Improving the technology of obtaining high-quality castings from steel in sand-clay molds

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Abstract. This article examines the technology for producing high-quality steel and alloy castings in sand-clay molds. The optimization of the sand-clay compound mold composition is explored, focusing on bentonite and kaolin clays as binders. The mold composition is refined based on the research conducted on these binding clays, resulting in the production of gas-free cast products. Additionally, the gas permeability of the sand-clay molds increased by 14-16%. The study also presents a test analysis of the gas permeability property, a crucial aspect of sand-clay mold quality. Furthermore, a mathematical model of the process was developed from the research findings to predict gas permeability values with varying amounts of binding clays, eliminating the need for further testing.

1 Introduction

Today, in order to obtain high-quality cast products, not only the methods of optimal melting of the alloy, but also a number of factors such as the quality of the molds, the composition of the mold made of sand-clay compound, its specified properties, the geometry of the alloy placement in the mold, and the right selection and calculation of the casting systems play an important role.

Obtaining high-quality cast products requires that the cavity of the mold is not deformed during the pouring of liquid metal into the mold made of sand-clay. In this case, it is necessary to use binding materials that provide enough strength to the quartz sand of the mold. The main binders are clay. Kaolin, halloysite, hydromica, montmorillonite, polygorskite, vermiculite and allophane are used as binders of clay-rich minerals in foundry production. A material that contains bentonite as a binder for one-time molding compounds is

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montmorillonite. Another important aspect is that the increase in the amount of sand moisture leads to a decrease in gas permeability [1].

In world practice, many studies are being conducted on obtaining high-quality cast products in disposable molds. One of the world's leading scientists, Nigerian scientists conducted research on the effect of binders on obtaining thin-walled castings. In this work, 6%, 9%, and 12% amounts of bentonite, kaolin, and cassava binders were investigated as binder clays for obtaining 3 mm thick-walled sands. And in the final conclusion, kaolin binder was selected as an alternative for obtaining thin-walled castings. Kaolin-bound sand-clay composition gave high strength properties 650 KN/m^2, at 6% binders. At this value, the properties of the samples are significantly improved. But in this work, researches for steel castings were not carried out [2-5]. Korean researchers have developed an algorithm for studying the distribution of the gas permeability of the mold made of sand-clay compound over the volume. The developed model was used to evaluation permeability. In addition, the process of simulation of the effect of gas permeability has been developed. The optimal process for maximum gas permeability was obtained in the range of moisture level of the compound 3.9-9.5, binding clay content 8.75-10.5% [6-8]. Indian researchers have been working on the effect of binders on sand grain sizes. The number of binders, the bonding period of the mold, and the mechanical properties were studied through laboratory studies. Their mechanical properties increased with increasing amount of binding clays. The size of sand grains increased and decreased [9-10].

2 Materials and methods

Two different compositions of the mold made of sand-clay compound were given as samples to the "Casting-mechanics" shop of Uzmetkombinat JSC. At this enterprise, large-sized shafts are cast from 35ХГСЛ (Т35SiCrMn11) low-alloyed steel. The goal is to develop cast shaft details on the basis of economically inexpensive and resource-efficient technologies.

Casting defects of shaft parts cast into mold made of sand-clays were thoroughly analyzed in the workshop. The main problem is non-metallic inclusions in liquid metal, gas pores remaining in the composition due to the low gas permeability of the mold and Problems such as streaking during solidification of the liquid metal in the mold were observed (Figure 1). These defects are the main factors affecting the quality and mechanical properties of cast products [11-12].

