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DIMENSIONAL STABILITY OF MULTIPLEX PLYWOOD WITH MAINLY UNIDIRECTIONAL GRAIN ORIENTATION

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ABSTRACT

Multilayer plywood made from wood veneers with mainly unidirectional grain orientation known as multiplex panels represent a significant group of modern wood-based panels. Application of these panels in modern construction and in other application areas necessitates achieving higher physical and mechanical characteristics of these materials, their consistency during prolonged water impact, humidity, heat, as well as their dimensional stability.

The aim of the research presented in this paper is to study the dimensional stability of experimental multiplex plywood reinforced with cotton based prepreg. The cotton prepreg was made form cotton fabric pre-impregnated with alcohol-soluble phenol-formaldehyde resin.

The experimental multiplex plywood was made of eleven layers of peeled beech veneers with thickness of 1,85 mm. Alcohol-soluble phenol-formaldehyde resin was used as plywood binder. The orientation of the veneers in the plywood structure is parallel to the longitudinal axis of the panel, with exception of the subsurface layers whose orientation is transverse to the longitudinal axis of the panel. The cotton prepreg reinforcements were inserted in each adhesive layer of plywood.

To define the dimensional stability of the panels, laboratory tests on the most important physical properties were performed, as well as on bonding quality through the shear strength test. Tests of water absorption and thickness swelling were performed during prolonged water treatment.

Keywords: plywood, multiplex, reinforcement, prepreg, pre-impregnated cotton fabric, alcohol-soluble phenol-formaldehyde resin, dimensional stability, physical properties, shear strength.

1. INTRODUCTION

Plywood industry is facing the need for new product innovations and new product applications. Therefore, research in the field of production of plywood should continue in the direction of production of plywood with improved characteristics required for their proper application, primarily for structural purposes.

Multilayer plywood made from wood veneers oriented parallel to the longitudinal axis of the panel known as multiplex panels represent a significant group of modern wood-based panels. Application of these panels in modern construction and in other application areas necessitates achieving higher physical and mechanical characteristics of these materials, their consistency during prolonged impact of water, humidity, heat, as well as their dimensional stability.

Regarding this, the research presented in the paper is aimed at studying the possibilities to make experimental multilayer plywood from beech raw material with characteristics that will enable their application in different areas (for example: construction, transport industry - equipping vehicles etc.).

Scientific findings in the field of wood composite materials show that the characteristics of wood and wood-based products can be improved by combining them with other non-wood materials that can be applied as outer layers of wooden panels, acting as protective barriers from external atmospheric

influences, as well as in the structure of the panels (Davalos et al., 2000; Hardeo and Karunasena, 2002; Choi et al., 2011; Zīke and Kalniņš, 2011, Xu et al., 1996, Xu et al., 1998, Brezović et al., 2002, Brezović et al., 2003, Brezović et al., 2010, Biblis and Carino, 2000, Hrázský and Král, 2007, Maniņš and Zīke, 2011, Jakimovska Popovska and Iliev, 2019).

There is a possibility to reinforce wood with pre-impregnated materials-prepreg (Rowland et al., 1986). Different types of technical fabrics can be embedded in the adhesive layer of plywood (Kohl et al., 2013).

Cotton prepregs can be used as reinforcement materials of plywood structure (Jakimovska Popovska, 2014). The results obtained from application of this material as reinforcement of standard plywood (Jakimovska Popovska, 2014) are motive to conduct research regarding the possibility of application of this kind of reinforcement in multiplex plywood composition.

2. EXPERIMENTAL METHODS

For realization of the research experimental multiplex eleven-layered plywood was made from beech peeled veneers with thickness of 1,85 mm. The orientation of the veneers in the plywood structure was parallel to the longitudinal axis of the panel, with exception of the subsurface layers whose orientation is transverse to the longitudinal axis of the panel. The structure of the plywood was reinforced with pre-impregnated cotton fabric inserted in each adhesive layer of the panel (Figure 1). The orientation of the wrap of the fabric was parallel to the grain direction of the surface veneers.

The panels were overlaid with phenol formaldehyde-resin impregnated paper with a surface weight of 172 g/m^2. The paper was bonded during the hot pressing process. Plywood overlaying with this paper was made in order to improve its water resistance, having the fact that this plywood is intended for application in construction where it can be exposed to high humidity conditions.

