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RHEOLOGICAL STUDY OF INDUSTRIAL VARNISHES AT VARIOUS TEMPERATURES

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ABSTRACT

Superior surface finishing in furniture manufacturing requires an understanding of varnish product rheology. The rheological properties of acrylic primer, basecoat and topcoat, intended for roller varnishing and UV curing are examined in the study. Two methods were used to measure viscosity: Brookfield rheoviscometer and Ford cup. The results discuss the effect of increasing temperature on a decrease in viscosity. Rheological modeling using the Ostwald de Waele power law model explained the non-Newtonian, shear-thinning, rheostable behavior of liquid. It was shown that the flow index of some varnish products in Standard Conditions for Temperature was close to the Newtonian fluid. However increasing consistency index parameter indicates the pseudoplastic behavior of the fluid. The findings highlight the importance of controlling viscosity and temperature during varnish product application processes to ensure optimal coating quality. This research provides valuable insight into the rheological properties of industrial coatings, facilitating advances in coating technology and quality control practices.

Keywords: acrylic varnish; conventional viscosity; apparent viscosity; Ostwald de Waele rheological model.

INTRODUCTION

Due to the development of the furniture industry, manufacturers must provide the highest quality furniture to meet customer expectations. Raising the standards of surface finishing directly affects the development of customers' first aesthetic impressions when choosing furniture. Understanding the rheological characteristics of varnish products is essential to raising the quality and efficiency of coating production (Bekhta *et al.,* 2018; Henke *et al.,* 2022).

Rheological tests are necessary to develop the recipe for a varnish product, design paint installations and control the quality of the product and the technological process. The basic value characterizing rheological properties is viscosity. Liquids whose viscosity under isothermal conditions is constant and does not depend on the shear rate or the time of shear stress are called Newtonian fluids. All other liquids with a variable viscosity determined by the value of these parameters, tested using rheometers, are classified as non-Newtonian materials. They include rheostable materials with viscosity depending only on the shear rate, rheologically unstable materials with properties that change over time, and viscoelastic materials revealing the cumulative properties of solids and liquids. In industrial practice, viscosity is determined using the Ford viscosity cup. This method is very popular in contacts between the manufacturer of varnish products and their recipients - production companies (Wiśniewski, 1988). An advanced method of determining apparent viscosity is the Brookfield rheoviscometer. Varnish products experience different shear rates during application (Proszyk *et al.*, 1995).

Low viscosity varnishes are easier to spread, ensuring seamless coating, and are ideal for spray application. The lower the viscosity of the product, the thinner the layer. However, the coatings may have poor adhesion. The high viscosity of the products provides greater control over the process, but their application is more demanding. If the product's viscosity is too high, the adhesion of the formed coatings may be incorrect due to the difficult distribution of the varnish. The condition for achieving good quality coatings is also proper preparation of varnishes by mixing them thoroughly. Insufficient mixing of the products results in uneven viscosity of the products. This results in the appearance of streaks, air bubbles and unevenness (Butt, 2022; Ozdemİr *et al.*, 2013; Proszyk, 1999; Saranjam *et al.*, 2016).

Proszyk (1999) indicated the importance of the effect of temperature on viscosity. The annual temperature range in the production hall forces manufacturers to look for solutions that ensure constant conditions for the applied varnish (Schramm, 1998). Makarewicz (1991) observed that the components and their interactions have a significant impact on the shear behavior of liquids. Unstable viscosity in the process can affect the color and gloss of coatings due to uneven pigment dispersion as well as the orientation and distribution of matting agents (Makarewicz, 1991; Zheng and Chen, 2023).

The aim of this work is to analyze the viscosity of industrially produced varnishes using two methods, with emphasis on its dependence on temperature. The results of the conducted research will be of significant importance for the manufacturing industry, indicating the need to control the application processes of paint products and improving the quality of final products. They will also contribute to understanding the mechanisms influencing the properties and performance of coating systems, which is crucial for the further development of technologies in this field.