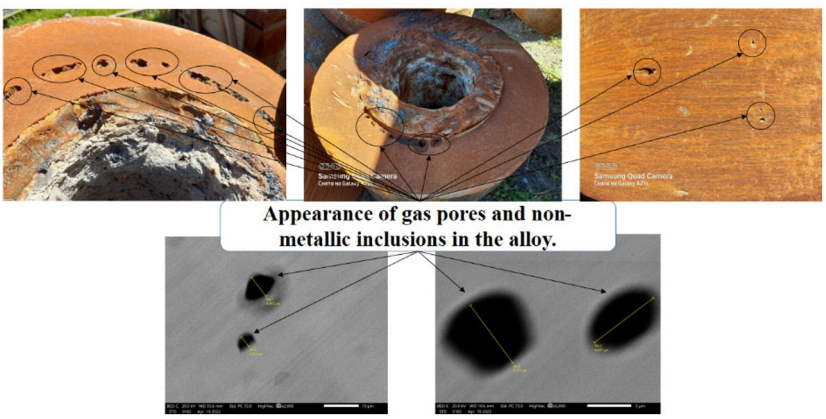

Fig. 1. Appearance of gases and non-metallic inclusions in micro and macrostructure.

Table 1. The composition of the mold made of sand-clay compound previously used in the production enterprise.

The compound used, %	Quartz sand, %	Kaolin clay, %	Water, %	Heating the mold, ^{o}C
65 – 69	26 – 28	5 – 6	4 – 5	– 500

2.1 Improving the composition of the mold made of sand-clay compound

Table 2. Proposed composition of the mold made of sand-clay compound based on analysis of defects in cast products.

The compound used, %	Quartz sand, %	Bentonite clay, %	Water, %	Thickness of anti-burn paint layer, mm	Heating the mold, ^{o}C	Time of heating the mold, hours
61 – 66	20 – 22	5 – 6	4 – 5	1-2 mm is applied to the inner surface of the mold.	100 – 150	3

Kaolin and bentonite clays are mainly used as binders in the mold compound when pouring high-quality bulk products into mold made of sand-clays. When one of these clays, bentonite clay, is used, the gas permeability of the mold compound is considered higher than that of kaolin clay. This, in turn, serves to obtain gas-free bulk products. Scientific studies on optimiation of the composition of the mold made of sand-clay compound were initially conducted in the laboratory of the “Foundry Technologies” department of Tashkent State Technical University (Figure 2).

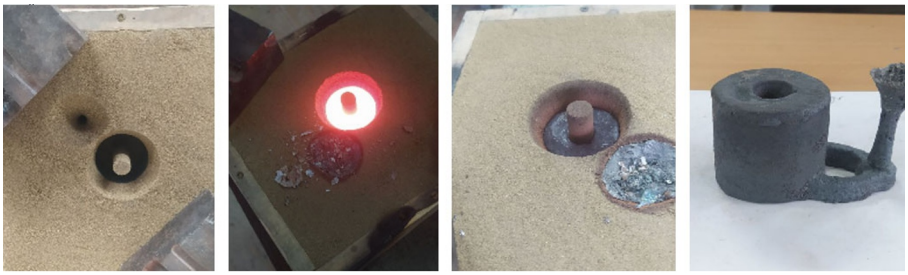

Fig. 2. Laboratory test analysis processes.

3 Results and discussion

3.1 Compression strength test analyses

Analysis of the compressive strength of sand-clay formwork compound is shown in Figure 3. The kaolin binder gave high bond strength at all percentages of binders i.e. 470, 525, 600, 640 and 670 kN/m^2 for 4, 5, 6, 7 and 8 % binders respectively. These values were tested 5-7 times for each value of the binders and the average value was obtained. Metallostatic pressure occurs in the parts that come into contact with the liquid metal in the mold cavity. Adequate compressive strength is required to ensure the integrity of the geometric dimensions of the mold walls.

Table 3. Chemical composition of bentonite binder clay.

Content	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	CaO	K_2O	TiO_2	MgO	LOI
Wt. %	71.1	17.95	3.22	3.56	0.87	0.76	0.34	2.20	0

Table 4. Chemical composition of kaolin binder clay.

Content	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	CaO	K_2O	TiO_2	MgO	LOI
Wt. %	50.1	40.86	2.54	0.38	0.26	0.75	0.07	0	5.04

Bentonite binder showed lower binding properties than kaolin at additions of 4, 5, 6, 7 and 8%, which were 300, 400, 450, 470 and 510 kN/m^2, respectively. These values were tested 5-7 times for each value of the binders and the average value was obtained.