Pure alcohol-soluble phenol-formaldehyde resin was used for pre-impregnation of cotton fabrics used as reinforcements of experimental plywood. The same resin was also used for veneer bonding. The resin was a product of the company “Fenoplast 99” OOD, Ruse, Republic of Bulgaria, supplied under the name RFE-2, and has the following characteristics:

- form - brown-reddish viscous liquid;
- content of dry matters – 51 %;
- viscosity by Vz4/20°C – 33 s;
- gel time at temperature of 150°C – 96 s.

Methyl alcohol was used as resin solvent.

For plywood reinforcement, cotton fabric was used which is a product of the company „Beloteks 95” from Zlatograd, Republic of Bulgaria and was procured by the company “Laminati Com” from Prilep. This fabric was supplied in the form of a roll with width of 150 cm, which after impregnation with resin was cut to the required format. The surface mass of the cotton fabric was 152,8 g/m^2 and with thickness of 0,30 mm.

The fabric was made with simple "plain" weaving with the following technical characteristics, tested by the manufacturer:

- wrap threads: 31 tex;
- fill threads: 30 tex;
- Wrap density (threads /10 cm): 234/10 cm;
- fill density (threads /10 cm): 236/10 cm;
- tensile strength to wrap (dN): 47;
- tensile strength to fill (dN): 50,2.

Pre-impregnation of the fabric was done on an impregnation machine, where the fabrics pass through a system of rollers that guide the fabric through the adhesive container so that it is applied double-sided to the fabric. The cotton fabric was pre-impregnated with resin in quantity of 300 g/m^2. The thickness of the pre-impregnated fabrics was 0,6 mm.

The veneers and cotton prepregs were assembled in multiplex plywood composition. Moisture content of the veneers was 9,77 %. Pure alcohol-soluble phenol-formaldehyde resin with concentration of 51 % was used as plywood binder, applied on the veneers in quantity of 180 g/m^2. The panel was pressed in a hot press using the following parameters:

- specific pressure of 1,8 kg/cm^2;
- pressing temperature of 155ºC;
- pressing time of 30 min.

On completion of the pressing process, the plywood panel was cooled to the ambient temperature of 20ºC into the press for 30 minutes under reduced pressure in order to obtain flat panel and to reduce its warping and deformation.

The dimensions of the experimental plywood model were 1050×1000×17,98 mm. The density of the panel was 1012,59 kg/m^3.

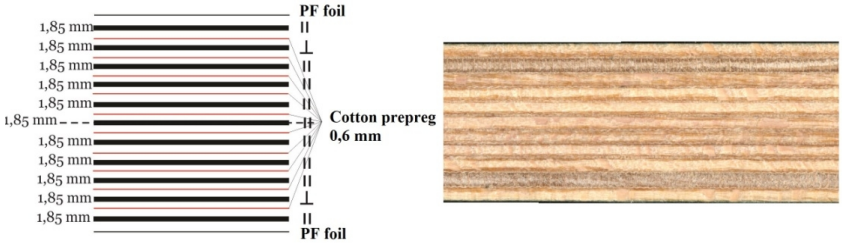

Figure 1. *Pattern and cross-section of the multiplex plywood model*

Tests for thickness swelling and water absorption were made after immersion in water for prolonged period in controlled laboratory conditions. Measuring of thickness, length, width and mass of plywood test specimens for determination of these properties was made after immersion in water for the period of 1 day (24 hours) to 12 days. Control measuring was done in intervals of: 1 day, 2, 3, 4, 6, 8 and 12 days.

The test specimens with standard dimensions of 100×100 mm for research and analysis were made according to the national standard for wood-based panels MKS D.C8.100. The thickness swelling and water absorption of plywood were tested according to the national standard MKS D.C8.104.

Bonding quality of multiplex plywood was tested trough the shear strength test according to EN 314. The shear strength was tested on conditioned test specimens, as well as after immersion of the test specimens for 6 h in boiling water and 2 h in cold water (t=20±2°C). The shear strength was tested in subsurface veneers of plywood.

The obtained data were statistically analyzed. One way ANOVA was used to determinate the significance of the effect of water treatment duration on the values of the tested physical properties. Tukey's test was applied to evaluate the statistical significance between the mean values of the properties at different duration of the immersion in water.