MATERIALS AND METHODS

Materials

The tests included acrylic varnishes: primer, basecoat and topcoat intended for UV curing in industrial conditions (Table 1). The manufacturer's specified varnish composition is as follows:

- Primer: calcium carbonate ≥ 40–<60%; ethoxylated propylidynotrimethanol, esters with acrylic acid ≥ 20–<40%; 4,4'-Isopropylidenediphenol, oligomeric reaction products with 1-chloro-2,3-epoxypropane, esters with acrylic acid ≥ 5–<10%; and 1-metoksypropan-2-ol ≤ 0.5%.
- Basecoat: titanium dioxide ≥ 40–<60%, propylidinetrimethanol ≥ 10–<20%; 4,4'-Isopropylidenediphenol, oligomeric reaction products with 1-chloro-2,3-epoxypropane, esters with acrylic acid ≥ 5–<10%; alkoxylated pentaerythritol tetraacrylate ≥ 5–<10%; diacrylic dipropylene glycol ≥ 3–<5%; polymer based on polyoles and modified acrylic acid esters ≥ 2.5–<5%; phenyl-bis(2,4,6-trimethylbenzoyl-)phosphine oxide ≥ 0.1–<1%; and 2-propenoic acid, 1,1'- [(1-methyl-1,2-ethanediyl) bis[oxy(methyl-2,1-ethanediyl)]]ester, reaction products with di-ethylamine ≥ 0.1–≤0.5%.

- Topcoat: propylidinetrimethanol, ethoxylated, esters with acrylic acid 20–40%; 4,4'-Isopropylidenediphenol, oligomeric reaction products with 1-chloro-2,3-epoxypropane, esters with acrylic acid 10–20%; titanium dioxide (1-methyl ethane-1,2- diyl)-bis[oxy(methyl ethyl-2,1-diyl)] diacrylate 10–20%; diacrylate (1-methyl ethane-1,2- diyl)-bis[oxy(methyl ethyl-2,1-diyl)] 5–10%; 2,2-bis(acryloxymethyl)butyl acrylate 2.5–5%; methyl benzoylformate 2.5–5%; amorphous silica (silica gel, precipitated silica) 1–2.5%; tetrabutylammonium bromide 1–2.5%; 2-propenoic acid, 1,1'-[(1-methyl-1,2-ethanediyl) bis[oxy(methyl-2,1-ethanediyl)]]ester, reaction products with diethylamine ≤ 0.5%; and photoinitiator ≤ 0.1%.

Tab. 1 Basic properties of varnish products.

Parameter	Type of Varnish		
	Primer	Basecoat	Topcoat
Density [g/cm^3]	1.63 ± 0.15	1.73 ± 0.15	1.30 ± 0.15
Solids content [%] acc. to the PN-EN ISO 3251:2019 standard	95.3 ± 0.5	98.3 ± 0.5	97.8 ± 0.5

Viscosity measurement

The varnishes were taken from the production warehouse and tested in the production laboratory. Apparent viscosity was determined using a Brookfield rheoviscosimeter model DVII + EXTRA using a temperature manual controller. The test was performed using spindle no. 27 at temperatures of 25 and 40°C. The spindle speed was increased in ten-time intervals every 2 minutes from 15 to 60 RPM (revolutions per minute) for primer and from 100 RPM to 145 RPM for basecoat and topcoat. Spindle speeds were selected experimentally according to the manufacturer's recommendations to ensure that the spindle operated above 10 percent of the device scale.

Ford cup No. 4 was used to determine the conventional viscosity. Four different test temperatures were selected: 15, 25, 40, 55°C, which represent both extreme and typical temperatures of varnish products occurring in a transitional temperate climate characterized by four seasons (Schramm, 1998). The temperature was measured using a pyrometer. Six measurements were performed for each variant (Dziubiński *et al.*, 2014).