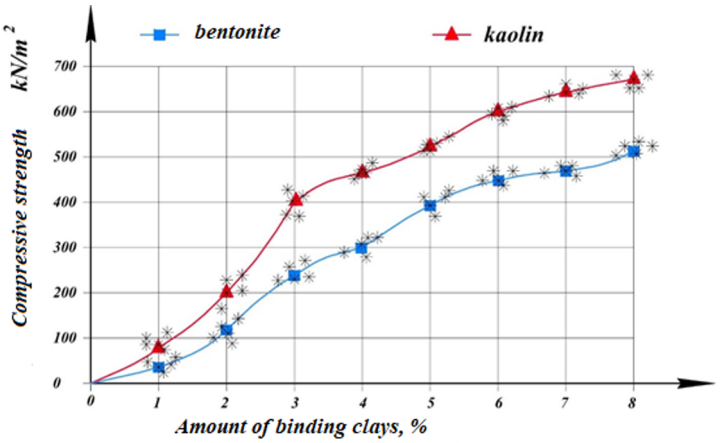

Fig. 3. Values of compressive strength of the mold made of sand-clay compound with different amounts of kaolin and bentonite binder clays, taking into account the moisture content of the compound.

3.2 Mold compound moisture test analyses.

If the moisture amount of the mold compound is low, the strength of the mold, i.e. the compressive strength, will decrease. An increase in the amount of moisture causes the liquid metal to boil during casting into a mold made of sand-clay. As a result, the casting is being defective. The moisture content of the developed mold compound was obtained according to the results of the research in accordance with the amount of binding clays.

Table 5. Moisture values according to binders.

Amount of clay		3	4	5	6	7	8	9
Moisture	Bentonite	6.2	5.2	4.8	4.4	4.1	3.9	3.8
	Kaolin	8.1	7.0	6.1	5.8	5.4	5.0	4.6

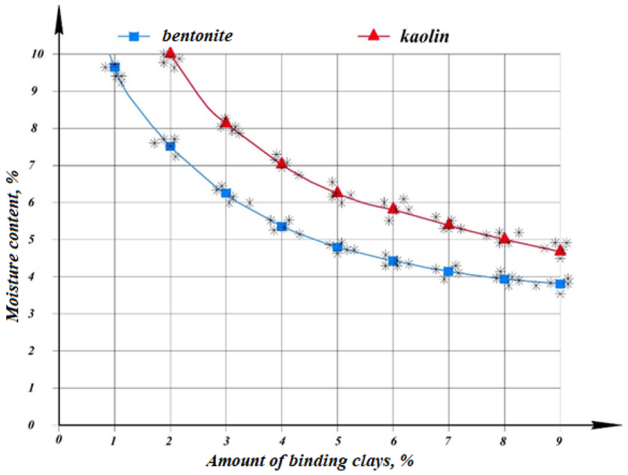

Fig. 4. Moisture values of the mold made of sand-clay compound with different amounts of kaolin and bentonite binding clays.

3.3 Gas permeability test analyses

The air in the mold compound, the gases formed during casting, must be easily released during the pouring of liquid metal into the mold. Otherwise, they reduce the mechanical properties of the cast product. At the same time, it causes a decrease in the casting properties, that is, the fluidity of the liquid metal. Values of gas permeability of the mold made of sand-clay compound are shown in Figure 5. High gas permeability was found in the mold compound bound with bentonite clay, i.e. 64, 60, 57, 40 and 27 cm^3/kg min for 4, 5, 6, 7 and 8% binding clay additives. It was found that the gas permeability values were 53, 45, 34, 28 and 13 cm3/kg min in the mold compound with the same amount of 4, 5, 6, 7 and 8% kaolin clay binder. These values were tested 5-7 times for each value of the binders and the average value was obtained. Another important point is that the gas permeability of the mold made of sand-clay compound decreases with the increase in the amount of binding clay additives in the composition.

