# PREDICTION OF BINDER POLYMERIZATION RATE IN THE GLASS WOOL CURING OVEN

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Binder polymerization in the curing oven was investigated experimentally in the glass wool production. First focus was on the measurements of glass wool layer temperature distribution along the curing oven. The different temperature curves were compared with fiber density distribution in a layer of glass wool, measured with the X-ray device. The maximum difference between the temperature curves amounted to 60 °C and fiber density distribution deviated for  $\pm 8\%$  according to nominal density. With a near infra-red spectroscopy binder polymerization rate was measured and compared with a set average temperature of curing oven, where the regression model was determined. With temperature reduction for 9 °C and polymerization rate decreasing for 2% were defined optimal product quality. In the next study, binder polymerization rate was predicted with aid of set temperatures and fan rotational frequency as input process parameters and near infra-red spectroscopy as continuous response variable, where the temperature shown bigger impact than fan rotational frequency. Next prediction was done with aid of the input parameters and the magnitude of the fan rotational frequency and temperature as a response variable. In this case, the input quantities represent: a type of product, curing oven saturation, the ambient temperature, micronaire, area weight of the product, and binder amount in the glass wool product. For each zone of the curing oven, an equation was determined to predict the magnitude of the fan rotational frequency and temperature. Regression models results showed high correlation with the determination coefficient,  $R^2$ , higher than 0.85.

Key words: glass wool, curing oven, regression model, binder polymerization

## Introduction

Glass wool (GW) is one of the most widely utilized thermal insulation materials [1, 2]. Apart from GW, silicate materials are often used as thermal insulation coatings [3]. However, waste is produced as by-products of the production process and is considered to be impossible to recycle completely [4]. It is reported that about 800000 tons of GW waste is produced in Europe every year and most of it are landfilled or unutilized [5]. The manufacturing process of GW includes the addition of raw materials, mainly trash glass, into the furnace followed by melting at a temperature of around 1300 °C. The stabilization channel receives the molten glass mixture before it is poured through the funnel and into the revolving spinners. Melt is extruded

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through spinner holes to generate fibers, which are subsequently coated with binder. The fibers are oriented downward toward the collecting chamber by the coaxial blow-away air flow with adjustable pressure and finally collected to form raw GW and then transported through the polymerization chamber, where the binder polymerisation process occurs.

The curing oven channel in the GW production process is a crucial part since it allows the smoke fumes to heat the GW and initiate the polymerization process. The binder polymerization process begins when the temperature of the GW layer rises over the activation temperature. The GW contains about 5 wt.% to 10 wt.% of organic resin, often phenolic binder, and sugar-based binder to enable the operation [6]. While sugar-based binders are created by polycondensing naturally occurring plant-based components, phenolic binders are created via a polymerization reaction involving phenol, formaldehyde, and urea. The selection of resins is typically based on improving the processability and achieving desirable attributes including plasticization, coloring, and flame retardancy. It is crucial to understand that phenol-formaldehyde resin begins to break down during GW production at a temperature higher than 250 °C. At such temperatures, the binder begins to harden, resulting in successive lacing of fibers which provides characteristic mechanical properties such as tensile, compressive, and bending strengths [7]. Pavlin et al. [8] studied the influence of the curing regime and liquid-to-solid ratio utilized in GW and stone wool containing organic binder and detected superior mechanical properties in GW with organic binders. Xu et al. [9] studied the mechanical properties of aluminate cement mortar mixed with chopped steel fibers and basalt fibers under high temperature and reported improved mechanical properties.

The curing oven enables continuous adjustment of layer thickness and velocity of the GW layer to achieve the desired specific density. Layer velocity must be corrected on a permanent basis due to interdependent factors such as layer thickness, specific mass, and conveyor belt velocity.

The single variable that affects GW capacity is conveyer belt velocity, which varies with layer thickness and density. The mass of the GW layer is measured to adjust the transporter velocity. The variable velocity impacts the retention period in the curing oven, which influences the bonding process. This influences the aero-thermodynamic properties of circulating smoke gases. The regulation of aero-thermodynamic variables in the polymerization process is crucial for ensuring the functionality of the production process and minimizing fuel consumption. Factors like circulation system sealing, smoked gas removal, and transporter perforations influence the formation of functional areas of transition velocity of smoked gases [10].

