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Influence of Ceramic Coatings on the Mechanical Properties of Ceramic Moulds Used in the Replicast CS Technology

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Abstract

The paper discusses the issues related to the Replicast CS technology. The research concerning the indication of the bending strength of ceramic moulds depending on the type and configuration of the shells will determine the effect of the type of binder and powder on the mechanical properties of shell moulds. The experimental studies presented in the paper include the manufacture of polystyrene models, followed by the application of 6 layers of ceramic coatings of different types and configurations on sets of polystyrene and wax models. Next, the studies test the bending strength of the obtained samples of ceramic moulds, depending on the type and configuration of the coatings. The presented research has shown the relationship between the different configurations of the materials used for the manufacture of ceramic coatings and their bending strength. It has been shown that, by the appropriate selection of the ceramic coatings, it is possible to obtain ceramic moulds with a possibly high bending strength.

Keywords: Replicast CS technology, Refractory ceramic coatings, Models of polystyrene, Castings, Ceramic coatings

1. Introduction

The method of lost wax casting was already known in the ancient times, when bee wax was used to make a model, which was then covered with clay, thus creating a casting mould. This technology was mainly used to manufacture liturgical objects, sculptures or ornaments [1].

In 1958, H. F. Shroyer patented a process of metal casting with the use of disposable polystyrene models [2]. In this method, the model was assembled and glued together out of pieces of EPS panels and next, it was moulded by means of classic moulding sands. However, the EPS models manufactured by this method did not fulfill the assumed requirements, i.e. size-shape precision and coarseness of the casts. In time, the method of lost foam casting was perfected (in 1964, T.R.1 Smith used dry quartz sand without a binder instead of the moulding sand), and, owing technology development, underwent a boom and was applied for the mass production of iron and non-ferrous alloy casts [3].

The development of the industry and the increasing demand for high quality casts stimulated the search for more interesting and innovative casting techniques. That is why the lost foam technology was separated into three basic methods of obtaining precision models: Replicast CS (empty mould method), and Lost Foam and Full Mould (full mould method) [4].

The Replicast CS method is a relatively new technology, elaborated by the British company SCRATA [5]. It is very attractive economy- and environment-wise, as compared to the full mould technology and the lost wax method. In the Replicast CS technology, the EPS model is removed during the burning of the ceramic coating in an electric furnace, whereas, in the full mould methods, the polymer model is removed only at the moment of filling the mould (the model becomes gasified). Owing to this, the casts obtained in this method are free of defects connected with model gasification [6,7]. And so, it is possible to use models of a higher density, which provides models of a better surface and a higher size and shape precision. The surface quality of the obtained casts is close to that of the casts made in the lost wax technology. The omission of the stage of removing the models from the mould cavity, as is the case in the lost wax method, reduced the costs and the energy consumption of the process. Another advantage of the application of polystyrene models is their weight. Model sets covered with ceramic coatings are significantly lighter than wax models, which makes the handling of such a set easier during the application of the coating. There is also the possibility to manufacture casts of larger sizes.

In the Replicast CS technology, the EPS model is covered with ceramic coatings, so that, after their burning, a self-supporting mould can be obtained. The selection of the appropriate amount and configuration of the ceramic coatings is crucial due to the necessity of enduring the stresses created during the filling of the mould with metal as well as during the solidification of the cast.

The coating consists of a fine-grained refractory matrix, a binder and hardening substances. The manufacture of the ceramic mass consists in mixing the binder with the powder refractory matrix in the appropriate proportion so that the obtained mass provides a proper projection of the model's shape. The ceramic mass, during the hardening process, transfers from the liquid state (before hardening, the moulding sand has the form of dense slime) into the solid state. The hardening consists in removing the ethyl alcohol (when ethyl silicate is the binder), the water (when Sizol and Ludox are the binders) and the remaining volatile substances from the mass. That is why the ceramic mass undergoes drying, during which the liquid substances volatilize, as well as burning, on order to improve its mechanical properties.
The protective coating should have the following properties: the appropriate plasticity and mechanical strength so that it does not crack during the mould filling, as well as the appropriate gas and liquid permeability and shear strength. It is optimal when the coating applied on the model has a uniform density on the whole surface, which is provided by the specific viscosity.