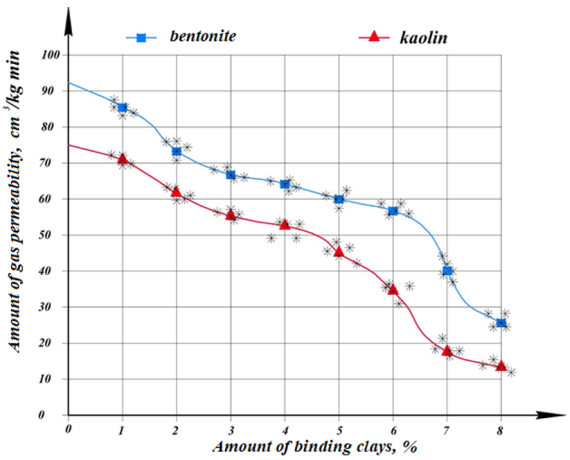

Fig. 5. Gas permeability values of the mold made of sand-clay compound with different amounts of kaolin and bentonite binding clays.

As a result of the analysis of the study, it was seen that bentonite binding clays have lower compressive strength of the molding compound than kaolin binding clays. However, gas permeability was found to be high. The shaft detail molds we cast do not have high-precision geometric dimensions or thin-walled parts. Therefore, the compressive strength of the mold compound using bentonite binding clays is enough. Due to the presence of gas pores in the analyzed defects, it is necessary for the mold compound we need to have a high gas permeability.

Fig. 6. A mold made of sand-clay made on the basis of the technologies applied to the production process as a result of research.

The image above shows the introduction of the new content developed into the production enterprise. This mold compound is designed for low-alloyed steel alloy. Anti-burn paint is applied to the contact surfaces of the mold with melted metal. The composition consists of 8-11% aluminum oxide fireclay, 4-5% electrocorundum, 2.9-4.4% zirconium, 1.5-2.5% refractory clay, 1.5-2.9% kaolin, liquid glass 4.5-5% and water. Anti-burn paint is applied 1-2 mm and dried at room temperature. Then it was held in a heating oven at a temperature of 100-150 ºC for 3 hours.

3.4 Mathematical modeling of the effect of binding clays on gas permeability of the mold made of sand-clay compound

Experiments were conducted using two types of binding clays. We make a mathematical expression of the gas permeability of the mold compound for each binding clay.

First of all, we make a mathematical expression of connectedness of the gas permeability of the mold compound on different amounts of kaolin clay in the mold made of sand-clay compound. For this, we take the amount of kaolin binding clay as the independent variable. It is necessary to construct a function representing the gas permeability of the mold compound. For this, we construct Lagrange polynomial interpolation nodes, reduce the problem to the algebraic form of solving a system of equations, determine the unknown coefficients, and derive the polynomial of the gas permeability function of the mold as follows.

y – gas permeability, cm^3/kg min;

x – amount of kaolin binding clay, in %;

$$y = f(x); \tag{1}$$

$$\begin{cases} 4^5x_1 + 4^4x_2 + \cdots + 4x = 53 \\ 5^5x_1 + 5^4x_2 + \cdots + 5x = 45 \\ 6^5x_1 + 6^4x_2 + \cdots + 6x = 34 \\ 7^5x_1 + 7^4x_2 + \cdots + 7x = 28 \\ 8^5x_1 + 8^4x_2 + \cdots + 8x = 13 \end{cases}; \tag{2}$$

$x_1 = -0.03$ $x_3 = -1.64$ $x_5 = 49.83$
$x_2 = 0.48$ $x_4 = -8.3$

(2) To solve the above system of equations, we brought it to the matrix point. And it is necessary to find the unknowns using the system of equations using Cramer's method. For this, first of all, we find the determinant Δ of the formed matrix.

$$\Delta = \begin{vmatrix} 1024 & 256 & 64 & 16 & 4 \\ 15625 & 3125 & 625 & 25 & 5 \\ 7776 & 1296 & 216 & 36 & 6 \\ 16807 & 2401 & 343 & 49 & 7 \\ 32768 & 4096 & 512 & 64 & 8 \end{vmatrix} = -4191344640 \quad (3)$$