Industrial ovens significantly impact product quality, but energy consumption, complex thermo-physical processes, and monitoring difficulties pose challenges. Yi *et al.* [11] improved curing cycle time in industrial continuous convection ovens by numerically modeling air flow. They found that higher line speed reduces product temperature, and higher air-flow velocities increase it. Several experimental and numerical studies focused on optimizing a curing oven, focusing on uniform temperature, optimal pressure, sensitive products, energy loss minimization, insulation use, internal air flow balance, and temperature optimization using simulation [12-14]. Yuksel *et al.* [15] proved that the effective thermal conductivity of GW reinforced aluminium samples increases uniformly with increasing the temperature. The addition of extra layers in samples reduces effective thermal conductivity at low temperatures, resulting in improved insulation.

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The quantity of waste GW has to be reduced from the production cost reason and the environmental side. One of the main reasons for the waste GW material is polymerization process. If will be well described and understood, then GW production would drive the process more optimal and make value added to the productivity and environment.

The current study evaluates the temperature characteristics of GW layers as they progress through the curing oven. The fiber density distribution in a layer of GW was studied with X-ray equipment, and the binder polymerization rate was determined using near infrared (NIR) spectroscopy. The binder polymerization rate was predicted using varied fan rotational frequency and temperature settings per curing oven zone. The regression model employed the kind of GW product, saturation, ambient temperature, micronaire, binder content, and fan rotational frequency to forecast the fan rotational frequency and temperature in each zone of the curing oven.

### **Methods**

For better understanding of polymerization process the measurements of GW layer temperature characteristics along the curing oven were performed, fiber density distribution in a layer of GW was studied and binder polymerization rate NIR was analysed.

# Measurements of GW layer temperature characteristics along the curing oven

One of the important diagnostic parameters is also the knowing of temperatures in the GW layer at its transition through the curing oven. According to the possibilities of local temperature changes in the layer, periodical temperature measurement in the GW layer turns out to be the appropriate method. This method requires the implementation of a thermo isolated PC unit, fig. 1, with six connected thermocouples. The isolation of the PC unit prevents the temperature in the unit to rise above the allowed 70 °C while the measurements of GW transition through the curing oven are performed. The installation scheme for the implementation of the measuring system is shown in fig. 2. The installed experimental equipment is moving together with the GW layer through the curing oven. During this, the current measured temperature values captured by particular sensors are saved on the PC. Because the movement velocity along the oven is constant during the experiment, the longitudinal position of the curing oven according to the measured local temperatures in the GW layer is also clearly determined.



Figure 3 represents the function scheme of flow of smoke gases passing through the GW layer. The displayed segment includes the basic components which are present in a real polymerisation process.

The GW layer continuously enters the curing oven which consists of two separated areas. These two areas are separated by a layer of GW that is located between two perforated conveyor belts which are moving together with the layer through the oven. The pressure difference is generated by the circulation fan that moves the smoke gases through the GW layer. At

a given functional velocity of smoke gases, the pressure difference depends on the aerodynamic-resistive characteristics of GW. Smoke gases from the oven area of negative pressure enter the gas burner where they are heated up by the combustion of fuel and controlled supply of air necessary for the combustion. The circulation fan transports the heated smoke gases into the lower chamber with overpressure. At nominal volume rate of flow, this fan must overcome the pressure losses in the circulation system and the aerodynamic losses that occur when the smoke gases pass through the GW layer. Since the fuel combustion in the combustion chamber supplies the sufficient energy to heat up the GW layer and polymerise the binder, the quantity of smoke gases in the circulation system increases. The generated quantity of smoke gases mostly depends on the amount of fuel, supplied air and water that evaporates when the layer is heated up. To remove the smoke gases, the negative pressure circulation system is connected to the suction fan. This fan sustains the stationary pressure conditions in the circulation system and transports the redundant smoke gases into the system of smoke gas combustion and further through the filters into the atmosphere. The operating regime of the suction fan depends on pressure conditions in the circulation system and on the amount of newly formed smoke gases. Usually, the operating point of this fan is adaptively set so that the absolute pressure in the smoke gases is the same as the pressure in the atmosphere where the smoke gases are passing through the GW layer. This ensures the minimal transition of smoke gases into the environment and optimal fuel consumption [10].

