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Optimisation of recycled moulding sand composition using the mixture design method

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ABSTRACT

In the cast iron industry, mould sand quality and the most efficient recovery of used sand into the system are critical. For this purpose, the optimum values of the factors (humidity, active bentonite and coal dust) affecting the green strength, gas permeability and shear strength of the mould sand were determined in this study. The optimum mixture ratio, which makes the green strength, gas permeability and shear strength of the mould sand the best, was made by using the mixture design method. As a result of the studies, optimum casting sand composition; the percentage of moisture content, the percentage of coal dust, the percentage of active bentonite and the percentage of recycle sand were determined as 3.92%, 0.05%, 0.30% and 95.73%, respectively. The green compression strength(B_1) 23.5 N/cm^2, shear strength(B_2) 7.7 N/cm^2 and gas permeability (B_3) 91 mmWS of the conventional cast sand prepared in this optimum composition were measured.

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KEYWORDS
Used sand; recovery; optimisation; mixture design method; casting; coal dust; humidity; bentonite

1. Introduction

Statistical data show that more than 75% of the companies that do iron-based alloy casting in the world still use traditional bentonite casting sand as mould material [1–3]. Moulding sand for a casting process; it must have physical and chemical superior properties such as moulding, refractoriness, not reacting with liquid metal (chemical resistance), permeability of gases formed during casting [4,5]. Mould sand contains basic ingredients such as silica sand, binder (bentonite), coal dust and moisture. The size and shapes of the silica sand here affect the characteristics of the mould, such as green compression strength, shear strength and gas permeability [5]. Bentonite, which is another mixing element of moulding sand and used as a binder, is coated with moisture on the surface of the sand to form a layer and holds the sand particles together [6]. For example, when the liquid starts to flow into the mould, as the amount increases, the pressure it exerts on the mould will increase. In addition, the gases formed will apply a separate pressure inside the mould. The binder (bentonite) must maintain the form of the mould in such harsh conditions by keeping the mould components such as silica sand together [7,8]. In addition, it can be said that bentonite is responsible, even indirectly, for casting surface quality [9]. Water is kept by bentonite in the mould sand mixture and together with bentonite, it keeps silica sands together as a flexible and adhesive structure [10]. Coal dust provides the formation of reductive gases by the effect of the heat formed by the introduction of liquid metal into the mould cavity, and these gases prevent the oxidation of iron [11].

The properties expected from casting sand can be listed as green compression strength, gas permeability, shear strength, fluency and dispersibility. In other words, when the liquid metal flows into the mould cavity and until the mould fills the mould completely, the features such as the mould does not deteriorate, it does not react with the liquid metal, and the gases that may occur during casting can come out of the mould easily. When previous literature studies are examined, there is an inverse proportion between gas permeability and green compression strength [3,12–14]. As the increase in the amount of bentonite and moisture in the composition will bind the silica sand better, the shear and compression strengths increase significantly. But since bentonite is very fine grained and when combined with moisture, silica sand swells in the voids, filling the voids naturally reduces the gas permeability value. In this case, it is necessary to determine the optimum composition of a green sand mixture, where both the gas permeability and the shear and compression strength of the green sand are maximum.

In previous studies, the researchers controlled the mechanical properties of green sand using the Factorial [15–17] and Taguchi method [18,19]. However, many of the researchers have done studies on new (unused) sand. On the other hand, Saikaew

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conducted a study in 2012 using the mixture design method to improve the compressive strength and gas permeability of used (recycled) sand [12]. Saikaew has not studied the shear strength property. In this study, we focused to optimise the compression, shear and gas permeability properties for the best incorporation of used (recycled) sand into the system. After reviewing the above studies, it was revealed that in most of the work, Taguchi and factorial design methods were used to optimise moulding sand properties. But, it is well stated in literature that mixture design method is the best way to optimise a blend properties [20]. For this purpose, mixture design-optimal method was used, which many researchers preferred for 'optimisation of mixtures' and obtained good results [13,20–22]. The experimental design was created with the mixture design-optimal method in the Desing Expert software, these experiments were performed and the mechanical properties of the used sand were tried to be improved. Finally, the data obtained at the end of the experimental studies and the data created with the help of mathematical equations were evaluated.

