to the load direction, and 18.3 MPa for CLT. Similarly, Lee *et al*. (2021) evaluated larch lumber with a specific gravity of 0.52, finding an average compressive strength of 43.3 MPa. Lee and Kim (2021) further reported that the compressive strength of CLT made from mixed species ranged from 19.4 MPa to 27.7 MPa, depending on the species composition. Considering these reports, the compressive strength of 37 MPa observed for the CP specimens in this study highlights its high potential for use as a construction material, demonstrating competitive performance relative to traditional lumber and CLT products.

Fig. 3. Photographs of failure modes in the compressive strength tests of plywood (A: The left side displays the failure mode from the front view, while the right side shows the cross-section of RP. B: The left side presents the failure mode from the front view, while the right side illustrates the cross-section of CP.)

Bending Test Results of Plywood

The results of the bending tests for the plywood specimens are summarized in Table 4. The MOR values exhibited significant variation depending on the major direction of the plywood. For the RP specimens, the MOR in the major direction was 2.5 times higher than in the minor direction, while for the CP specimens, the MOR in the major direction was 2.3 times higher than in the minor direction. Furthermore, the MOE values were notably superior in the major direction of specimens, which contained a higher proportion of long fiber grain orientation.

According to the KS F 3113 (2014) standard, the bending strength specifications for Grade 1 structural plywood are defined as an MOR of at least 22 MPa and an MOE of at least 5.5 GPa parallel to the grain, and an MOR of 18 MPa and an MOE of 3.5 GPa perpendicular to the grain. The RP specimens did not meet the MOE requirement for Grade 1 and were therefore classified as Grade 2 structural plywood. In contrast, the CP specimens satisfied the Grade 1 structural plywood criteria.

Comparative studies provide further insight into the bending performance of structural panels. Wang *et al*. (2015) assessed the bending strength of structural CLT made from Lodgepole pine (*Pinus contorta*) and aspen poplar (*Populus tremuloides*), with an average specific gravity of approximately 0.42. These tests, accounting for species arrangement and fiber orientation, yielded MOR values ranging from 35.37 to 48.19 MPa and MOE values between 9,727 and 11,609 MPa. Similarly, Yang *et al*. (2024) investigated structural CLT using Larch (*Larix kaempferi* (Lamb.) Carriere) with an average specific gravity of 0.57. Their results indicated an MOR of 39.66 MPa and an MOE of 11,839 MPa for the CLT. Based on these comparative findings, the MOR of 56.8 MPa and MOE of 12,372 MPa observed for the CP plywood in this study demonstrate its superior mechanical properties and excellent potential for use as a high-performance structural material.

Table 4. Result of Bending Strength Test for Plywood

Plywood Type	Direction	Bending Strength (MPa)	Mean
RP	Major	MOR	51±8.8
		MOE	12,102±2,438
	Minor	MOR	20.6±3.4
		MOE	3,442±580
CP	Major	MOR	56.8±16
		MOE	12,372±3,659
	Minor	MOR	24.2±4.8
		MOE	5,086±396

In timber construction, the correlation between the MOR and the MOE is a critical parameter in the design of bending members. To design appropriate structural members for specific applications, it is essential to accurately determine physical properties, such as allowable stress, in advance. However, within the same species, factors such as growth conditions, climate, the presence of knots, and drying techniques can significantly influence the mechanical strength of wood, resulting in substantial variability in material properties. Consequently, a thorough understanding of the physical properties of wood materials is vital for the design of timber structures.

Among these properties, MOR serves as a fundamental indicator of material performance in timber construction. However, because measuring MOR requires destructive testing, rendering the material unsuitable for structural use, MOE is often measured as a non-destructive means of predicting MOR. Wood and wood-based materials typically exhibit a positive correlation between MOR and MOE, although the reliability of this relationship depends on achieving a high coefficient of determination (R^2) in regression analysis. Thus, analyzing the correlation between MOR and MOE is a crucial aspect of assessing the suitability of plywood for structural applications in this study. This analysis aids in determining whether the plywood meets the required performance standards and can be effectively utilized in construction.

