

Influence of Rheological Size Parameters on Yarn Properties

Abstract

The paper describes the results of changed size viscosity as a function of the temperature, concentration and shear stress. The rheological properties of size with various concentrations in combination with components of synthetic sizing agents based on polyvinyl alcohol (PVA) and carboxymethyl cellulose (CMC) were investigated. The size viscosity increased with decreasing temperatures and the increasing spindle speed of the viscometer. The breaking force and abrasion resistance of yarn sized under different rheological conditions by changing the temperature of sizing were examined. Measurement results show that by changing the size temperature from 50 °C to 80 °C the breaking force of the yarn mostly increased too. A change in the size temperature affects the yarn abrasion resistance, but these changes do not follow the linearity of the breaking force either, which is expressed by a comparison of the synthetic sizing agents with the same concentrations.

Key words: rheological properties of size, size viscosity, Newtonian and non-Newtonian fluids, size concentration.

Introduction

The investigation of rheological size properties is interesting in the technological sizing process both for manufacturers of sizing agents and for makers of sizing machinery. Rheological changes in the size, mostly expressed by changed viscosity as a function of the squeeze effect, the speed and time of the size flow, the size box temperature, concentration, the warp tension within the size box etc., affect the uniformity of the size pick-up on the warp and its good wettability.

Size viscosity decreases with rising temperature. Within broader temperature intervals it was experimentally found that the activating energy decreases with rising temperature. The activating energy of the viscose flow is constant only within narrow temperature intervals. As with other liquids it is supposed that the viscosity is not only affected by molecular kinetic energy but also by the free area between the molecules, which increases with rising temperature. Viscosity control by changing the temperature is of great importance since each sizing agent

in the size has a temperature constraint in the technological process. Size viscosity increases when the molecular mass of polymers increases. A possible theoretical explanation of these independences can be the assumption of the formation of intermolecular bonds with very long molecules, resulting in a stable area network that quickly increases the structural viscosity of the structure. Viscosity does not depend only on the indicators mentioned but also on molecule forms, e.g. the degree of branching [1 - 3].

Since sizing agents have a different structure, it is most important to find their optimal proportion in the size, which will cause the least warp end breaks in the weaving process. There have been no standardised recipes so far which will ensure maximum productivity and fabric quality. It is a problem even today, especially when sizing different yarns or using a greater number of sizing agents in the size.

Theoretical part

Sizes are multicomponent fluids whose viscose behaviour varies and is determined by their chemical composition, temperature conditions, squeeze force, concentration and shear stress. These individual components disclose great differences in their viscose properties and chemical structure, hence by mixing, because of intermolecular action, marked deviations in the viscosity measured versus the viscosity expected according to mathematical calculations based on component properties may be observed. The viscosity of a certain fluid can be calculated on the basis of the constant

viscosity of individual agents for specific conditions. Aggravating possibilities of maintaining constant conditions in the sizing process did not allow to determine the size viscosity [4].

One of the fundamental conditions for good and cost-effective sizing is uniform size pick-up while processing a whole batch. In order to achieve this, it is necessary to keep the following sizing parameters constant: concentration, viscosity, size temperature in the size box, speed of the warp through the size box, entry moisture of the warp, exit moisture of the warp, the squeeze force, and thread tension in the box [5, 6].

Rheological size properties

The rheological properties of sizes depend on the shear stress, temperature, hydrostatic pressure, molecular weight, molecular weight distribution, molecule form, concentration, the dwell time, and size mixing at a specific temperature. Viscosity is an important feature of each fluid and represents a measure of internal friction acting as resistance to a change in the molecule position during the flow of fluids and gases when they are affected by shear stress. Viscosity is identical to internal friction among fluid particles if they move in a way that a thicker fluid causes higher friction than a thinner one. For most macromolecules in the size, the relation of internal friction is somewhat more complex. When altering the speed, the dynamic friction is changed or the dynamic tenacity determines the viscosity. Therefore at a relative size viscosity Newton's Law is not responsible for a corresponding change in speed. At low speed gradients or low shear stresses the