2. Materials and method

The technical information and contents of the consumables used are presented in Table 1. Values in Table 1 were obtained from raw materials. In other words, recovered mould sand was used as sand here. Calcium-based bentonite is used as bentonite and its technical properties are given in Table 1. Bituminous coal powder was used as coal powder and its technical characteristics are given in Table 1. Pure water is used as a moisture stabiliser.

Experimental studies were carried out in several steps. Firstly, 5 kg capacity laboratory-type Mixmuller brand sand mixing unit has been mixed until the homogeneous sand components determined in the proportions. The moisture content of the sand was determined with 5 gr sand taken from the mixer in the MA50R brand infrared moisture analyser. During the experiment, the temperature of the sand was measured as 298 ± 5 K with the Weather Forecast brand device. Determination of green compression and shear strength was done on Simpson universal strength test device and 145 gr sand was used for each sample. The samples are 50 mm in diameter and 50 mm in length in accordance with DIN 1048 standards and again prepared on Simpson device. The gas permeability test was carried out with samples of the same dimensions in a Jung brand gas permeability metre in 40–50 s.

A preliminary optimisation study was carried out to better select the limit values to be used in the optimisation study. In the preliminary studies, the mixture design method, which is one of the response surface methods and accepted in the literature for the optimisation of mixtures, was preferred [12,13]. Pre-experiments were carried out with sand preparation operations using the D-optimal experiment design, which is a sub-design option of this method. Physical tests (% moisture, green compression strength, shear strength and gas permeability) were carried out for each parameter separately. With the data obtained from the pre-optimisation study, a better limit value was determined and the final optimisation study was performed. Experimental steps and process conditions have been carefully made to obtain optimum data and the whole process has been tried to be controlled. After the optimisation study, the results were tried in high-pressure moulding line like DISA.

3. Results and discussion

Change intervals of independent variables in line with the results obtained at the end of preliminary studies; 3.90 <% moisture (A_1) <4.40, 0.05 <% coal (A_2) <0.1, 0.10 <% bentonite (A_3) <0.30 and 95.20 < % recycling sand (A_4) <95.95. Mixture design/D-optimal experiment design made with the Design Expert program is presented in Table 1. Casting sands were prepared according to the experimental design and were then tested. That is, the gas permeability (B_3), compression (B_1) and shear (B_2) strength of the sand, which changes depending on the independent variables A_1, A_2, A_3 and A_4, are determined and these results are presented in Table 2. In addition, the estimated results obtained from the mathematical models (Equations 1, 2 and 3) developed using these results are presented in the same table. When the data in this table are analysed, it is seen that the results obtained from the mathematical models and experiments are very similar.

Table 1. Technical properties of consumables used.

Grain size (AFS)	65	Fixed carbon amount (%)	62	Humidity rate (%)	10.44
Sintering temperature (°C)	1500	Ash amount (%)	22.6	Montmorillonite ratio (%)	81
Loss of glow (%)	0.20	Volatile matter amount (%)	31.4	Green compressive strength (N/cm^2)	7.00
The amount of clay (%)	0.20	Sulphur amount (%)	0.8	Green tensile strength (N/cm^2)	0.25
Moisture amount (%)	0.25	Moisture amount (%)	5.8	Swelling index (ml)	13.75

Table 2. Experimental sets and results obtained via D-optimal mixture design method.