The following materials are usually used as binders in the Replicast CS method [8]:

- **Ethyl silicate** – produced for the casting purposes by the Wacker Chemical Corporation. It is a colourless liquid, density 1060 – 1070 kg/m³ (at 20°C), which is the initial material for the manufacture of the binder of a high refractoriness and mechanical strength. It consists of silicon oxide: from 40,8 to 41,7 %, hydrochloric acid: max 0,0010 %, tetraethyl orthosilicate: about 20 % and alcohol: up to 1 %. Unfortunately, it is an expensive material (it costs about 14,75 PLN per 1 kg), and so, in industry, it is mainly applied on the model alternately with Sizol and Ludox.
- **Ludox** – colloidal silica produced by Grace GmbH & Co. KG. It is a water slurry of the density from 1,19 to 1,21 g/m³ at 20° C. It is a mixture of 30% solid substances of the molecular size equalling 12 nm. Its viscosity equals 12 mPa·s at 20° C. It is the most frequently used binder in the casting industry, as it costs only 4,19 PLN per 1 kg.
- **Sizol** – produced by the Chemical Plant Rudniki S.A. It is an opalescent milk-blue, odourless liquid, density 1,2 g/cm³ at 20° C. It consists of silicon oxide: from 29 to 31 % and sodium oxide: max 0,36 %. The solution's Ph is within 9 – 10 (below 9, the substance begins to gelate). It is not included in the index of hazardous substances. It is a more expensive alternative for Ludox (it costs about 4,95 PLN per 1 kg)

The material filling the binder is:

- **Quartz flour** – it consists of about 96,5 % silicon oxide, 015 % dialuminium trioxide, 0,03 % iron(III) oxide and 0,03 % titanium oxide. It is the most frequently used material in the production of ceramic coatings by the Replicas CS technology.
- **Resracorse flour** (brad name) – material mainly used for research purposes.

The application of a protective coating by way of spraying is applied mostly for models without internal canals, whereas models of complicated shapes are usually coated by way of submerging the model set in the coating, which makes it possible to precisely cover the model. After the application of the coating, it is best to wait until its excess flows off and the coating acquires a uniform thickness, which also assures a uniform permeability [9]. Next, the coating applied in this way is covered with a fine-grained material (quartz sand) and held for about 24 h until it gets dry. The step of applying and covering the coating is repeated from to 8 times.

The appropriate application of the first and the second coating is especially important for the quality of the cast [10]. It is also important for the first and the last layer of the coating to have a higher viscosity, which has an effect on the mechanical strength of the ceramic coating. Besides, it is crucial for the quartz sand with which the model is covered to have the appropriate type of fraction. The smaller the size of the sand grains, the better projected the surface of the model, which provides the model with the required quality. That is why the first and the second layer are covered with sand of the grain size below 0,1 mm. The viscosity of the mixture and the granularity of the sand for the particular ceramic coatings, for an exemplary coating configuration used in the manufacture of a ceramic mould, are shown in Table 1.

Table 1.
Exemplary coating configuration considering the ceramic mixture viscosity of the sand granularity in particular coatings

No. of coating	Binder type	Viscosity [s]	Quartz sand granularity [mm]
1	Ludox	30	< 0,1
2	Sizol	14 - 15	< 0,1
3	Ethyl silicate	17 - 18	0,4 - 0,8
4	Ethyl silicate	18 - 20	0,4 - 0,8
5	Sizol	18 - 20	0,6 - 1,2
6	Ethyl silicate	22 - 24	0,6 - 1,2
7	Ethyl silicate	28 - 30	0,6 - 1,2

The ceramic moulds prepared in this way are placed in a chest and gently covered with the sand to assure their stability [11]. Next, the trolleys with the moulds are burned in a tunnel furnace for about 7 hours at the temperature from 800° C to 1000°C. Under the effect of high temperature, the model is removed by way of burning and the ceramic mould is fixed, owing to the phase transformation of the quartz sand, which forms ceramic bonds, thus improving the mechanical properties of the ceramic mould (the ceramic mould is chemically entirely unreactive). The process of removing and hardening the mould lasts about 7 hours.

Owing to the appropriately applied and fixed ceramic coating, it is possible to manufacture casts of the highest size and shape precision as well as of a very good surface quality.

2. Test methodology

The research was conducted at the Department of Materials Engineering and Production Systems of the Lodz University of Technology. In order to examine the effect of the type of the coatings on the strength properties of ceramic moulds, such models made of polystyrene were manufactured which corresponded to the shape and size of the wax model. An exemplary image of the model is shown in Figure 1.