Determination of the rheological model

Based on the obtained test results, it was decided to use the power Ostwald de Waele rheological model. The data from the experiments were approximated with an appropriate rheological model, and then the parameter values of this model were determined based on the formula below (Proszyk *et al.*, 1995).

$$\tau = k \cdot (\dot{\gamma})^{n1} \qquad (1)$$

Where: τ – shear stresses

k – consistency index

$\dot{\gamma}$– shear rate

$n1$ – flow index

RESULTS AND DISCUSSION

Viscosity measured using rheoviscometer

Table 2 shows the results of the rheological parameter of varnish products at various temperatures and presents them in Figures 1-6.

Table 2. Rheological parameters of the Ostwald de Waele model as a function of temperature.

Temperature [°C]	Model parameters		Correaltion coefficient R^2 [-]
	k [mPa·s]	n1 [-]	
Primer			
25	2858	0.996	0.999
40	1719	0.907	0.999
Basecoat			
25	568	0.933	0.995
40	419	0.859	0.997
Topcoat			
25	449	0.996	0.993
40	497	0.824	0.997

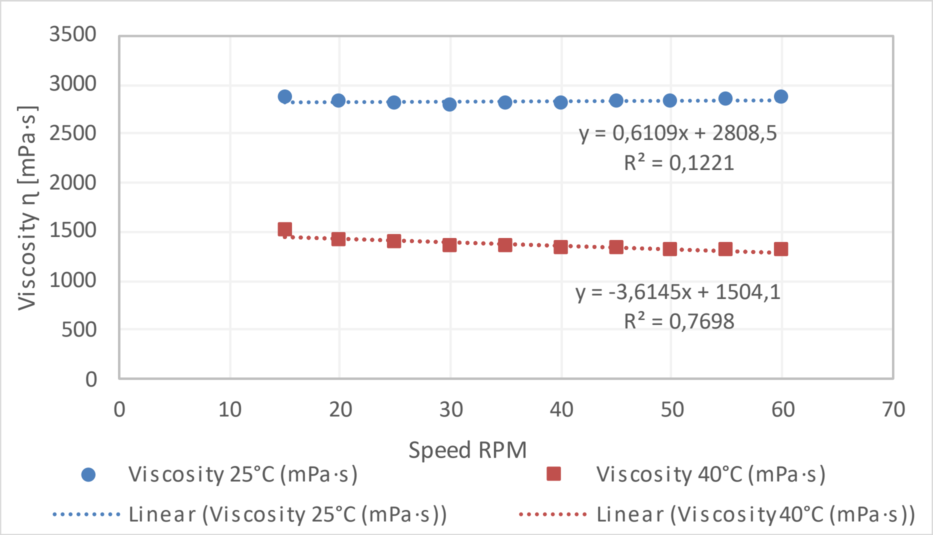

Fig. 1 Dependence of viscosity (η) on RPM at two various temperatures for the primer.

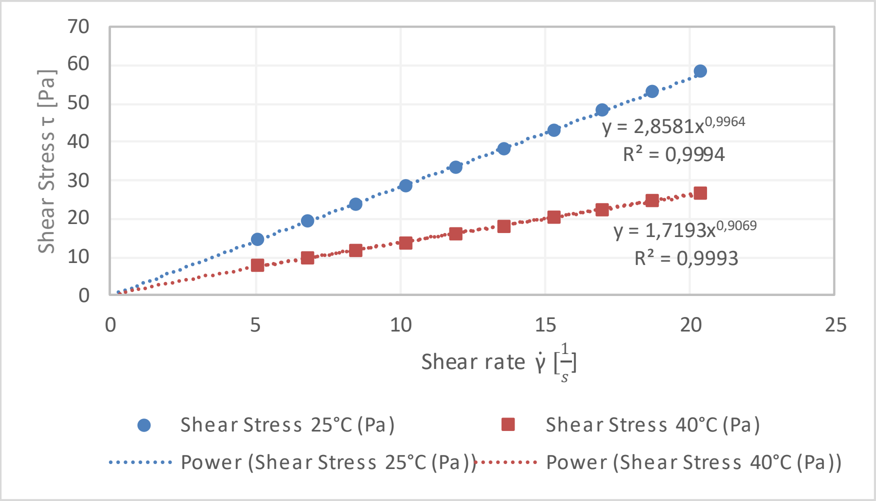

Fig. 2 The influence of temperature on the flow curves of the primer approximated using the Ostwald de Waele rheological model.