Statistical software SPSS Statistic was used for statistical analysis of the obtained data.

3. RESULTS AND DISCUSSION

The obtained results from the tests of physical properties of the experimental multiplex plywood are shown in tables 1 and 2 and on figures 2, 3 and 4.

The analysis of the obtained results for relative water absorption, thickness swelling and volume swelling of experimental multiplex plywood (Table 1, Table 2, Fig. 2, 3 and 4) showed increasing of the mean arithmetical values of these properties by prolongation of the duration of water treatment.

The values of relative water absorption were within the limits of 8,80 % after immersion in water for 1 day to 21,95 % after 12 days. Increment in relative water absorption has highest intensity in the initial period of water treatment (period of 1 to 2 days). Increase in the mean value of relative water absorption in this initial period of immersion was 40,83 %. Further increasing of the relative water absorption had weaker intensity, so in the period from 48 to 72 hours (from the second to the third day) increment in the mean value of this property was twice as low as the increment in the mean value of relative water absorption for the period of 24 up to 48 hours (Table 2). Compared to the value of the relative water absorption after 1-day immersion in water, the value of this property after 12 days of immersion was higher by 149,43 %. In the period from 4 days to 6 days immersion in water, there was a noticeably higher intensity of rise in the value of this property compared to the previous period from

the third to the fourth day of immersion. This kind of tendency of increasing is also noticed in relative thickness and volume swelling (Table 2).

The ANOVA: ($F(6;28) = 186,381$; $p<<0,001$) indicated that there is statistically significant difference in the mean values of relative water absorption between different durations of water treatment. The post-hoc Tukey's test showed that there is a statistically considerable difference between the mean values of relative water absorption of all control measurements up to 6 days immersion in water. After this period, from 6 days up to 12 days the differences in the mean values of relative water absorption between two successive procedures of measuring are not statistically significant.

Table 1. *Statistical values for relative water absorption, relative thickness swelling and relative volume swelling of multiplex plywood*

Property	***Duration of water treatment***	***N***	***Mean (%)***	***Std. Deviation (%)***	***Std. Error (%)***	***95% Confidence Interval for Mean (%)***		***Min (%)***	***Max (%)***
						Lower Bound	***Upper Bound***		
WA	24 h	5	8,80	0,59	0,27	8,06	9,53	8,00	9,53
	48 h	5	12,39	0,72	0,32	11,49	13,28	11,30	13,03
	72 h	5	14,93	0,80	0,36	13,93	15,92	13,65	15,53
	96 h	5	16,96	0,83	0,37	15,93	17,98	15,66	17,67
	6 days	5	19,39	0,89	0,40	18,28	20,49	17,99	20,29
	8 days	5	20,69	0,85	0,38	19,64	21,74	19,36	21,63
	12 days	5	21,95	0,71	0,32	21,06	22,83	20,82	22,75
TS	24 h	5	3,46	0,43	0,19	2,93	4,00	2,79	3,98
	48 h	5	4,92	0,35	0,16	4,48	5,36	4,42	5,32
	72 h	5	5,59	0,42	0,19	5,06	6,11	4,97	6,08
	96 h	5	6,10	0,44	0,19	5,56	6,64	5,51	6,55
	6 days	5	6,74	0,63	0,28	5,96	7,53	5,89	7,42
	8 days	5	7,09	0,63	0,28	6,31	7,88	6,21	7,72
	12 days	5	7,40	0,70	0,31	6,54	8,27	6,42	8,08
VS	24 h	5	3,81	0,44	0,20	3,27	4,35	3,10	4,26
	48 h	5	5,38	0,29	0,13	5,02	5,74	4,99	5,76
	72 h	5	6,15	0,36	0,16	5,70	6,61	5,65	6,65
	96 h	5	6,75	0,34	0,15	6,33	7,17	6,36	7,15
	6 days	5	7,51	0,55	0,25	6,83	8,19	6,77	8,16
	8 days	5	7,90	0,54	0,24	7,22	8,57	7,16	8,47
	12 days	5	8,25	0,62	0,28	7,48	9,01	7,40	8,87

Table 2. *Increment of the mean value of relative water absorption (ΔUr), relative thickness swelling (ΔBr) and relative volume swelling between two successive procedures of measuring (ΔBvr)*