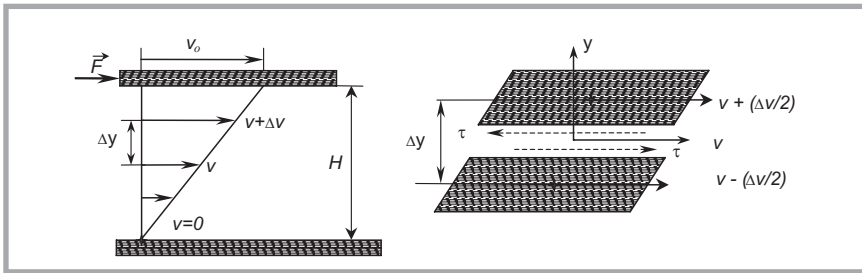


Figure 1. Schematic representation of fluid flow; a) deformation of one fluid part, b) influence of shear stress; F – external force in N .

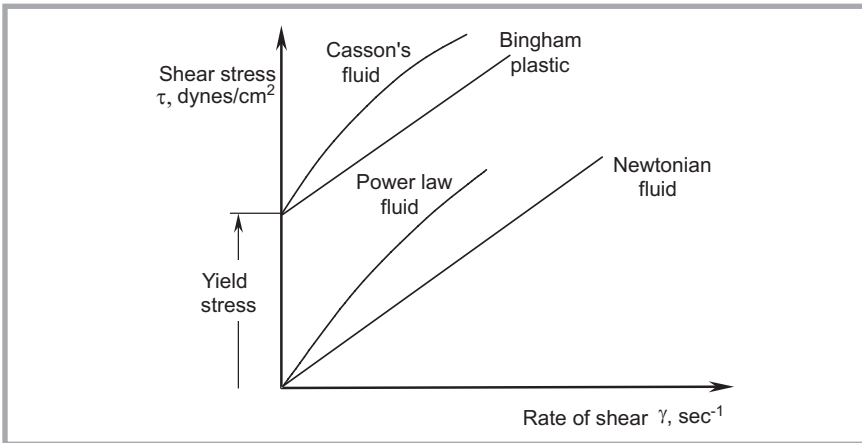


Figure 2. Curves of flow for different fluids.

course of the flow curve follows Newton's Law. The viscosity of these fluids is not constant, and it does not depend only on the temperature but also on the speed, shear stress and other parameters mentioned. Fluid speed through layers is different. The layers closer to the walls move more slowly because of friction than those closer to the centre or where the shear force is the greatest. The speed gradient when the fluid moves changes from zero in the vicinity of a solid wall to the maximum value at the points of the highest shear force \vec{F} .

Depending on the flow mode, the fluids are divided into Newtonian and non-Newtonian ones. If the Newtonian fluids move at height H (Figure 1) under the influence of an external force \vec{F} , in the stationary laminar flow mode, the external force is balanced through internal fluid resistance.

During the flow of real fluid, internal friction forces in the fluid play an important role. Size viscosity depends on molecular fluid movement and manifests itself in a way that during a relative shift of the size layers towards adjacent ones, friction forces occur in the size. In the vicinity of the wall, shear stress is caused

by viscosity. The area where this condition predominates is called the laminar sublayer [7 - 10].

For Newtonian fluids the shear stress is proportional to the gradient of the rate of fluid movement, hence

$$\tau = \eta \cdot \left(\frac{dv}{d\eta} \right) \quad (1)$$

τ – shear stress in N/m^2
 η – dynamic fluid viscosity in Pas
 v – rate of fluid flow in m/s .

A shift of one layer is transferred to another at distance h , which will happen in a specific time, being the relative slippage velocity v/h or lowering shear rate [11].

$$D = \lim_{\Delta y \rightarrow 0} \left(\frac{\Delta v}{\Delta y} \right) = \frac{dv}{dy} \quad (2)$$

D – decreasing rate of shear in $1/s$.

To characterise non-Newtonian fluids, the following models are applied.