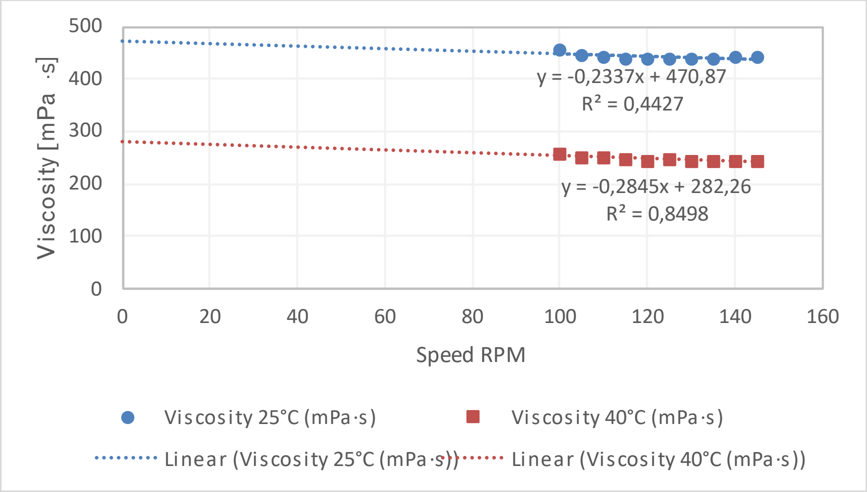

Fig. 3 Dependence of viscosity (η) on RPM at two various temperatures for the basecoat.

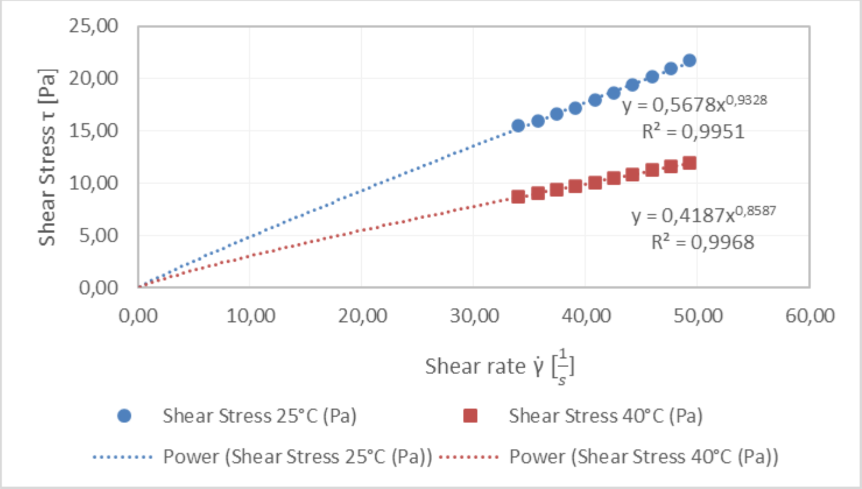

Fig. 4 The influence of temperature on the flow curves of the basecoat approximated using the Ostwald de Waele rheological model.

Based on the presented analyzes of flow curves determined graphically and data from the determined Ostwald de Waele rheological model, the data tested in the above ranges were classified into the category of non-Newtonian, shear-thinning, rheostable fluids. In the literature, these liquids are also called pseudoplastic liquids (Proszyk *et al.*, 1995; Zorll, 1980).