A regression analysis was conducted to investigate the correlation between the MOR and the MOE. The analysis demonstrated a strong positive correlation, with a coefficient of determination (R^2) of 0.9, as shown in Fig. 4. Based on the regression results, the experimental relationship was expressed by Eq. 7:

$$MOR = 3.88MOE + 6.26 \quad (7)$$

Equation 7 provides a predictive model for estimating MOR from measured MOE values. These findings have meaningful implications for the assessment of plywood's structural suitability, offering a reliable method for predicting bending strength based on elasticity measurements. This predictive capability is expected to enhance the design and application of plywood in structural engineering contexts.

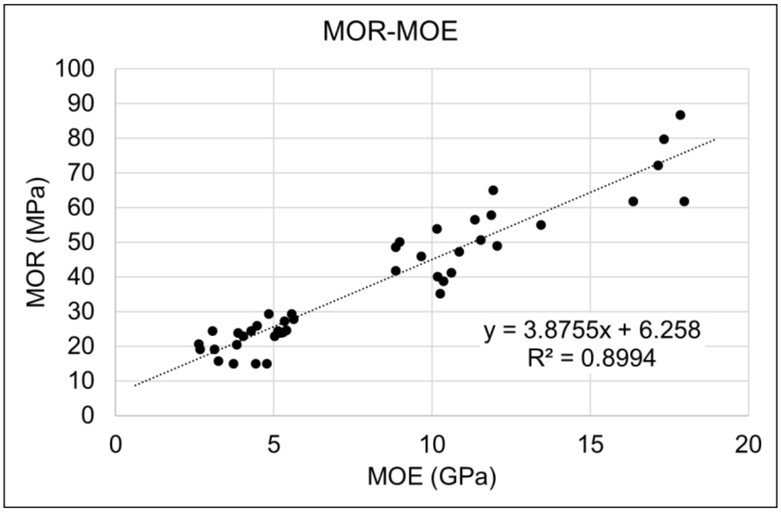

Fig. 4. Regression analysis graph of MOR and MOE for Korea plywood

Rolling Shear Test Results of Plywood

The results of the rolling shear tests on the plywood specimens are summarized in Table 5. The RP specimens exhibited an average rolling shear strength of 3.2 MPa, which is considered excellent. In comparison, the CP specimens demonstrated an average rolling shear strength of 2.3 MPa, indicating satisfactory performance. For context, Oh (2018) reported the rolling shear strength of three types of oriented strand board (OSB) and structural plywood, with OSB exhibiting average rolling shear strengths ranging from 1.32 MPa to 1.99 MPa, and structural plywood showing an average rolling shear strength of 1.71 MPa.

Table 5. Result of Shear Stress Test for Plywood

Plywood Type	Direction	Mean (MPa)
RP	Major	3.2±0.2
	Minor	3.2±0.5
CP	Major	2.3±0
	Minor	2.4±0.3

The failure patterns observed in the rolling shear test specimens, as depicted in Fig. 5, showed no visible failure in the face and back layers, with most of the failure occurring within the core layer. This failure mode is characteristic of an ideal rolling shear failure pattern, indicating effective stress distribution within the plywood layers.