Figure 2 illustrates curves of the flow of different fluids. The curves of flow for a Newtonian fluid, Power law fluid, Bingham plastic and Casson fluid are represented. The Newtonian fluid and Bingham plastic fluid are linear, whereas

the Power law and Casson fluids are non-linear.

The characteristic of flow of non-Newtonian fluids in the channel can be represented according to

$$\frac{p H}{2 u_m^2 \rho} = \frac{6}{Re} \quad (3)$$

p – pressure per length unit ($\Delta p/L$) in Pa
 H – channel height in m
 u_m – average rate of fluid flow in m/s
 ρ – density in kg/m^3
 Re – Reynolds' number

The Reynolds' number is taken as

$$Re = \frac{u_m H \rho}{\eta_r} \quad (4)$$

During fluid flow in the channel, whereby $B/H \rightarrow \infty$, an analogy of the flow through the tube is obtained. Thus the relative rate of shear for a non-Newtonian fluid may be represented in form of

$$D_r = \frac{4Q}{H^2 B} \quad (5)$$

Q – flow through in m^3/s
 B – channel length in m .

It is assumed that the flow through is

$$Q = u_m B H \quad (6)$$

where B is the channel length.

The relative rate of shear results from Equation 5

$$D_r = \frac{4 u_m}{H} \quad (7)$$

The representative dynamic viscosity of the fluid has the following form

$$\eta_r = K \left(\frac{4 u_m}{H} \right)^{n-1} \lambda \quad (8)$$

η_r – representative dynamic viscosity of fluid ($Pa s$)

K, n, C, a, A, c, d, e – fluid characteristics

$$\lambda = \frac{2}{3} \left(\frac{2+1}{\frac{n}{2}} \right)^n \quad (9)$$

variable λ from Equation 12 is determined for $n = 0.5$ to 3 .

The kinematic viscosity of the fluid has the form

$$v = \frac{\eta_r}{\rho} \quad (10)$$

v – kinematic viscosity of fluid in m^2/s .

The kinematic viscosity of a size may be defined as a function of the internal fluid properties and flow conditions. It manifests itself in a way that forces of friction occur in the size at the relative shifting of the size layers towards adjacent ones.

Experimental part

The investigation of rheological size properties was carried out by sizing cotton yarn of 17 tex. Laboratory sizing equipment was constructed to size yarns under different sizing conditions. This sizing equipment enabled to trace specific parameters affecting size pick-up. The following parameters were measured: yarn moisture directly before immersing it in the size, yarn moisture at the exit of the size box, size concentration, throughput speed of yarn through the size box, size temperature and yarn tension at the entrance of the size box.

The dynamic size viscosity was measured by a Brookfield rotation viscometer, model LV/1. The size viscosity was measured over 4 temperature steps: 50, 60, 70 and 80 °C. Measurements were carried out at lower temperatures to determine the difference in the properties of the size and sized yarn.

Determination of the breaking force was investigated on a Textechno tensile tester, model Statimat M, with 100 measurements carried out for each sample. The pre-stress force during the examination was 0.5 cN/tex. Thread break occurred within 20 ± 3 s.

A Zweigle abrader was used to measure the abrasion resistance. Standards prescribed by the manufacturer were applied for the investigations. The measurement of abrasion was carried out with 20 ends simultaneously up to a break. The number of left – right shifts of the abrading roller was registered by reading the counter for each thread breakage. A roller coated with emery cloth 800 P over the length of 7 cm yarn was used for abrasion.

Sizing conditions during the investigations were similar to those in the technological process: sizing rate, squeeze pressure, warp tension, concentration, recipes, sizing temperature and sizing agents. The yarn was examined in an air-conditioned room (rel. humidity $65 \pm 5\%$ and temperature 20 ± 2 °C), hence the yarn had air-conditioned moisture during the examination.