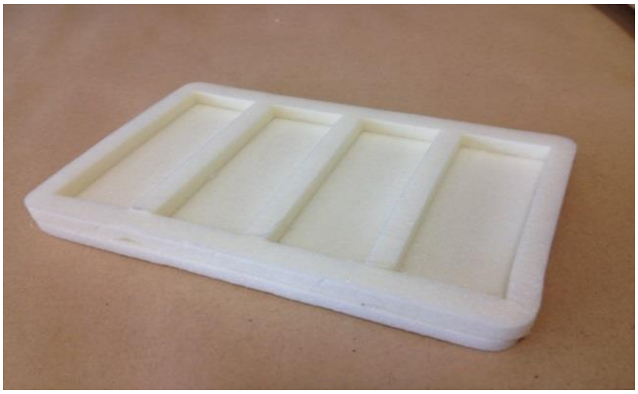

Fig. 1. Exemplary model made of a macromolecular material

The models were cut out on a thermal plotter and next their particular elements were hot glued. The ready polystyrene model had four cavities, which made it possible to project samples necessary for the further tests.

Ceramic coatings made of different types of binders and flour were applied on the priorly prepared 12 models of EPS master die models and 6 wax models (the wax die models used in the research were provided by the Armatura company) for the indication of the bending strength. The coatings were applied in such a way so as to assure the filling of the four perpendicular cavities of the die, which projected the samples necessary for the indication of the bending strength.

Below, in Tables 2 – 13, one can see different configurations of the ceramic coating layers applied on twelve EPS models and six wax models.

Table 2.
Ceramic coating layers for model 1

(EPS model and wax model)		
No. of coating	**Name of binder**	**Type of flour**
1	Ludox	Quartz flour
2	Ludox	Quartz flour
3	Ludox	Quartz flour
4	Ludox	Quartz flour
5	Ludox	Quartz flour
6	Ludox	Quartz flour

Table 3.
Ceramic coating layers for model 2

(EPS model and wax model)		
No. of coating	**Name of binder**	**Type of flour**
1	Sizol	Quartz flour
2	Sizol	Quartz flour
3	Sizol	Quartz flour
4	Sizol	Quartz flour
5	Sizol	Quartz flour
6	Sizol	Quartz flour

Table 4.
Ceramic coating layers for model 3

(EPS model and wax model)		
No. of coating	**Name of binder**	**Type of flour**
1	Ethyl silicate	Quartz flour
2	Ethyl silicate	Quartz flour
3	Ethyl silicate	Quartz flour
4	Ethyl silicate	Quartz flour
5	Ethyl silicate	Quartz flour
6	Ethyl silicate	Quartz flour

Table 5.
Ceramic coating layers for model 4

(EPS model and wax model)		
No. of coating	**Name of binder**	**Type of flour**
1	Ethyl silicate	Quartz flour
2	Sizol	Quartz flour
3	Ethyl silicate	Quartz flour
4	Ethyl silicate	Quartz flour
5	Sizol	Quartz flour
6	Ethyl silicate	Quartz flour

Table 6.
Ceramic coating layers for model 5

(EPS model and wax model)

No. of coating	Name of binder	Type of flour
1	Ludox	Quartz flour
2	Sizol	Quartz flour
3	Ethyl silicate	Quartz flour
4	Sizol	Quartz flour
5	Ethyl silicate	Quartz flour
6	Ethyl silicate	Quartz flour

Table 7.
Ceramic coating layers for model 6

(EPS model and wax model)

No. of caoting	Name of binder	Type of flour
1	Ethyl silicate	Quartz flour
2	Sizol	Quartz flour
3	Ethyl silicate	Quartz flour
4	Ethyl silicate	Quartz flour
5	Ludox	Quartz flour
6	Ethyl silicate	Quartz flour

Table 8.
Ceramic coating layers for model 7

(EPS model)

No. of caoting	Name of binder	Type of flour
1	Ludox	Refracorse flour
2	Ludox	Refracorse flour
3	Ludox	Refracorse flour
4	Ludox	Refracorse flour
5	Ludox	Refracorse flour
6	Ludox	Refracorse flour

Table 9.
Ceramic coating layers for model 8

(EPS model)

No. of coating	Name of binder	Type of flour
1	Sizol	Refracorse flour
2	Sizol	Refracorse flour
3	Sizol	Refracorse flour
4	Sizol	Refracorse flour
5	Sizol	Refracorse flour
6	Sizol	Refracorse flour