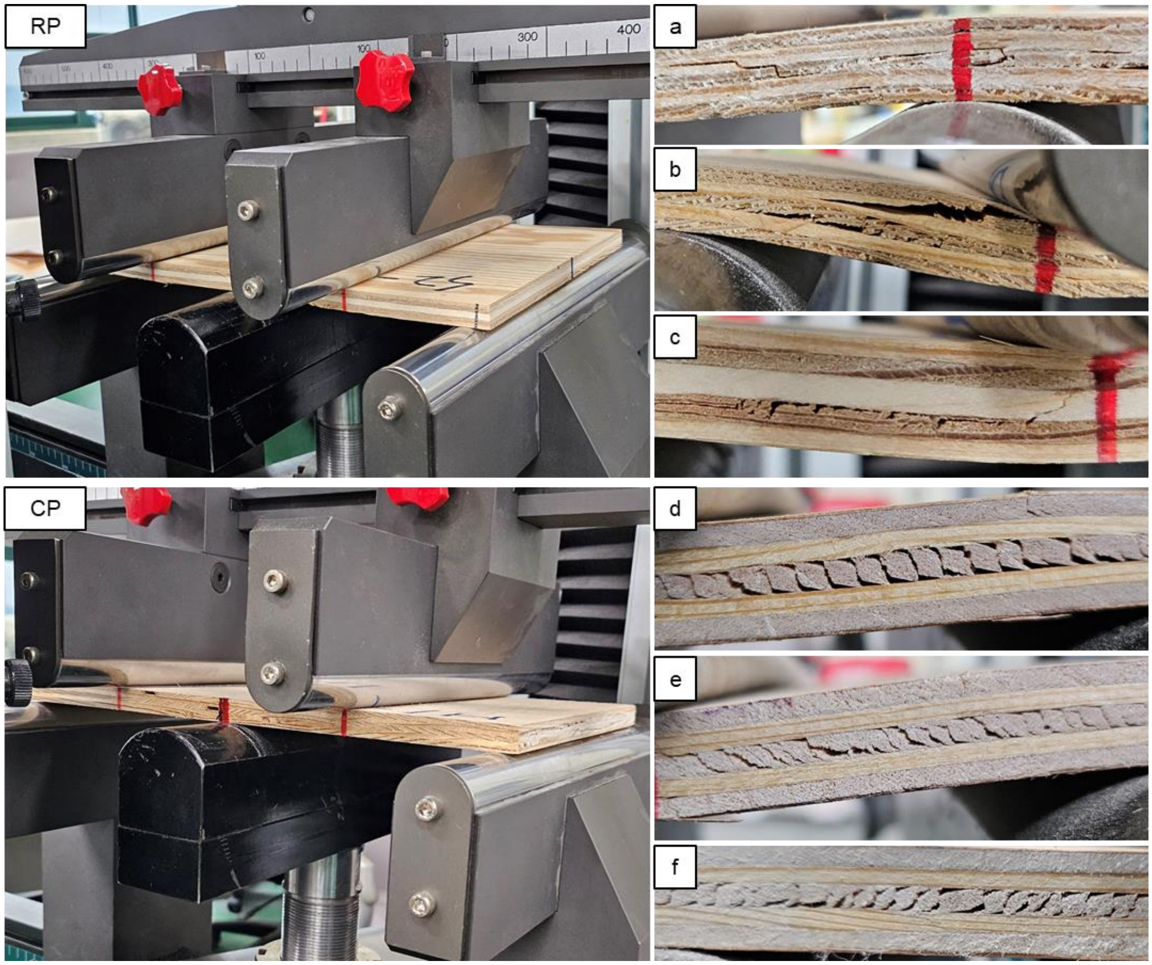

Fig. 5. The top four images illustrate the failure modes of RP, while the bottom four images depict the failure modes of CP (a, b, c: show rolling failure modes observed in the cross-section of RP, d, e, f: present rolling failure modes seen in the cross-section of the CP layer).

Further comparisons with data from Ehrhart *et al*. (2015) highlight the rolling shear strength of six European structural wood species: 1.4 MPa for Norway spruce (*Picea abies* (L.) H. Karst), 1.7 MPa for Scots pine (*Pinus sylvestris* L.), 2.7 MPa for birch (*Betula pendula* Roth), 4 MPa for beech (*Fagus sylvatica* L.), and 2.2 MPa for poplar (*Populus* spp.). Based on these comparative results, the plywood examined in this study demonstrates sufficient rolling shear strength, highlighting its potential for structural applications in timber construction.