Table 1. Size viscosity according to proportions of sizing agents, concentration, temperature for different rates of shear; PVA - polyvinyl alcohol, CMC - carboxymethyl cellulose, n - speed of the spindle in the viscometer in min^{-1} , K_{1-6} - concentrations in %, T - temperatures in °C, η - dynamic viscosity of fluid in mPas.

Recepies	K_{1-6} , %	T , °C	n in min^{-1}						
			0.6	1.5	3	6	12	30	60
50% PVA + 50% CMC	$K_1 = 10.5$	80	98	151	212	232	238	218	220
		70	221	254	276	325	390	388	390
		60	267	355	411	419	427	447	411
		50	380	396	470	527	491	471	420
	$K_2 = 8.3$	80	50	58	84	118	116	109	111
		70	110	134	179	185	192	168	172
		60	167	239	255	264	239	231	220
		50	210	276	306	288	268	269	270
	$K_3 = 6.5$	80	14	24	30	54	69	71	80
		70	22	24	39	68	75	75	86
		60	26	32	57	87	121	127	133
		50	30	48	78	107	128	136	142
	$K_4 = 4.5$	80	8	11	18	21	25	23	17
		70	5	17	22	35	39	48	44
		60	11	17	37	55	67	78	88
		50	17	23	42	63	88	96	108
100% PVA	$K_5 = 8$	80	0	0.5	3	9	19	18	15
		70	0	0.5	4.8	8.2	22	22.5	21
		60	0	2	6.5	14.5	28	25	26
		50	0.5	3	10	22	36	30	29
100% CMC	$K_6 = 8$	80	50	88	158	194	238	256	232
		70	55	120	289	523	658	688	682
		60	255	650	820	1100	1080	1090	1233
		50	300	980	1210	1425	1493	1491	1520

Discussion

In this work four different concentrations with the same proportion of synthetic sizing agents (polyvinyl alcohol PVA and carboxymethyl cellulose CMC) were used. Sizes containing one synthetic sizing agent were also examined, the concentration being the same (**Table 1**). Size viscosity is a function of the speed, temperature and concentration ($\eta = f(v, T, K)$), therefore these parameters were examined too. Keeping the temperature at 50, 60, 70 and 80 °C was undertaken by warming or cooling and by temperature control with a thermometer immersed in the size. In **Table 1** and **Figures 3** and **4** (see page 44), it is observable that the size viscosity at lower speeds swiftly increases up to a specific value and then slowly decreases or increases with rising temperature or speed. The greatest changes in viscosity occur in a relatively short range, i.e. up to 10 r.p.m. of the viscometer spindle, whereas values change slightly in the case of further acceleration to 60 min^{-1} . In order to clearly show the viscosity in relation to the speed of the viscometer spindle, diagrams are shown with logarithmic speed values According to **Table 1** and **Figure 3.a** (see page 44), the highest size viscosity is $\eta_{\text{max}} = 527$ mPas,

specifically at the highest concentration ($K = 10.5\%$), the lowest temperature ($T = 50$ °C) and the speed of the viscometer spindle is $n = 6$ to 12 min^{-1} . Viscosity mostly rises until the spindle reaches 5 to 10 min^{-1} , and then it falls or rises gradually to a specific value. The size with a somewhat lower concentration $K = 8.3\%$ has a maximum viscosity $\eta_{\text{max}} = 306 \text{ mPa s}$ (**Table 1**, **Figure 3.b**, see page 44). At the start of the viscometer spindle rotation, the viscosity also increases quickly, while at a rate higher than 10 min^{-1} it falls gradually. Investigation of a size with lower concentrations ($K = 6.5\%$ and 4.5%) containing the same proportion of PVA and CMC showed an increase in viscosity from 10 to 15 min^{-1} , and afterwards at temperatures 50 and 60 °C the viscosity is similar to that at 70 and 80 °C (**Figures 3.c** and **3.d**, see page 44). Generally speaking, by increasing the spindle speed over 15 min^{-1} the viscosity does not change noticeably, and temperature differences are greater at lower concentrations (**Figure 3**, see page 44).