The oven in our case is divided into nine zones with exchanging direction of circulation flows. The number of zones is dependent from product area weight and power of fans. In the first five zones, the pressure in the upper area, position 1, fig. 3, is lower than the pressure in the bottom area of the oven, position 2, fig. 3. Opposite situation is in last four zones.



Figure 3. Functional scheme of the curing oven

Table 1 presents four operating points by constant fan rotational frequency, n, and changes only by temperature, T, per curing oven zone. To stabilize the temperature in the polymerization chamber, the experiments were performed at two-hour intervals. The GW samples were taken for measuring the degree of polymerization, NIR, by each operating point. During the test, fiber density distribution in a layer of GW was measured with an X-ray device. Temperature profiles in the polymerization chamber were measured using calibrated thermocouples and a data logger device, type Q18 with an accuracy of  $\pm 0.5$  °C. The GW line speed was 36 m per minute and product area weight 1.3 kg/m<sup>2</sup>.

Op. point no.	$T_1$ [°C]	<i>T</i> <sub>2</sub> [°C]	<i>T</i> <sub>3</sub> [°C]	<i>T</i> <sub>4</sub> [°C]	<i>T</i> 5 [°C]	<i>T</i> <sub>6</sub> [°C]	<i>T</i> <sub>7</sub> [°C]	<i>T</i> <sub>8</sub> [°C]	<i>T</i> 9 [°C]
1	240	245	250	260	270	275	280	280	275
2	230	230	240	250	260	270	270	270	275
3	280	260	230	230	230	250	260	260	250
4	255	275	240	225	225	240	240	250	250
Op. point no.	$n_1$ [min <sup>-1</sup> ]	$n_2$ [min <sup>-1</sup> ]	$n_3$ [min <sup>-1</sup> ]	$n_4$ [min <sup>-1</sup> ]	$n_5$ [min <sup>-1</sup> ]	$n_6$ [min <sup>-1</sup> ]	$n_7$ [min <sup>-1</sup> ]	$n_8$ [min <sup>-1</sup> ]	<i>n</i> 9 [min <sup>-1</sup> ]
1	400	350	350	300	300	300	300	350	350
2	400	350	350	300	300	300	300	350	350
3	400	350	350	300	300	300	300	350	350
4	400	350	350	300	300	300	300	350	350

Table 1. Setting parameters by curing oven zones

Note: The temperature is described with  $T_1 - T_9$ ,  $n_1 - n_9$  represents the fan rotational frequency.

Operating point 1 represents the standard temperature and fan rotational frequency settings. In operating point 2, the temperatures were reduced to 9 °C on average. In operating point 3, the temperatures were additional decreased compared to operating point 2. Only in zones 1 and 2 did the temperatures increase with the assumption of faster water evaporation and consequently early polymerization beginning. In operating point 4, temperatures were reduced by 6 °C on average related to the test 3. According to operating point 3, the temperatures in zone 1 and zone 2 were set opposite. The lower value was set in zone 1 and higher in zone 2.

Figure 4 presents the results of GW temperature measurements. The results are calculated to a longitudinal position in the oven. That enables the connection of local temperatures with local particularities inside the oven. Position 1 in the chart legend presents GW temperature on the right side of transporter belt moving and position 6 left side, fig. 2. The vertical gray continuous lines in the diagrams marked from 1 to 6 indicate the first 6 zones in the curing oven. The diagram in fig. 4 describes the temperature of the GW at operating point 2.



Figure 4. Temperature distribution in the GW layer along the curing oven

Data logger device starts showing value at 18 °C. That presents ambient temperature. Measuring device in the GW shows 30 °C, which is before curing oven. After that all six curves were increased to 60 °C where the polymerization begins. That is happening at the beginning of the third zone. From here, the curves rise intensively to zone 6 and continue slightly to the end of the curing oven, where the GW reaches from 190 °C to 210 °C.