Table 10.
Ceramic coating layers for model 9

(EPS model)

No. of coating	Name of binder	Type of flour
1	Ethyl silicate	Refracorse flour
2	Ethyl silicate	Refracorse flour
3	Ethyl silicate	Refracorse flour
4	Ethyl silicate	Refracorse flour
5	Ethyl silicate	Refracorse flour
6	Ethyl silicate	Refracorse flour

Table 11.
Ceramic coating layers for model 10

(EPS model)

No. of coating	Name of binder	Type of flour
1	Ethyl silicate	Refracorse flour
2	Sizol	Refracorse flour
3	Ethyl silicate	Refracorse flour
4	Ethyl silicate	Refracorse flour
5	Sizol	Refracorse flour
6	Ethyl silicate	Refracorse flour

Table 12.
Ceramic coating layers for model 11

(EPS model)

No. of coating	Name of binder	Type of flour
1	Ludox	Refracorse flour
2	Sizol	Refracorse flour
3	Ethyl silicate	Refracorse flour
4	Sizol	Refracorse flour
5	Ethyl silicate	Refracorse flour
6	Ethyl silicate	Refracorse flour

Table 13.
Ceramic coating layers for model 12

(EPS model)

No. of coating	Name of binder	Type of flour
1	Ethyl silicate	Refracorse flour
2	Sizol	Refracorse flour
3	Ethyl silicate	Refracorse flour
4	Ethyl silicate	Refracorse flour
5	Ludox	Refracorse flour
6	Ethyl silicate	Refracorse flour

After the application and drying of the ceramic coatings, 4 samples were separated from each model for the indication of the bending strength.
The separated sets of samples (4 samples in each set) had different sizes, so it was necessary to calculate the mean value of the width and thickness of the samples from each set. The obtained sizes of all the sample sets for the bending strength indication are presented in Table 14.
The bending strength test of the sample sets of the model masses (dry) obtained from each model set was indicated from formula (1). The bending strength – R_g is the stress which is expressed by the ratio of the breaking moment of bending – *Mg* to the section modulus of the bent element – W_x. The manner of performing the tests is described in the standard PN – EN ISO 178.

$$R_g = \frac{3 \cdot F \cdot l}{2 \cdot b \cdot h^2} \quad (1)$$

The bending strength was indicated with the use of the universal apparatus for moulding sand indication: LRu – 1. The apparatus is constructed of two levers on a mutual horizontal axis. With the use of the leading screw, the weight moves on one of the levers, whereas the handles of the strength samples are fixed to the other one. During the test, the examined sample is placed on the piles of the stand.
The indication of the bending strength of the dry model masses is performed according to the classic scheme presented in Figure 2, where the sample is loaded with the force - *F applied at a particular rate, at the point equaling a half of the distance between the supports.*

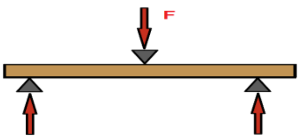

Fig. 2. Scheme of the bending strength test

It should, however, be noted that, instead of the master sample (according to PN - EN ISO 178) of the width b_p = 22,36, the thickness h_p = 8mm and the support spacing l_p = 150 mm, samples of a different width – *b, thickness* - *h* and spacing *l* = 47 mm were used – Table 3. That is why it was necessary to calculate the force F applied during the test from equation (2). Exemplary values have been inserted in equation (2).
The constant of the force *F [N] used during the bending tests of ceramic moulds was calculated based on the rearranged equation* (2):

$$R_{g1} = \frac{3 \cdot F \cdot l}{2 \cdot b \cdot h^2}$$
$$F = \frac{R_{g1} \cdot 2 \cdot b_p \cdot h_p^2}{3 \cdot l_p} = \frac{4 \cdot 2 \cdot 22{,}36 \cdot 8^2}{3 \cdot 150} = 25{,}44\ [N] \quad (2)$$

where:
R_{g1} – the bending strength of the sample from die 1 equalling 4 [MPa],
b_p – the width of the master sample equalling 22,36 mm,
h_p – the thickness of the master sample equalling 8 mm,
l_p – the spacing of the supports for the master sample equalling 150 mm.