The size composed of one component – PVA – with a concentration of 8%, has a low viscosity $\eta = 0 - 36 \text{ mPas}$ (**Table 1**) compared with other cases, where

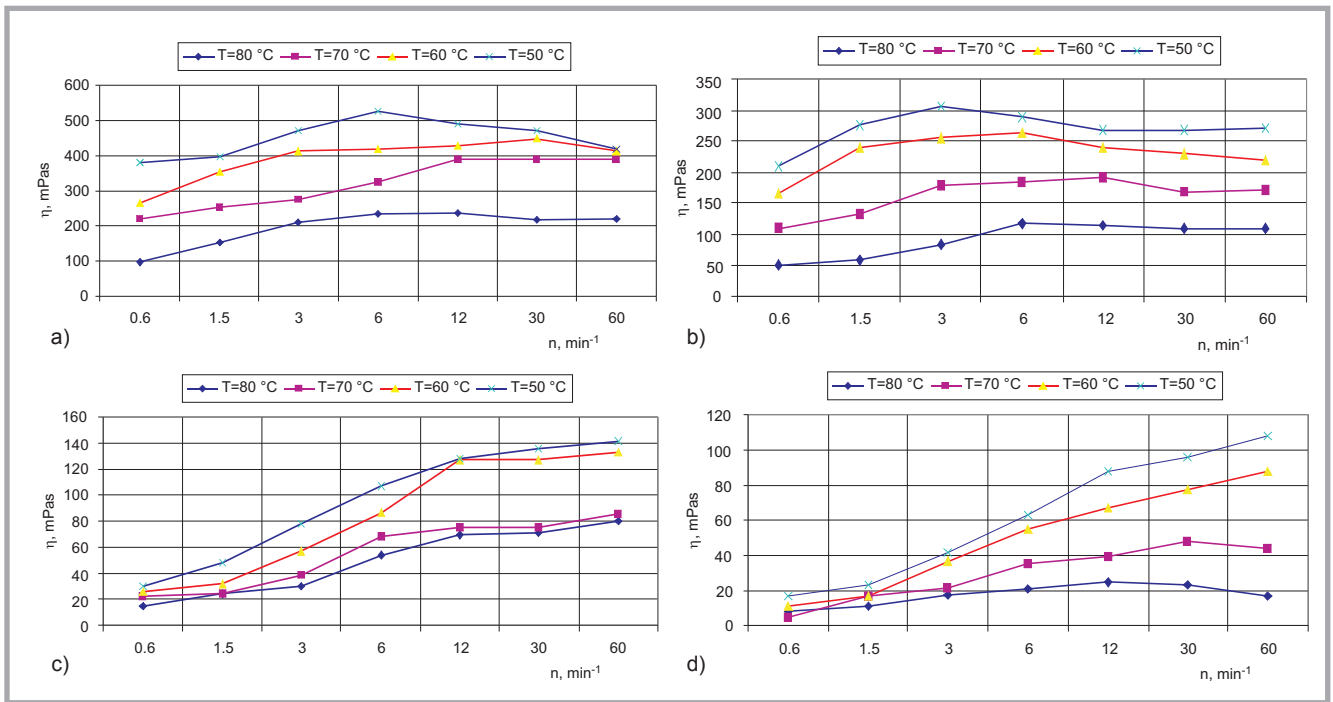


Figure 3. Dependence of dynamic size viscosity on the speed of the spindle in the viscometer at temperatures 50, 60, 70 and 80 °C for a concentration of: a) 10.5%, b) 8.3%, c) 6.4% & d) 4.5% and proportion of sizing agents 50% PVA + 50% CMC.