CONCLUSIONS

This study presents a comprehensive analysis of the rolling shear strength, bending strength, compressive performance, adhesive strength, and composition ratios of Korean plywood for roof (RP) and plywood for concrete form (CP). The key findings were as follows:

1. Both RP and CP specimens met the adhesive strength requirements stipulated by the KS F 3101 (2016) and KS F 3113 (2014) standards for structural plywood. Notably, the CP specimens demonstrated an average tensile shear adhesive strength of 0.75 MPa, exceeding the standard and indicating high water-resistance performance.
2. The RP major specimens exhibited enhanced compressive strength and compressive modulus of elasticity (MOE) compared to the short grain specimens, a trend also observed in the CP specimens. This suggests that a higher parallel ratio between fiber direction and load direction positively influences compressive performance.
3. The RP specimens showed superior performance in both modulus of rupture (MOR) and MOE measurements due to its high long grain ratio. In contrast, while the CP specimens had a lower long grain ratio than RP specimens, it still demonstrated commendable overall performance. RP was classified as Grade 2 due to a slightly insufficient MOE, whereas the CP specimens met the Grade 1 structural plywood standards. A high correlation between MOR and MOE (R^2 = 0.9) was established, leading to the empirical equation MOR = 3.88MOE + 6.26, which effectively predicts MOR from MOE.
4. The RP specimens exhibited an average rolling shear strength of 3.2 MPa, reflecting excellent performance, whereas the CP specimens had an average rolling shear strength of 2.3 MPa, indicating satisfactory performance. These results suggest that both RP and CP specimens possessed adequate rolling shear strength for their respective applications. Furthermore, despite exhibiting an ideal veneer failure pattern for rolling shear strength in the core layer, the specimens demonstrated satisfactory performance

Overall, CP specimens are considered to have meaningful potential for structural applications, while RP specimens also demonstrate favorable strength properties. This study provides valuable insights into the physical properties and adhesive strength of plywood and is expected to enhance the applicability of plywood within Korea.

ACKNOWLEDGMENTS

This research was supported by a Research Project (FE0100-2024-02) through the National Institute of Forest Science (NIFoS), South Korea.

REFERENCES CITED

ASTM D2718 (2000). "Standard test methods for structural panels in planar shear (rolling shear)," ASTM International, West Conshohocken, PA, USA.

ASTM D2719 (2013). "Standard test methods for structural panels in shear through-the-thickness," ASTM International, West Conshohocken, PA, USA.

ASTM D2915-10 (2017). "Standard practice for sampling and data-analysis for structural wood and wood-based products," ASTM International, West Conshohocken, PA, USA.

ASTM D3043 (2005). "Standard test methods for structural panels in flexure," ASTM International, West Conshohocken, PA, USA.

ASTM D3501-05 (2018). "Standard test methods for wood-based structural panels in compression," ASTM International, West Conshohocken, PA, USA.

Ehrhart, T., Brandner, R., Schickhofer, G., and Frangi, A. (2015). "Rolling shear properties of some European timber species with focus on cross laminated timber (CLT): Test configuration and parameter study," in: *International Network on Timber Engineering Research: Proceedings of Meeting* 48 (Vol. 2015), Timber Scientific Publishing, KIT Holzbau und Baukonstruktionen, Croatia, pp. 61-76.

Fekiač, J., Gáborík, J., and Vojtkuliak, M. (2021). "Properties of plywood made from perforated veneers," *Forests* 12(12), article 1709. DOI: 10.3390/f12121709

He, M., Sun, X., and Li, Z. (2018). "Bending and compressive properties of cross-laminated timber (CLT) panels made from Canadian hemlock," *Construction and Building Materials* 185, 175-183. DOI: 10.1016/j.conbuildmat.2018.07.072

Hrázský, J., and Král, P. (2005). "Assessing the bending strength and modulus of elasticity in bending of exterior foiled plywoods in relation to their construction," *Journal of Forest Science* 51(2), 77-94. DOI: 10.17221/4546-JFS

Kang, E., Lee, S. M., and Park, J. Y. (2017). "Adhesion performance of plywoods prepared with different layering methods of thermoplastic resin films," *Journal of the Korean Wood Science and Technology* 45(5), 559-571.

KS F 3101 (2016). "Ordinary plywood," Korea Standard, Korean Agency for Technology and Standards, Seoul, Korea.