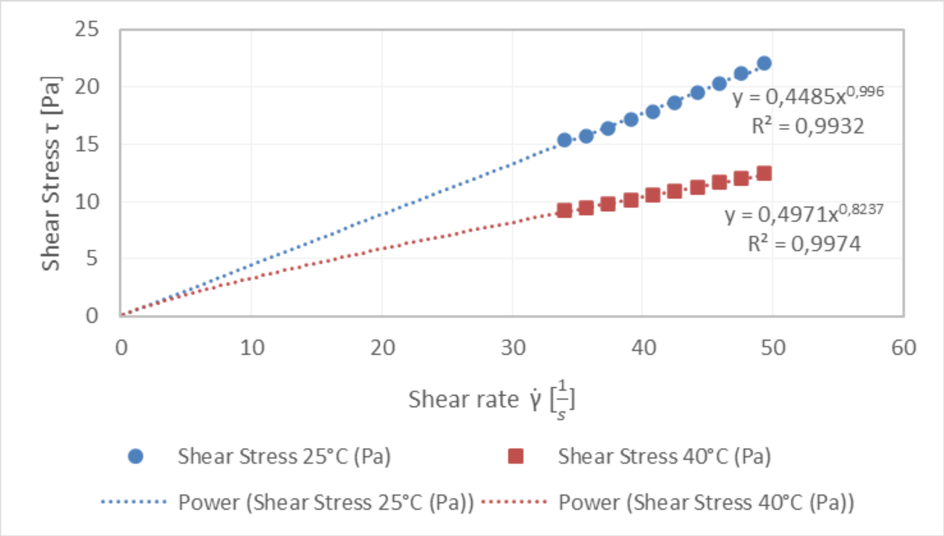

Fig. 6 The influence of temperature on the flow curves of the topcoat approximated using the Ostwald de Waele rheological model.

Based on the figures, it was found that the viscosity η of the varnish product decreases with an increase in the γ value. The highest viscosity is represented by the primer, then the basecoat, and the topcoat. An increase in temperature caused a decrease in viscosity by 40-45%. Table No. 2 presents the values of the rheological parameters of the Ostwald de Waele power model. High values of the correlation coefficient R^2 at the level of 0.993 – 0.999 confirm the good fit of the model to the data and prove its suitability for rheological descriptions of the tested products. According to the evaluation criteria of Kembłowski and Wiśniewski, the tested varnish products in the tested area of γ values meet the following relationship: $\eta' = \tau / \gamma \neq$ const (Kembłowski, 1973; Wiśniewski, 1988). In rheological modeling, the power exponent n1 is a measure of the fluid's deviation from a Newtonian fluid; n1<1 determines whether the fluid is classified as a non-Newtonian fluid. As the value of n1 decreases, the fluid shows a more and more clearly non-Newtonian character (Krystofiak, 2023). In the conducted analyses, n1 was at the level of 0.824-0.996.

Primer and topcoat at a temperature of 25°C exhibit rheological properties at the boundary of non-Newtonian and Newtonian liquids. This assessment was made on the basis of the high n1 level and the almost rectilinear arrangement of points on the viscosity η [mPas] – spindle speed (RPM) graph. However, the flow index decreases for a temperature of 40°C, indicating pseudoplastic properties. In the case of primer, this decrease was 8.9%, and in the case of basecoat 7.9%. The greatest decrease in the n1 index was recorded for the topcoat, it amounted to 17.3%. This is an important indication for some parameters in production practice. Especially when the main goal is to obtain defect-free coatings (Dziubiński *et al.,* 2014; Krystofiak, 2023).

Based on the results obtained, it can be concluded that the rheological parameter of the Ostwald de Waele model, which distinguishes the tested fluids, is consistency index k. The higher the k value is, the faster the material responds to changes in shear stress is. The highest k coefficient was recorded for primer. Also, for this product, the highest decrease in this parameter was recorded with an increase in temperature, which amounted to 40%. In the case of basecoat, a reduction of 26% was observed. Different rheological behavior in terms of consistency index k1 is represented by the topcoat, for which a 10% increase with increasing temperature was recorded.