We solve the matrices and find the following values of the unknowns,

$$x_1 = \frac{\Delta_1}{\Delta} = \frac{125412000}{-4191344640} = -\frac{37325}{1247424}; \qquad x_2 = \frac{\Delta_2}{\Delta} = \frac{-2021974080}{-4191344640} = \frac{300889}{623712};$$

$$x_3 = \frac{\Delta_3}{\Delta} = \frac{6949350240}{-4191344640} = -\frac{2068259}{1247424}; \qquad x_4 = \frac{\Delta_4}{\Delta} = \frac{34854469440}{-4191344640} = -\frac{5186677}{673712};$$

$$x_5 = \frac{\Delta_5}{\Delta} = \frac{-208841928960}{-4191344640} = \frac{7769417}{155928};$$

We solve the above system of equations, we identified the unknowns, the function representing the gas permeability of the mold made of sand-clay compound depending on the amount of kaolin binding clay is as follows:

$$y = -0.03x^5 + 0.48x^4 - 1.64x^3 - 8.3x^2 + 49.83x; \quad (4)$$

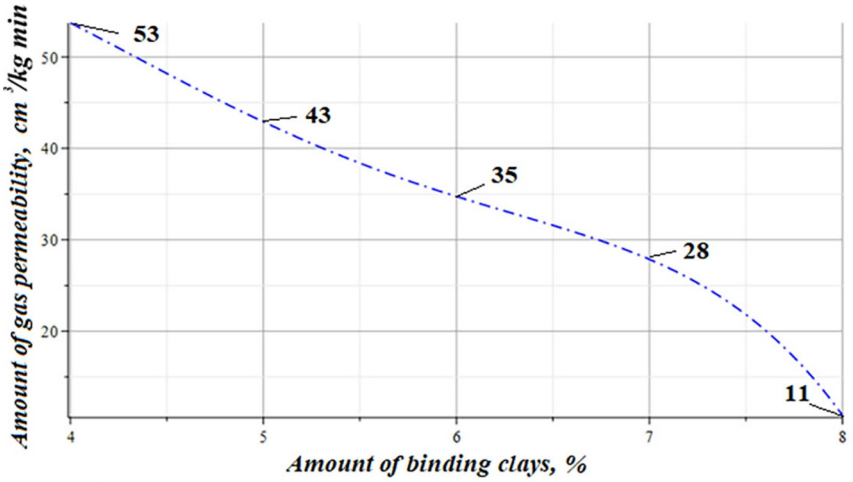

Fig. 7. Correspondence of the mathematical model obtained on the basis of the research results to the actual results.

After that, First of all, we make a mathematical expression of connectedness of the gas permeability of the mold compound on different amounts of bentonite clay in the mold made of sand-clay compound. For this, we take the amount of bentonite binding clay as the independent variable. It is necessary to construct a function representing the gas permeability of the mold compound. For this, we construct Lagrange polynomial interpolation nodes, reduce the problem to the algebraic form of solving a system of equations, determine the unknown coefficients, and derive the polynomial of the gas permeability function of the mold as follows [13, 14].

y – gas permeability, cm^3/kg min;

x – amount of bentonite binding clay, in %;

$$y = f(x); \quad (5)$$

$$\begin{cases} 4^5x_1 + 4^4x_2 + \cdots + 4x = 64 \\ 5^5x_1 + 5^4x_2 + \cdots + 5x = 60 \\ 6^5x_1 + 6^4x_2 + \cdots + 6x = 57 \\ 7^5x_1 + 7^4x_2 + \cdots + 7x = 40 \\ 8^5x_1 + 8^4x_2 + \cdots + 8x = 27 \end{cases}; \quad (6)$$

$x_1 = 0.022$ $x_3 = 1.04$ $x_5 = 17.25$

$x_2 = -0.32$ $x_4 = -0.9$

(6) To solve the above system of equations, we brought it to the matrix point. And it is necessary to find the unknowns using the system of equations using Cramer's method. For this, first of all, we find the determinant Δ of the formed matrix.

$$\Delta = \begin{vmatrix} 1024 & 256 & 64 & 16 & 4 \\ 15625 & 3125 & 625 & 25 & 5 \\ 7776 & 1296 & 216 & 36 & 6 \\ 16807 & 2401 & 343 & 49 & 7 \\ 32768 & 4096 & 512 & 64 & 8 \end{vmatrix} = -4191344640 \quad (7)$$