After the calculation of the force *F*[N], it was possible to determine the constant coefficient of the apparatus *P* for the examination of the bending strength of the samples of the particular model sets according to equation (3). It was necessary, as the value of the bending strength - R_g read on the scale of the apparatus was adjusted for the support spacing equaling 150 mm and the size of the master samples of 22,36 x 8 x 172 mm

$$P = \frac{\frac{3 \cdot F \cdot l}{2 \cdot b \cdot h^2}}{\frac{3 \cdot F \cdot l_p}{2 \cdot b_p \cdot h_p^2}} = \frac{2 \cdot b_p \cdot h_p^2 \cdot l}{l_p \cdot 2 \cdot b \cdot h^2} \quad (3)$$

where:
P – the constant coefficient of the apparatus for bending strength tests,
F – the bending force equalling 25,44 [N],
b – the width of the sample from the die (1 – 12) [mm],
b_p – the width of the master sample equalling 22,36 [mm],
h – the thickness of the die (1 – 12) [mm],
h_p – the thickness of the master sample equalling [mm],
l – the support spacing for the examined samples equalling 47 [mm],
l_p – the support spacing for the master sample equalling 150 [mm].

Next, we substitute the obtained constant coefficient of the apparatus *P* in equation (4) and recalculate the read mean bending strength values for the samples from the model sets (1 -12) for the support spacing of 47 mm.

$$R_g = P \cdot R_{z(1-12)} \quad (4)$$

where:
R_g – the bending strength for the support spacing of 47 mm [MPa]
$R_{g(1-12)}$ – the mean bending strength read from the apparatus for the samples of the models (1 – 12) [MPa],
P – the constant coefficient of the apparatus for strength tests.

3. Test results

The studies concerning the effect of the type of coatings on the strength properties of ceramic moulds used in the Replicast CS technology were performed on twelve combinations of various types of ceramic coatings (Table 2 - 13). The measurement of the basic bending strength parameters was made on the apparatus for indicating the strength of moulding sands Lru – 1.

For each sample from the model set 1 – 12 the constant coefficient of the apparatus P was calculated. This coefficient depends on the mean thickness and width of the examined sample and it was calculated from equation (3). The mean sizes of the samples used in the calculations of the coefficient *P* are presented in Table 14.

Next, the calculated *P was substituted in the bending strength formula for the support spacing of* 47 mm (4), whereas, in the place of the data $R_{g(1-12)}$, the mean bending strength was used, taken from Table 15 for the die sample sets 1 - 12.

Table 14.
Mean sizes of samples from particular dies

Averaged sizes for samples sets for each model				
	EPS model samples		Wax model samples	
Model	Mean sample thickness – h	Mean sample width – b	Mean sample thickness – h	Mean sample width – b
Model 1	6,35 mm	20,50 mm	7,10 mm	19,80 mm
Model 2	5,20 mm	20,40 mm	7,10 mm	19,80 mm
Model 3	7,20 mm	20,60 mm	6,40 mm	19,80 mm
Model 4	7, 30 mm	20,75 mm	6,60 mm	20,00 mm
Model 5	6,60 mm	20,30 mm	6,75 mm	19,90 mm
Model 6	7,00 mm	20,80 mm	6,15 mm	19,90 mm
Model 7	7,55 mm	20, 45 mm	-	-
Model 8	6,15 mm	21, 65 mm	-	-
Model 9	6,80 mm	20,95 mm	-	-
Model 10	7,00 mm	21,15 mm	-	-
Model 11	6,10 mm	21,95 mm	-	-
Model 12	7,00 mm	20,25 mm	-	-

From the calculations of the mean bending strength for the samples from models 1 – 12, the following results were obtained:

1. Samples from model 1:
   - (EPS) – 2,32 MPa
   - (wax) – 2,93 MPa
2. Samples from model 2:
   - (EPS) – 2,87 MPa
   - (wax) – 2,36 MPa
3. Samples from model 3:
   - (EPS) – 3,98 MPa
   - (wax) – 3,83 MPa
4. Samples from model 4:
   - (EPS) – 3,18 MPa
   - (wax) – 3,29 MPa
5. Samples from model 5:
   - (EPS) – 3,85 MPa
   - (wax) – 3,88 MPa
6. Samples from model 6:
   - (EPS) – 3,62 MPa
   - (wax) – 3,68 MPa
7. Samples from model 7 (EPS) – 3,87 MPa
8. Samples from model 8 (EPS) – 4,97 MPa
9. Samples from model 9 (EPS) – 5,10 MPa
10. Samples from model 10 (EPS) – 3,36 MPa
11. Samples from model 11 (EPS) – 3,52 MPa
12. Samples from model 12 (EPS) – 3,99 MPa

Table 15.
Results of bending strength tests $R_{z(1-12)}$ obtained on apparatus Lru – 1.