Similar temperature curve shapes were obtained at all four operating points. Differences were observed at operating point 3, when we increased the temperatures in zones 1 and 2. Due to the increase in temperatures, the temperature of the GW previously reached 60 °C, but the polymerization started not earlier. In operating point 4, a lower temperature was set in zone 1 and a higher temperature in zone 2. The shape of the temperature curves in the GW has not changed. Consequently, 230 °C can be determined as the optimal temperature for the first two zones.

The curves of temperature here differ from each other. This implies that the GW is non-homogenous. Local non-homogeneities of GW are local specific density, presence of non-homogenous binder distribution and humidity part.

## Fiber density distribution in a GW layer

The X-ray device works on a non-contact principle. Above the device main structure, a radiation source is located while the radiation detector is placed below the line belt. The X-ray radiation from the source penetrates the measured material and is partly absorbed in it, depending on the quantity and specific weight of the analyzed material. The unabsorbed radiation component is picked up by the detectors and converted into electrical signals for further evaluation.

The absorption is given by:

$$I = I_0 \mathrm{e}^{-\mu_m \rho x} \tag{1}$$

where *I* is the remaining radiation intensity after passing through the material of thickness *x*,  $I_0$  – the intensity of the radiation before entering into the material,  $\mu_m \,[\text{m}^2\text{kg}^{-1}]$  – the mass attenuation coefficient of the material, and  $\rho \,[\text{kgm}^{-3}]$  – raw density of the material. The mass attenuation coefficient is a material attribute which depends on the chemical composition of the material. The area weight, *f*  $[\text{kgm}^{-2}]$ , can be calculated directly from the corrected intensity values:

$$f = \frac{\log\left(\frac{I_0}{I}\right)}{\mu_m} \tag{2}$$

From the area weight, f, and the material thickness, x, the raw density, eq. (3), is calculated [5, 11]:

$$\rho = \frac{f}{x} \tag{3}$$

Figure 5 presents fiber density distribution in period when all four GW temperature measurements were performed. Fibre density distribution was measured with the X-ray measurement device with a spatial resolution of 300 mm  $\times$  300 mm and is described with  $\pm$ 8% deviation according to nominal density value.



Figure 5. Fibre density distribution in a GW layer

#### Binder polymerization rate

The NIR is an analysis method that uses the NIR region of the electromagnetic spectrum (800-2500 nm). It measures the absorption of light from the sample in the NIR region at different wavelengths. The recorded NIR spectrum consists of overtones and combination vibrations of molecules that contain CH, NH, or OH groups. When light is reflected from solid

surfaces or particles in powders, pellets or granulates, it is called diffuse reflection, fig. 6. In an integrating sphere light is directed in a broad nearly parallel beam onto a sample. The diffusely reflected light is well distributed in the sphere by multiple diffuse reflections at the gold-plated inner surface, homogenizing the light. Therefore, an integrating sphere is well suited for inhomogeneous samples as well as for fine powders. Depending on the sample, light may penetrate beyond the surface a significant distance, *e.g.* for powders its approximately 2 mm to 4 mm depending on particle size, wavelength, and density, thus enabling the quantification of components within the sample [16].

The GW samples were taken at three points in the transverse direction of the production line. Each sample was splitted into three equal parts by



Figure 6. The NIR spectroscopy

GW height and was used on a NIR device to determine the degree of polymerization of the binder. According to experience, optimal polymerization rate of the binder is estimated at  $80 \pm 2\%$ .

Curing oven fans from zone 6 to zone 9 transports hot air on the upper side of GW. Temperatures in operating point 1 are used from experience and confirms 79.2% polymerization of GW. Excessive temperature settings are in zones 1 to zone 5, which is confirmed by NIR measurements (88.7%). In these zones, the fans transfer hot air to the GW from the bottom side.