Time span of calculating the increments	***ΔUr [%]***	***ΔBdr [%]***	***ΔBvr [%]***
1→2d	40,83	42,09	41,24
2→3d	20,49	13,49	14,36
3→4d	13,61	9,17	9,65
4→6d	14,33	10,59	11,27
6→8d	6,72	5,16	5,19
8→12d	6,05	4,37	4,42

**d-days*

The mean value of the relative thickness swelling is within the limits of 3,46 % for the immersion period of 1 day to 7,40 % after water treatment of 12 days. The increment of the mean value of relative thickness swelling in this initial period of immersion is 42,09 %. Further increase in the relative thickness swelling is with lower intensity, so in the period from 48 to 72 hours (from the second to the third day) the increment in the mean value of this property is three times as low as the increment in the mean value of relative thickness swelling for the period of 24 up to 48 hours. Compared to the value of relative thickness swelling after 1 day immersion in water the value of this property after 12 days of immersion is higher by 113,87 %.

The ANOVA: ($F(6;28) = 33{,}936$; $p << 0{,}001$) indicated that there is statistically significant difference in the mean values of relative thickness swelling between different durations of water treatment. The post-hoc Tukey's test showed that the mean value of this property after 24 h immersion in water statistically differs from the values of all other control measurements. After immersion period of 1 day (24 h) up to 12 days the differences in the mean values of relative thickness swelling between two successive measurements are not statistically significant.

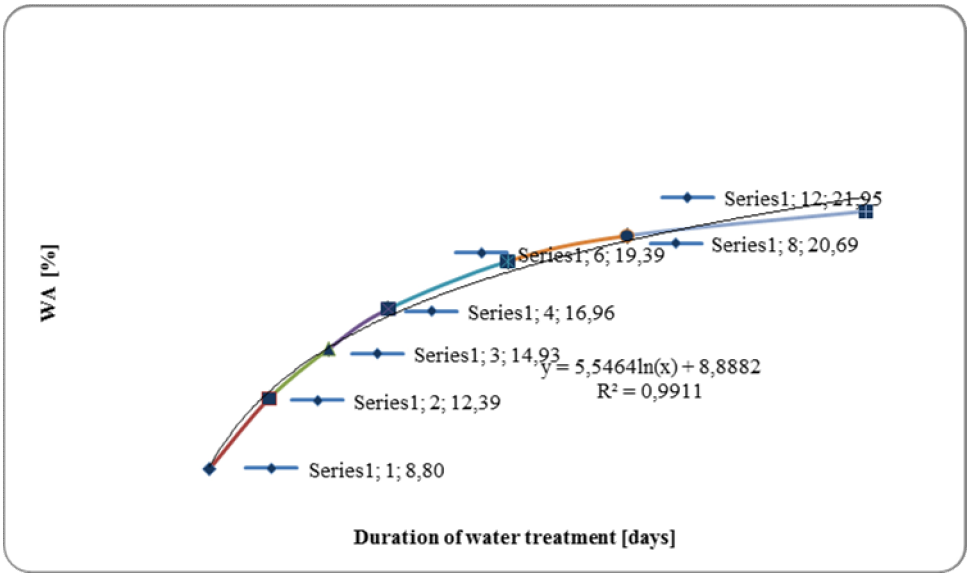

Figure 2. *Increase in the mean arithmetical values of relative water absorption for period of 1 to 12 days*