	EPS die samples					Wax die samples				
No. of die	**Test 1** [MPa]	**Test 2** [MPa]	**Test 3** [MPa]	**Test 4** [MPa]	**Mean value** [MPa]	**Test 1** [MPa]	**Test 2** [MPa]	**Test 3** [MPa]	**Test 4** [MPa]	**Mean value** [MPa]
1	4,00	4,05	4,60	4,00	**4,27**	Sample crack	4,20	6,40	5,20	**5,26**
2	3,80	3,40	Sample crack	Sample crack	**3,60**	6,20	6,60	6,40	6,40	**6,40**
3	10,40	12,20	10,40	9,20	**10,55**	8,20	7,80	9,80	6,00	**7,95**
4	6,40	8,60	8,60	7,80	**7,85**	7,20	6,20	5,80	6,40	**6,40**
5	8,80	7,40	7,40	6,80	**7,60**	8,40	7,20	8,20	7,60	**7,85**
6	8,00	8,80	7,80	8,40	**8,25**	5,80	6,80	6,10	6,00	**6,18**
7	8,50	10,10	9,80	9,20	**9,40**	-	-	-	-	-
8	11,20	9,10	7,10	8,90	**9,08**	-	-	-	-	-
9	9,00	11,80	11,40	11,90	**11,03**	-	-	-	-	-
10	7,40	8,60	7,00	7,20	**7,55**	-	-	-	-	-
11	6,50	5,70	5,60	6,60	**6,10**	-	-	-	-	-
12	8,80	8,80	8,60	9,10	**8,83**	-	-	-	-	-

It should, however, be noted that models 1 – 6 had two sets of samples each (EPS and wax models). The samples from both the EPS and the wax die had the same combination of coatings, yet, they differed in the sizes, and so it was necessary to calculate the constant coefficient of the apparatus P for each of them. *The values of the bending strength of the ceramic mass for the samples from the EPS and the wax die were similar, so the mean strength for the samples from die* 1 – 6 was calculated.

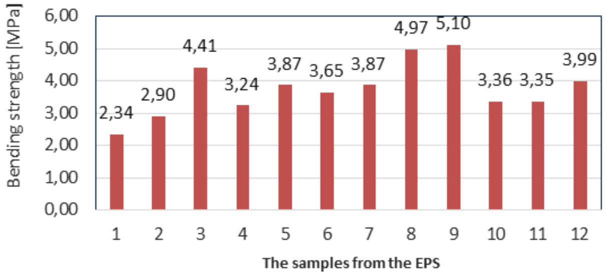

Fig. 3. Bending strength of samples for models 1 – 12

Figure 3 shows the bending strength value for the sample from the model sets 1 – 12, made on EPS models. In the analysis of the obtained results, it was oberved that the highest bending strength properties were obtained for the sample sets 8 and 9, which contained the Refracorse flour, as well as the samples 3, containing quartz flour and an ethyl silicate binder.

4. Conclusions

The paper discussed the issue of the effect of applying different configurations of coatings on the strength properties of ceramic moulds. Based on the test results, it was possible to conclude that the best strength properties are exhibited by: samples 9, which combine ethyl silicate with the Refracorse flour, as well as sample 8, formed by Sizol and the Refracorse flour. Both binders, ethyl silicate and Sizol, are materials with better strength properties than those of Ludox. Also, the Refracorse flour is a better material for the matrix of the coating than quartz flour. In the comparison of samples 9 and 3, which contain ethyl silicate, one can see that a better bending strength is exhibited by the sample whose matrix is the Refracorse flour - similarly to samples 7 and 1, whose binder is Ludox. However, the industry uses mainly quartz flour for the production of ceramic coatings, as it is less expensive and more widely available, whereas the Refracorse flour is applied mainly for research purposes. Samples 1 and 2 have the worst strength properties (from 2,34 MPa to 2,89 MPa). These samples contain Ludox (sample 1) and Sizol (sample 2) as well as quartz flour.

Relatively high strength properties are exhibited by samples 5 and 7. According to the price and the strength properties, the following are the most frequently used as binders in the industry (in the following order): Ludox, Sizol, ethyl silicate, Sizol, ethyl silicate, ethyl silicate and ethyl silicate with a quartz flour base

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