Op. point no.	Average <i>T</i> , [°C]	NIR [%] (average)	NIR [%] (up)	NIR [%] (bottom)	NIR [%] (middle)
1	264	83.6	79.2	88.7	83.0
2	255	81.6	78.0	85.5	81.3
3	250	77.3	74.1	81.6	76.1
4	244	76.7	73.4	81.2	75.6

Table 2. Average temperature and polymerization rate for four operating point

The average temperature, decreased by 9 °C at operating point 2, shows a reduction in the polymerization at the upper, middle, and bottom level from 1.2% to 3.2% and present optimal polymerization rate. Temperatures in operating point 3 and 4 were reduced too much, indicating an average measurement of NIR with polymerization below 78%. Average temperature and average polymerization are in good correlation, what is confirmed by a high value of determination coefficient,  $R^2 = 0.91$ , indicating good quality of regression modelling:

$$NIR = -15.8 + 0.3776$$
 Average T (4)

## **Results and discussion**

The experiments were conducted in the curing oven in a real production process. More than one hundred experiments were performed at different fan rotational frequency and temperature per curing oven zone. Binder polymerization was measured by each operating point. Production process parameters were set in such manner that the product quality was adequate for packaging and sale, hence all measured variables corresponded to a set of real production parameters.

Op. point no.	<i>T</i> <sub>1</sub> [°C]	<i>T</i> <sub>2</sub> [°C]	<i>T</i> <sub>3</sub> [°C]	<i>T</i> <sub>4</sub> [°C]	<i>T</i> 5 [°C]	<i>T</i> <sub>6</sub> [°C]	<i>T</i> <sub>7</sub> [°C]	<i>T</i> <sub>8</sub> [°C]	<i>T</i> 9 [°C]	Measured NIR [%]
1	255	260	265	270	270	270	270	270	260	83.4
2	265	265	270	270	270	270	280	280	275	86
3	260	270	270	270	270	270	270	280	260	84.6
4	260	260	260	270	270	280	280	270	270	85.5
110	250	255	260	260	270	270	265	260	260	80
111	260	260	265	270	275	280	275	275	270	80.6
112	260	260	265	270	275	280	275	270	265	81.3
113	255	260	260	270	270	270	270	260	260	80.4
Op. point no.	$n_1$ [min <sup>-1</sup> ]	$n_2$ [min <sup>-1</sup> ]	$n_3$ [min <sup>-1</sup> ]	$n_4$ [min <sup>-1</sup> ]	$n_5$ [min <sup>-1</sup> ]	$n_6$ [min <sup>-1</sup> ]	$n_7$ [min <sup>-1</sup> ]	$n_8$ [min <sup>-1</sup> ]	<i>n</i> 9 [min <sup>-1</sup> ]	Calculated NIR [%]
1	500	550	550	600	600	600	600	600	600	82.9
2	650	700	700	800	800	900	900	800	700	85.7
3	550	600	650	700	750	650	600	550	500	84.6
4	600	700	850	900	950	900	850	800	800	83.7
110	400	400	450	450	400	400	400	400	400	78.8
111	400	400	400	400	350	350	350	350	350	79.7
112	600	550	600	650	600	550	550	600	600	81.2
113	450	500	500	500	500	500	500	500	450	80.5

Table 3. Setting parameters by curing oven zones

Note: The temperature is described with  $T_1 - T_9$ ,  $n_1 - n_9$  represents the fan rotational frequency. Binder polymerization is described with calculated and measured NIR value.

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A good correlation is expected between the binder polymerization rate, NIR, tab. 3, and the process input parameters,  $T_{1-9}$ ,  $n_{1-9}$ , tab. 3). This hypothesis will be confirmed by the following linear regression model:

$$y = b_0 + b_1 X_1 + b_2 X_2 + \dots + b_k X_k$$
(5)

where y is the continuous response variable, NIR,  $b_0$  – the constant,  $b_1$ ,  $b_2$ , ...,  $b_k$  are the coefficients,  $X_1$ ,  $X_2$ , ...,  $X_k$  are the values of the terms (temperatures and fan rotational frequency). Values of regression model constants are presented in tab. 4. Parameters with negative values inversely influence the binder polymerization rate. Their significance was checked with a *t*-test, tab. 4.