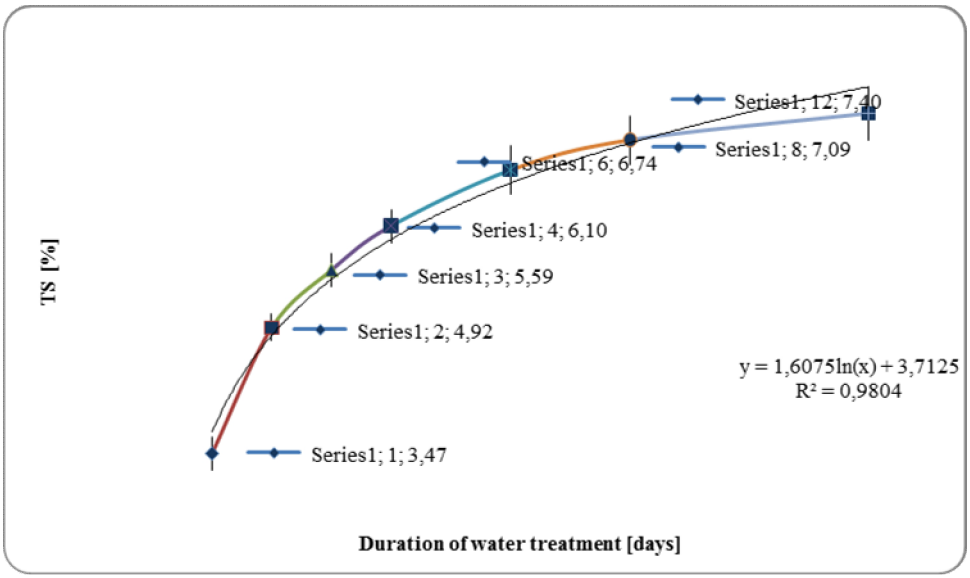

Figure 3. *Increase in the mean arithmetical values of relative thickness swelling for period of 1 to 12 days*

According to the tests results, the experimental multiplex plywood meets the requirements of the national standard MKS D.C5.032 for wood-based panels for use in construction, which defines 12 % as a limit for relative thickness swelling for immersion period of 24 hours. After water treatment of 12 days, the experimental plywood does not exceed the value of 12 %. This shows that the plywood model is dimensionally stable to water impact, which is one of the prerequisites for plywood application in high humidity conditions and for structural use in construction.

The analysis of the obtained test results for the relative volume swelling of multiplex plywood (Tables 1 and 2, Fig. 4) show increment in the mean values of this property by prolongation of the duration of the water treatment. The mean arithmetical value of this property is within the limits of 3,81 % for the immersion period of 1 day to 8,25 % after 12 days of water treatment. Highest intensity of increase in relative volume swelling is achieved in the initial period of water treatment (period of 1 to 2 days) during which rise in the value of this property is 41,24 %. The further increasing of the relative volume swelling is with lower intensity, so in the period from 48 to 72 hours (from the second to the third day) the increment in the mean value of this property is almost three times as low as the increment in the mean value of relative volume swelling for the period of 24 up to 48 hours.

From the obtained test results of relative volume swelling of experimental multiplex plywood it can be seen that the increasing of the relative volume swelling is very similar to the increase in the relative thickness swelling. This is due to the fact that volume swelling of plywood primary is a result of swelling in thickness. The changes of the dimensions of the plywood in length and width direction are minor and these changes have a marginal effect on the volume swelling of plywood. The biggest changes in length and width dimensions of the plywood panel occur after initial period of 1 day of immersion in water.

The ANOVA: ($F(6;28) = 57{,}161$ $p<<0{,}001$) indicated that there is statistically significant difference in the mean values of relative volume swelling between different durations of the water treatment. The post-hoc Tukey's test showed that the mean value of this property after 24-h immersion in water statistically differs from the values of all other control measurements. After immersion period of 1 day up to 12 days the differences in the mean values of relative volume swelling between two successive measurements are not statistically significant.