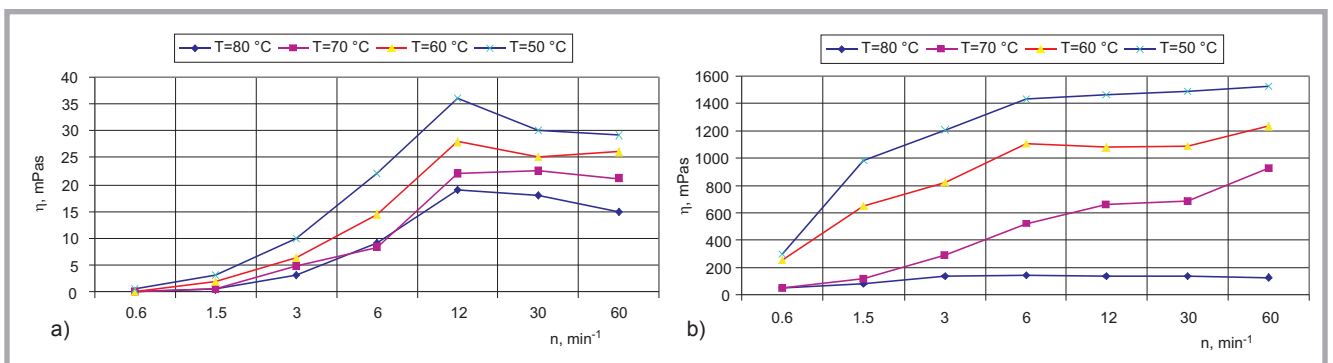


Figure 4. Dependence of dynamic size viscosity on the speed of the spindle in the viscometer at temperatures 50, 60, 70 and 80 °C for a concentration of 8% and sizing agent: a) 100% PVA and b) 100% CMC.

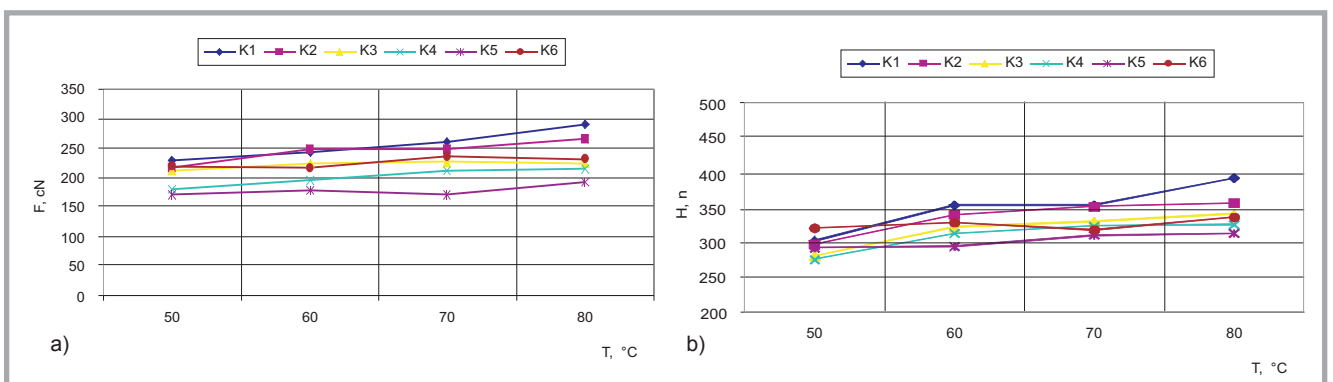


Figure 5. Dependence of the breaking force on size temperatures for different concentrations and recipes F - breaking force (cN), T - size temperature (°C), K_1 - 10,5% (PVA 50% + CMC 50%), K_2 - 8,3% (PVA 50% + CMC 50%), K_3 - 6,5% (PVA 50% + CMC 50%), K_4 - 4,5% (PVA 50% + CMC 50%), K_5 - 8% (PVA), K_6 - 8% (CMC).

PVC+CMC with the same proportions and concentration of 8.3% reaches a viscosity of $\eta = 50 - 306$ mPas. The PVA viscosity difference in dependence on

the temperature is lower compared with the sizes composed of two components (PVC+CMC), as shown in the preceding figures. A change in spindle speed causes

a change in viscosity. Initially it increases fast, and after $n = 10 - 15$ revolutions of the spindle viscosity it decreases slowly at all temperatures (**Figure 4.a**).