We solve the matrices and find the following values of the unknowns,

$$x_1 = \frac{\Delta_1}{\Delta} = \frac{-92579040}{-4191344640} = \frac{64291}{2910656}; \qquad x_2 = \frac{\Delta_2}{\Delta} = \frac{1369552320}{-4191344640} = -\frac{475539}{1455328};$$

$$x_3 = \frac{\Delta_3}{\Delta} = \frac{-4481022240}{-4191344640} = \frac{3111821}{2910656}; \qquad x_4 = \frac{\Delta_4}{\Delta} = \frac{2487216960}{-4191344640} = -\frac{863617}{1455328};$$

$$x_5 = \frac{\Delta_5}{\Delta} = \frac{-69265140480}{-4191344640} = \frac{6012599}{363832};$$

We solve the above system of equations, we identified the unknowns, the function representing the gas permeability of the mold made of sand-clay compound depending on the amount of bentonite binding clay is as follows:

$$y = 0.022x^5 - 0.32x^4 + 1.04x^3 - 0.9x^2 + 17.52x; \quad (8)$$

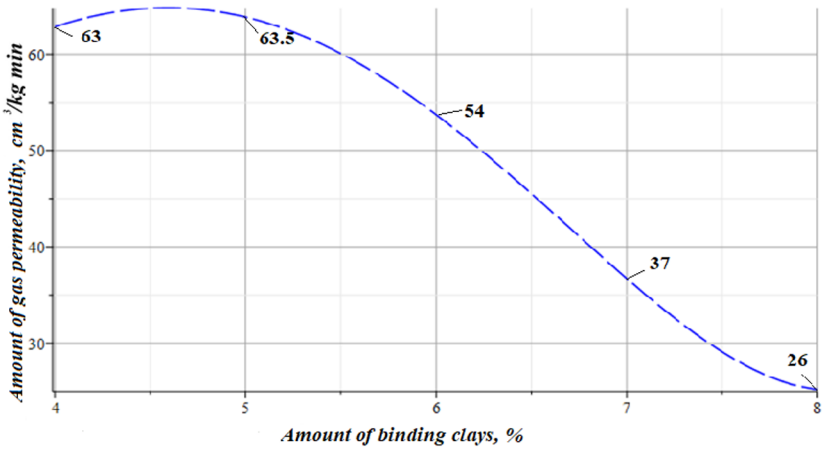

Fig. 8. Correspondence of the mathematical model obtained on the basis of the research results to the actual results.

4 Conclusion

In this research work, analyzes of the effect of binder clays in different amounts of the mold made of sand-clay compound are presented. Researches were mainly conducted on the preparation of mold compound for casting low-alloyed steel alloy. In this study, the results

of the compressive strength of the mold compound, the moisture content of the compound, and gas permeability, one of the main casting properties, were analyzed. And the following main conclusions were drawn from the main obtained research results:

1. The values of compressive strength in the amounts of 4, 5, 6, 7, and 8% of kaolin binder were compared with those of 4, 5, 6, 7, and 8% of bentonite binder, respectively. As a result, it was determined that the compressive strength of the mold compound is higher when kaolin binders are used compared to bentonite.
2. The values of the gas permeability of the mold made of sand-clay compound were found to be 64, 60, 57, 40 and 27 cm3/kg min at 4, 5, 6, 7 and 8% of bentonite clay. It was found that the gas permeability of the mold compound with 4, 5, 6, 7 and 8% kaolin clay binder was lower than that of bentonite.
3. Based on research analysis, the material of the detail that we have chosen as an object is low-alloyed steel. There are not thin-walled, highly geometric construction parts. Therefore, it is sufficient that the value of the binding force in compression is 300, - 450 kN/m^2. Gas permeability is required must be high. As a result, bentonite binders provided high gas permeability. Research conclusions recommend the use of bentonite binding clays for casting steel alloys.
4. A mathematical model of the influence of binding clays on the gas permeability of the mold made of sand-clay compound was developed. This mathematical model provides further research without experimental results.

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