	$b_0$	$b_1$	$b_2$	<i>b</i> <sub>3</sub>	$b_4$	$b_5$	$b_6$	<i>b</i> 7	$b_8$	<b>b</b> 9
Values	85.58	0.1115	-0.0635	-0.0582	0.0199	0.0007	-0.0676	-0.0040	0.1589	-0.1257
Prob >  t		0.548	0.554	0.514	0.493	0.510	0.577	0.702	0.752	0.685
	$b_{10}$	$b_{11}$	$b_{12}$	$b_{13}$	$b_{14}$	$b_{15}$	$b_{16}$	$b_{17}$	$b_{18}$	
Values	0.003267	-0.00115	-0.00952	-0.00633	0.01164	0.00334	0.00584	-0.00018	0.00002	
Prob >  t	11.8	11.1	11.7	13.6	14.7	15.1	14.1	13.3	11.1	

Table 4. Regression model coefficients values with the results of the *t*-test

The results presented in tab. 4 show the parameter impact on the binder polymerization rate. Parameters  $b_1$ - $b_9$  present the temperatures in curing oven zones and have the biggest impact on the binder polymerization rate. Smaller impact results from the rotational frequency of fans, parameters  $b_{10}$ - $b_{18}$ , used for circulation hot air through the GW.

The comparison between measured NIR and the ones calculated based on regression model is shown in fig. 7. A good agreement between calculated and measured values NIR is confirmed by a high value of determination coefficient,  $R^2 = 0.88$ , indicating good quality of regression modelling. Equation (6) describe correlation between measured and calculated NIR value:

Calculated NIR = 6.347 + 0.921 measured NIR

So far, we have focused on the correlation of fan rotational frequency and temperature with respect to the rate of NIR polymerization. The connection between the input parameters and the magnitude of the fan rotational frequency and temperature as a response variable is presented below. For each zone of the curing oven, an equation was determined to predict the magnitude of the fan rotational frequency and temperature. In this case, the input quantities represent:

A type of product where light rolls is marked LR (1), heavy rolls HR (2), light plates LP (3) and heavy plates HP (4).



Figure 7. Correlation between measured and calculated values of NIR ( $R^2 = 0.88$ )

(6)

- Saturation: Every two months, fibers are removed from the curing oven. Broken fibers saturate curing oven interior during the polymerization process and represent a certain resistance to the circulation of hot air. In the regression model, the time after curing oven interior cleaning, ranged from 1 day to 60 days, was taken into calculation.
- The ambient temperature depends on the season. Calendar year we divided into three parts, where the coldest ambient temperatures present wintertime (10), the warmest temperatures are on the summertime (30), and we combined spring and autumn time, where ambient temperatures are similar (20).
- Micronaire (MIC) is a measure of the air permeability of compressed GW fibers and is used as an indicator of fiber fineness. The micronaire presented in Table 5 ranges between 2.86 and 3.24. The dependence of the micronere on the fiber diameter and the standard deviation (SD) is described by eq. (7) [17]:

$$MIC = 1.7940 + 0.1177$$
 fiber diameter + 0.0633 SD of fiber diameter (7)

Area weight of the product, a, where ρ is the density and h are the thickness of the GW, eq.
 (8). The area weight presented in tab. 5 is ranged between 0.68 and 4.4 kg/m<sup>2</sup>.

$$a = \frac{\rho}{h} \tag{8}$$

- The binder represents 4.6 to 6.6% of the material content in the product.

Table 5 present values of 52 experiments performed at different types of GW product, saturation, ambient temperature, micronaire, and fan rotational frequency of zone 5.

Op. point no.	Type of product; LR (1), HR (2), LP (3), HP (4)	Saturation [day]	Ambient temperature [°C]	Micronaire [-]	Area weight [kgm <sup>-2</sup> ]	Binder [%]	<i>n</i> of zone 5 [min <sup>-1</sup> ]
1	1	40	30	3.00	1.05	4.6	300
2	2	46	30	3.10	1.55	5.6	450
3	4	4	30	2.88	2.00	6.6	600
4	1	35	20	3.20	0.98	4.6	250
49	3	45	20	2.96	2.15	5.6	500
50	2	14	10	2.90	4.80	5.6	650
51	1	56	20	2.86	1.35	4.6	400
52	4	60	20	3.14	2.00	6.6	550