The viscosity of the size composed of synthetic agent CMC is substantially higher than that of PVA size, amounting to $\eta = 50 - 1520 \text{ mPas}$ (Table 1). The viscosity reached its maximum value at about $n = 10 \text{ min}^{-1}$, and afterwards it rose slowly at low temperatures or fell slowly at high temperatures (Figure 4.b).

Table 2 and Figure 5.a show average breaking forces of the yarn sized with different size concentrations and temperatures. The yarn sized with a higher concentration and higher temperature of the size usually had a higher breaking force. The breaking force per concentration generally increased at rising size temperatures. For the size composed of two components it amounted to 13.89 cN (224.38 - 210.49) or 6.19% at a concentration of $K_3 = 6.5\%$ to 61.81 cN (290.12 - 228.31) or 21.30% at a concentration of $K_3 = 10.5\%$. The breaking force of the sized yarn also increased by increasing the temperatures for sizes composed of one component, namely of PVA, by 21.55 cN (192.55 - 171.00) or by 11.19% and of CMC by 16.42 cN (231.59 - 215.17) or by 7.63%. The yarn breaking force did not always rise by increasing the concentration for all size temperatures. An increase in the temperature and concentration caused a gradual increase in the breaking force, which reached its minimum value at a temperature of 50 °C and concentration of 4.5%, amounting to 180.29 cN. The highest breaking force of 290.12 cN was recorded at a temperature of 80 °C and concentration of 10.5%, meaning that a size with a higher temperature is more suitable for sizing because it penetrates interspaces more effectively and its higher tackiness protects the yarn from stress.

Size temperature affects yarn abrasion resistance. A higher temperature provides a lower size viscosity and a higher adhesive capacity, hence it sizes the yarn deeply, increasing its stability with respect to stress and abrasion resistance.

Table 2 and Figure 5.b show the impact of size temperature on abrasion resistance for different size concentrations and proportions of sizing agents. Changes in the yarn abrasion resistance almost followed changes in the breaking force under sizing conditions, meaning that a higher breaking force of yarn had a higher abrasion resistance and vice versa. For the sizes composed of 2 components the abrasion resistance in-

Table 2. Breaking force and abrasion resistance of the yarn by portions of sizing agents, concentration and temperature.

Recipe	K_{1-6} , %	T , °C	F, cN		H, n	
			x	CV	x	CV
50% PVA + 50% CMC	$K_1 = 10.5$	80	290.12	4.81	390.92	7.66
		70	260.07	4.27	352.66	8.29
		60	242.97	5.86	352.72	7.77
		50	228.31	7.33	302.55	9.22
	$K_2 = 8.3$	80	266.09	5.22	355.51	7.22
		70	248.71	6.71	350.19	6.18
		60	247.33	4.90	339.19	7.89
		50	215.85	6.73	297.29	6.09
	$K_3 = 6.5$	80	224.38	5.93	340.28	6.89
		70	226.88	6.88	329.67	8.29
		60	223.03	6.00	321.17	8.48
		50	210.49	5.88	280.73	8.40
	$K_4 = 4.5$	80	213.42	4.51	325.06	5.01
		70	210.41	4.21	322.91	5.77
		60	194.60	5.03	313.29	7.26
		50	180.29	4.88	275.88	9.00
100% PVA	$K_5 = 8$	80	192.55	5.82	313.22	4.67
		70	171.27	4.11	310.28	8.02
		60	178.39	4.70	294.45	7.55
		50	171.00	5.31	292.17	9.20
100% CMC	$K_6 = 8$	80	231.59	6.88	333.52	10.97
		70	235.29	7.81	317.92	9.33
		60	215.17	9.29	328.33	11.72
		50	218.72	7.22	320.29	10.55