KS F 3113 (2014). "Structural plywood," Korean Standards Association, Seoul, Korea.

Laccone, F., Malomo, L., Pérez, J., Pietroni, N., Ponchio, F., Bickel, B., and Cignoni, P. (2020). "A bending-active twisted-arch plywood structure: computational design and fabrication of the FlexMaps Pavilion," *SN Applied Sciences* 2, 1-9. DOI: 10.1007/s42452-020-03305-w

Lee, H. M., Jeon, W. S., and Lee, J. W. (2021). "Analysis of anatomical characteristics for wood species identification of commercial plywood in Korea," *Journal of the Korean Wood Science and Technology* 49(6), 574-590. DOI: 10.5658/WOOD.2021.49.6.574

Lee, I. H., and Kim, K. H. (2021). "Influence of adhesive and layer composition on compressive strength of mixed cross-laminated timber," *BioResources* 16(4), 7461-7473. DOI: 10.15376/biores.16.4.7461-7473

Lee, I. H., Song, Y. J., and Hong, S. I. (2021). "Evaluation of the compression strength performance of fiber-reinforced polymer (FRP) and steel-reinforced laminated timber composed of small-diameter timber," *BioResources* 16(1), 633-642. DOI: 10.15376/biores.16.1.633-642

Lee, J. J., Kim, G. C., and Lee, G. S. (2000). "Performance evaluation of softwood plywood as structural and concrete-form panels," *Journal of the Korean Wood Science and Technology* 28(3), 14-24.

Liu, Y., Xu, J. X., Wen, M. Y., Park, H. J., Zhu, J. Z., and Liu, Y. N. (2021). "Research on flame retardant plywood with different flame retardants," *Journal of the Korean Wood Science and Technology* 49(6), 667-678. DOI: 10.5658/WOOD.2021.49.6.667

Oh, S. C. (2018). "Planar (Rolling) shear strength of structural panels using 5-point bending test," *Journal of the Korean Wood Science and Technology* 46(5), 425-436. DOI: 10.5658/WOOD.2018.46.5.425

Park, H. J., and Jo, S. U. (2020). "Moisture absorption and desorption properties of Douglas fir, hinoki, larch, plywood, and WML board® in response to humidity variation," *Journal of the Korean Wood Science and Technology* 48(4), 488-502. DOI: 10.5658/WOOD.2020.48.4.488

Santarbárbara, A. G., Carrió, J. M., Sakata, H., and Sastre, R. S. (2022). "Active bending in plywood floor structures with in-plane curvature," *Informes de la Construcción* 74(568), article e473. DOI: 10.3989/ic.91082

Suh, J. S., Hwang, S. W., Hwang, K. H., Jeong, G. Y., and Joung, H. H. (2012). "Shear strength of nailed connection of domestic plywood as a substitute for OSB," *Journal of the Korean Wood Science and Technology* 40(4), 287-293. DOI: 10.5658/WOOD.2012.40.4.287

Wang, Z., Gong, M., and Chui, Y. H. (2015). "Mechanical properties of laminated strand lumber and hybrid cross-laminated timber," *Construction and Building Materials* 101, 622-627. DOI: 10.1016/j.conbuildmat.2015.10.035

Wen, M. Y., Zhu, J. Z., Zhu, M., Sun, Y. X., Park, H. J., and Shi, J. (2020). "Research on flame retardant formaldehyde-free plywood glued by aqueous polymer isocyanate adhesive," *Journal of the Korean Wood Science and Technology* 48(5), 755-764. DOI: 10.5658/WOOD.2020.48.5.755

Yang, S., Lee, H., Choi, G., and Kang, S. (2024). "Mechanical properties of ply-lam cross-laminated timbers fabricated with lumber and plywood," *European Journal of Wood and Wood Products* 82(1), 189-202. DOI: 10.1007/s00107-023-02010-w

Article submitted: September 23, 2024; Peer review completed: October 19, 2024; Revised version received: and accepted: October 31, 2024; Published: November 15, 2024.
DOI: 10.15376/biores.20.1.415-425