Viscosity measured using the Ford Cup method

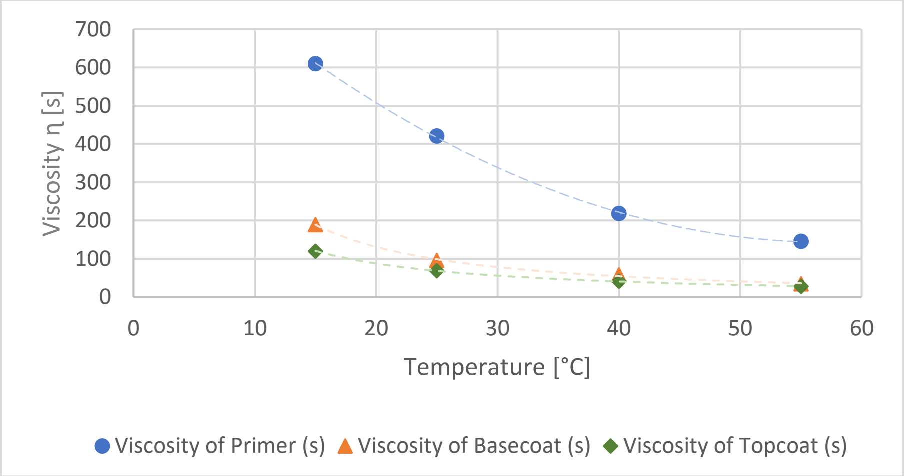

Fig. 7 The impact of temperature on varnish products viscosity.

Based on the data presented (Figure 7), it can be concluded that the viscosity decreases with increasing temperature. The most significant decrease (43% - 49%) in this parameter was recorded for varnishes when the temperature changed from 15 to 25°C, which indicates the need to condition varnish products for a sufficiently long time, especially in the winter season, in order to ensure the appropriate temperature during their application. The differences between 25 and 40°C were 48% for primer and 39-40% for topcoat and basecoat. Subsequent temperature increases to 40 and 55° resulted in a smaller decrease in viscosity.

The obtained results correspond to literature data on the influence of temperature on the viscosity of fluids (Klazly and Bognár, 2022). Research on coatings system based acrylic resin with UV absorber confirms a decrease in coating thickness with decreasing viscosity (Ozgenc, 2019). Due to the layer being too thick, an orange-peel effect may appear after the solvents are removed (Saranjam *et al.*, 2016). The viscosity of the products is adjusted based on the intended application method to prevent possible defects (Jakubíková *et al.*, 2023). Researchers also indicate that viscosity affects pumping efficiency. Ensuring a constant supply of the right amount of varnish to the applicator is a very important issue in engineering applications (Klazly and Bognár, 2022). To achieve high quality and effectiveness of products, it is necessary to comply with certain conditions in technological processes. Viscosity is an important analytical parameter that is monitored both during production and when assessing the use of products in various sectors of the chemical industry (Gosselin, 2024; Ruśkowska, 2010).

CONCLUSION

The findings mentioned above, along with the results of the analysis of flow curves determined graphically, allow for the tested acrylic products, i.e., primer, as well as both the base coat and the top coat, to be classified as non-Newtonian, shear-thinning, rheostable fluids, also known as pseudo-plastic liquids.

Understanding the influence of temperature on viscosity and the rheological model is not just theoretical knowledge. It allows for precisely adjusting the varnish product to the desired coating quality, underscoring the practical relevance of controlling this parameter.

What is more, both testing the viscosity using a Ford cup method and using the Brookfield viscometer, have provided significant information on how varnishes behave. The analysis of the rheological model allows for a better understanding of the properties of varnishes, whereas viscosity tests using the Ford cup method provide practical information that can be directly used during the application processes.

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