 Table 5. Rotational frequency of zone 5 as continuous response variable and values of the terms

 (type of product, saturation, ambient temperature, micronaire, product area weight, binder content)

In the regression eq. (5), y is the continuous response variable (rotational frequency of zone 5),  $b_0$  – the constant,  $b_1$ ,  $b_2$ , ...,  $b_k$  – the coefficients,  $X_1$ ,  $X_2$ , ...,  $X_k$  – the values of the terms (type of product, saturation, ambient temperature, micronaire, product area weight, and binder content). Values of regression model constants are presented in tab. 6. Parameters with negative values inversely influence the binder polymerization rate. Their significance was checked with a *t*-test and *P* value, tab. 6.

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	$b_0$	$b_1$	$b_2$	<i>b</i> 3	$b_4$	<i>b</i> 5	$b_6$
Values	1003	19.2	0.703	1.69	-368.8	49.27	64.7
Prob >  t		0.168	2.58	1.04	0.0130	0.129	0.111
P value		0.047	0.017	0.013	0.001	0.001	0.034

Table 6. Regression model coefficients values with the results of the *t*-test and *P* value

The results presented in tab. 6 show the parameter impact on the rotational frequency of zone 5. Parameter  $b_4$  presents the micronaire and has the biggest impact on the rotational

frequency of zone 5. Also important are the parameters  $b_1$ ,  $b_5$  in  $b_6$  which present a type of product, area weight and binder. The smallest impact results from the ambient temperature and saturation, parameters  $b_2$  and  $b_3$ . The probability, P value, that this hypothesis is valid was below 0.05, thus the regression is very significant.

The comparison between set and calculated values of rotational frequency on the basis of regression model is shown in fig. 8. A total of 52 experiments were performed at different types of GW product, saturation, ambient temperature, micronaire, product area weight, binder, and rotational frequency of zone 5. A good agreement between set and calculated val-



Figure 8. Correlation between set and calculated values of rotational frequency  $(R^2 = 0.89)$ 

ues is confirmed by a high value of determination coefficient,  $R^2 = 0.89$ , indicating good quality of regression modelling.

## Conclusions

The measurements of temperature distribution in the GW layer along the curing oven were performed. We measured the maximum temperature in the GW, determined the intensity of the temperature rise and started binder polymerization. Temperature sensors were located differently in the transverse direction of the curing oven and measured different temperature values. The curves of temperature here differ from each other. This implies that the GW is nonhomogenous. Local non-homogeneities of GW are local specific density, presence of non-homogenous binder distribution and humidity part.

The fiber density distribution in a layer of GW was measured with an X-ray device and compared with different temperature curves. The results show that lower density coincides with a higher temperature of the GW fibers. The maximum difference between the temperature curves amounted to 60 °C and fiber density distribution deviated for  $\pm 8\%$  according to nominal density. With a NIR spectroscopy was measured binder polymerization rate and compared with a set average temperature of curing oven, where the regression model was determined. With temperature reduction for 9 °C and polymerization rate decreasing for 2% were defined optimal product quality. Another prediction of binder polymerization rate was done with aid of set temperatures and fan rotational frequency as input process parameters and NIR spectroscopy as continuous response variable, where the temperature shown bigger impact than fan rotational frequency. Next prediction was performed specially for the operators on the curing oven. For each zone of curing oven, an equation was determined to predict the magnitude of the fan rotational frequency and temperature. When the operator in the excel table enter a type of product, curing oven saturation, the ambient temperature, micronaire value, product area weight and binder content in the GW product, the prediction equation for each zone of the curing oven calculate the proper set temperature and fan rotational frequency, with which an optimal binder polymerization is achieved. Regression models results showed high correlation with the multiple regression coefficient  $R^2$  higher than 0.85.

Further research in this area should include finite element simulations which exclude possible material fatigue or other mechanical problems. Warm outgoing smoke gases can be redirected again into the dryer or to another step in the process. Focus on adaptively set fan, so that the absolute pressure in the smoke gases is the same as the pressure in the atmosphere where the smoke gases are passing through the GW layer. This ensures the minimal transition of smoke gases into the environment and optimal fuel consumption.

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