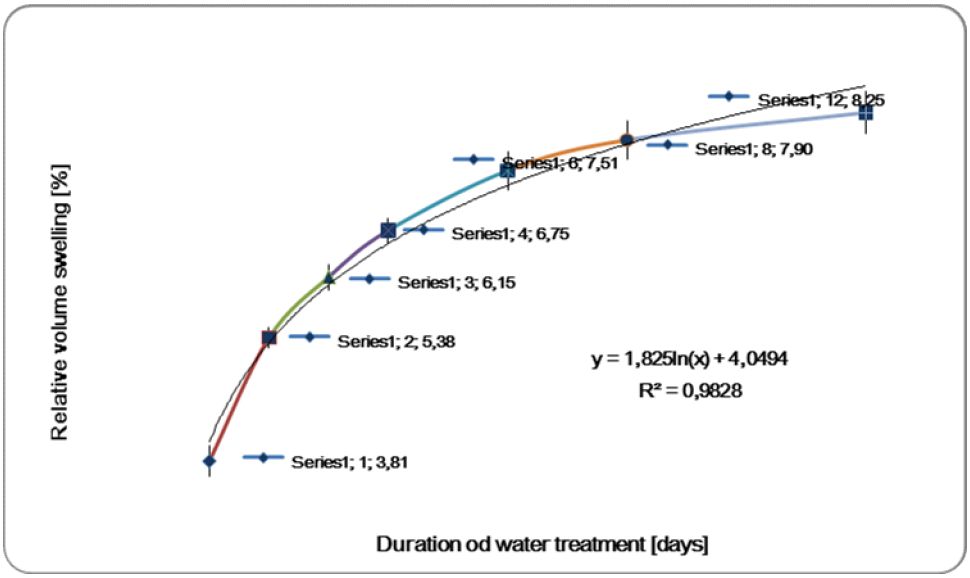

Figure 4. *Increase in the mean arithmetical values of relative volume swelling for period of 1 to 12 days*

The obtained results for relative water absorption, relative thickness swelling and relative volume swelling are within the limits of the values of these properties that give Jakimovska and Iliev (2021) for standard plywood reinforced with cotton prepreg. The authors give the values of relative water absorption of reinforced beech plywood of 8,00 % after 1 day immersion in water and 21,62 % after 12 days of immersion. The relative thickness swelling of this plywood was 2,68 % after 24-h immersion and 6,31 % after 12 days of immersion (Jakimovska and Iliev (2021).

When analyzing the results of the research of the physical properties of multiplex plywood during prolonged water exposure, a general statement can be made, according to which there is a tendency of rise in the mean arithmetical values of all tested properties when prolonging the duration of the water treatment of the test specimens. Increasing of the values of all tested properties is intense in the initial period of treatment.

Visual analysis of plywood test specimens after immersion in water for 12 days showed that there were no deformations, delaminating and warping of the plywood test specimens (Fig. 5). The stability of the form and the structure of the plywood panel after prolonged water exposure shows that high-quality multiplex plywood is made durable for application in high humidity conditions.

Figure 5. *Test specimen of plywood after immersion in water for period of 12 days*

Table 3. *Statistical values of shear strength of experimental multiplex plywood*

Property	***N***	***Mean (N/mm^2)***	***Std. Deviation (N/mm^2)***	***Std. Error (N/mm^2)***	***95% Confidence Interval for Mean (N/mm^2)***		***Min (N/mm^2)***	***Max (N/mm^2)***
					Lower Bound	***Upper Bound***		
Shear strength (conditioned test specimens)	5	6,55	0,47	0,21	5,97	7,13	5,99	7,10
Shear strength after immersion for 6 h in boiling water	6	3,92	0,29	0,12	3,62	4,23	3,51	4,40

Figure 6. *Shear strength test of experimental plywood*

The test results for plywood shear strength are presented in table 3. The obtained data show that the experimental multiplex plywood has high values of shear strength in the subsurface layers, which speaks for good bonding quality of plywood. The values of shear strength both in dry condition (conditioned test specimens) and after immersion for 6 h in boiling water and for 2 h in cold water are above the value of 1N/mm^2 which is defined in standard EN 314.

4. CONCLUSIONS

Based on the obtained results from the research it can be concluded that experimental multiplex plywood is characterized with good dimensional stability under water exposure, without delamination and deformation of the shape of the test specimens.

Mainly unidirectional grain orientation in multiplex plywood (where the veneers run parallel to the longitudinal axis of the panel, with the exception of the subsurface layers whose orientation is transverse to the longitudinal axis) gives opportunity for production of dimensionally stable plywood. The stability of the form and the structure of the plywood panel after prolonged water exposure show that high-quality multiplex plywood is made durable for application in high humidity conditions.

From the realized research can be concluded that the application of pre-impregnated cotton fabrics can be used as reinforcements of multiplex plywood.

The obtained values of shear strength of plywood speak for its good bonding quality.

The experimental reinforced multiplex plywood meets the requirements of the national standard and can be used as load-bearing panel in construction. After immersion in water for 12 days the plywood model does not exceed the limit value of 12% for thickness swelling defined by the standard.

The analysis of the research results showed that after the analyzed period of treatment of 12 days the values of the tested properties still have tendency to rise. The maximum value of these properties can be defined only by continuing the experiment for a time period longer than 12 days.

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