creased at higher size temperatures in all concentrations. The lowest increase in abrasion resistance was at the lowest concentration ($K = 4.5\%$), i.e. by $n = 49.18$ (325.06 - 275.88) of left-right roller movements in the abrader or by 15.13%. A higher abrasion resistance manifested itself at higher concentrations, therefore the concentration $K = 6.5\%$ increased the resistance by $n = 59.55$ (340.28 - 280.73) of left-right roller movements or by 17.50%, at a concentration of $K = 8.3\%$ the increase in the resistance was $n = 58.22$ (355.51 - 297.29) movements or by 16.38%, at a concentration of $K = 10.5\%$ by $n = 88.37$ (390.92 - 302.55) movements or by 22.61%. For the sizes composed of PVA, an increase in abrasion resistance from the lowest to the highest temperature was $n = 21.05$ (313.22 - 292.17) roller movements on the abrader or by 6.72%. For the CMC size an increase in abrasion resistance was lower in comparison to PVA, amounting to $n = 13.23$ (333.52 - 320.29) roller movements or by 4.00%.

Conclusions

According to the investigations performed it can be concluded that rheological size properties do not only depend on

the conditions of the sizing process, such as the temperature and shear rate, but also on other parameters such as the size type, the portion of individual agents and the chemical structure of agents.

Great differences in the rheological properties of size, even with small changes of temperature and the rate of shear (Table 1), were found. It was experimentally proven that size does not follow Newton's Law, and its viscosity depends on the rate of shear or shear stress; they are designated as Newtonian fluids or they belong to a group of structurally viscose fluids. The rheological properties of size depend on many parameters. Viscosity in the form of some parameters does not behave linearly. Therefore a wide range of measuring all the parameters for each size is necessary, as well as approximating experimental values of changes to a theoretical model. This represents the complexity of the rheological properties of size, thus fundamental investigations of yarn properties, sizing and weaving conditions are necessary.

By changing the sizing temperature, the quality of size pick-up and properties of the sized yarn are changed. Special attention should be paid to the viscose-temperature behaviour because high-quality

sizing is achieved especially by keeping and monitoring the temperature. Lower viscosity enabled better deep sizing, but the size pick-up was lower, which is more prominent at all sizing temperatures. Higher viscosity causes a slower penetration of yarn interspaces, and yarn is sized more on the surface, causing lower abrasion resistance and uneven yarn, which is more prominent at lower sizing temperatures. In this case yarn has a seemingly higher strength. But by yarn abrasion the size pick-up formed can be removed easily, and the yarn is without necessary protection during weaving. New synthetic sizing agents have very high tackiness, but these events are rare.

By increasing the rate of shear, viscosity increases to a certain extent and then falls or rises slowly and continuously (Figure 3-4). A difference in viscosity among synthetic sizing agents is evident. Carboxymethyl cellulose (CMC) has a higher viscosity than polyvinyl alcohol (PVA) at the same rate of shear and same concentration (Table 1). This difference is more prominent if the temperature is lower. When mixing these two synthetic sizing agents with the same proportion in the size, no average value of viscosity was obtained, being substantially lower. Polyvinyl alcohol mixed with carboxymethyl cellulose probably progressively weakens intermolecular bonds of carboxymethyl cellulose.

PVA sized yarn has a higher breaking force than CMC sized yarns, but the abrasion resistance is lower (Table 2). CMC sized yarn has higher smoothness and elasticity, whereas PVA sized yarn is stronger and stiffer. Because of the variety of these polymers, it is possible to find their proportion in the size that will cause minimum end breakage during weaving and minimum yarn deformation. It may be concluded that these two agents are very different, and by combining them in the recipe a sized yarn with desired properties may be obtained that will have minimum yarn breakages and minimum yarn deformation during weaving.

A higher size concentration imparted higher viscosity during all examinations. A change in size temperature in the size box caused a change in viscosity, as well as in the breaking force and abrasion re-

sistance of the yarn. Higher temperatures are more favourable as they provide better yarn properties.



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University of Bielsko-Biała
Faculty of Textile Engineering
and Environmental Protection
ul. Willowa 2, 43-309 Bielsko-Biała
tel. +48 33 8279 114, fax. +48 33 8279 100
E-mail: itimp@ath.bielsko.pl