Amounts of variables/%					Experimental results			Estimated results		
# Experiment	A_1 humidity	A_2 coal	A_3 bento-nite	A_4 recycled Sand	B_1 compressive strength (N/cm^2)	B_2 shear strength (N/cm^2)	B_3 gas perme-ability (mmWS)	B_1 compressive strength (N/cm^2)	B_2 shear strength (N/cm^2)	B_3 gas perme-ability (mmWS)
1	4.27	0.06	0.25	95.41	21.5	7.5	89	21.63	7.42	89.4
2	3.90	0.05	0.20	95.85	22.0	7.6	93	21.85	7.65	90.8
3	3.90	0.10	0.30	95.70	22.8	7.7	93	22.98	7.57	90.8
4	4.15	0.10	0.10	95.65	21.3	7.0	92	21.51	6.91	90.7
5	3.90	0.07	0.20	95.82	20.3	7.2	84	20.95	7.71	90.1
6	3.90	0.10	0.10	95.90	21.7	7.6	90	21.81	7.55	90.6
7	4.40	0.05	0.30	95.25	23.7	7.7	90	23.77	7.54	89.3
8	4.40	0.07	0.30	95.22	23.6	7.6	91	23.53	7.46	89.1
9	4.15	0.10	0.20	95.55	22.0	6.8	90	21.79	6.99	90.5
10	4.40	0.10	0.30	95.20	22.9	7.4	89	22.81	7.27	90.1
11	4.15	0.05	0.30	95.50	22.2	6.9	87	22.21	7.09	89.8
12	4.15	0.05	0.10	95.70	21.5	7.1	90	22.01	6.89	90.3
13	4.15	0.05	0.20	95.60	21.9	6.7	90	21.55	7.08	90.1
14	4.40	0.05	0.20	95.35	23.5	7.4	92	22.39	7.54	90.0
15	4.27	0.08	0.25	95.38	21.4	7.4	88	21.38	7.11	89.7
16	4.02	0.06	0.25	95.66	22.1	7.7	91	22.09	7.72	89.9
17	4.27	0.06	0.15	95.51	21.6	7.4	90	21.54	7.14	89.8
18	3.90	0.10	0.20	95.80	22.4	7.6	91	21.99	7.20	90.8
19	4.40	0.07	0.10	95.42	23.6	7.5	92	23.66	7.39	90.3
20	4.02	0.08	0.25	95.63	22.0	7.6	92	21.11	7.24	90.0
21	3.90	0.05	0.30	95.75	22.2	7.7	91	21.14	7.67	90.8
22	3.90	0.07	0.30	95.72	22.1	7.8	90	21.66	7.68	90.2
23	4.40	0.10	0.20	95.30	23.0	7.1	90	23.01	7.37	90.8
24	4.40	0.07	0.20	95.32	23.3	7.2	91	23.49	7.52	89.2
25	4.27	0.08	0.15	95.48	21.1	7.1	90	21.26	7.10	90.1
26	4.40	0.10	0.10	95.40	23.1	7.5	91	23.03	7.30	91.3
27	3.90	0.07	0.10	95.92	21.5	7.4	89	21.46	7.56	90.0
28	4.02	0.06	0.15	95.76	21.9	7.7	91	22.05	7.21	90.0
29	4.15	0.10	0.30	95.45	22.2	6.7	90	22.38	6.90	90.2
30	3.90	0.05	0.10	95.95	23.1	7.5	92	22.94	7.45	90.6
31	4.02	0.08	0.15	95.73	21.8	7.5	91	21.76	7.21	90.1
32	4.15	0.07	0.30	95.47	22.0	6.5	89	21.90	7.05	89.4
33	4.40	0.05	0.10	95.45	23.7	7.3	87	23.61	7.37	90.5
34	4.15	0.07	0.10	95.67	22.1	6.4	91	21.47	6.96	89.9

3.1. *Statistical analysis of experimental data*

The equations determined by the mathematical models defined by green compression strength (B_1), shear strength (B_2) and gas permeability (B_3) values are shown in Table 3 together with the coefficient of determination (R^2). These equations were used to obtain the predicted results shown in Table 2. Here R^2 value is a statistical measure of how close the data is to the placed regression line. It is also known as the coefficient of determination or multiple determination coefficient for multiple regression [23]. R^2 in Table 3 shows that a model fits well with response data, that is, the differences between the experimentally observed values and the predicted values of the model are small and insignificant. The increase of R^2 values in this study means that there is a good agreement between the independent input variables of the mathematical models obtained and the output response. R^2 values were 91.44%, 46.55% and 75.36% for B_1, B_2 and B_3, respectively. The regression curve used for B_1 and B_3 are compatible, but the regression curve used for B_2 is not compatible. Therefore, different regression graphics should be used for B_2. Different regression curves were investigated to increase the R^2 value in B_2 values, but the appropriate regression curve was not found in the program used. In the software used, proper regression curve Experimental B_1 and B_3 values are closer to the mathematical model and some significant differences are observed in B_2 values. On the other hand, it was determined that both predictive and experimental gas permeability values are between 75 and 150

Table 3. Simulated mathematical models.

Mathematical Model	R^2
B_1 (N/cm^2) = 1203374A_1 + (1.191E+0,8)A_2 + 436,652.4A_3 − 90,843A_4 − 3088826A_1A_2 − 313,271.3A_1A_3 − 18,784.7A_1A_4 − 2870332A_2A_3 − 2866035A_2A_4 − 6320.55A_3A_4 + 20,896.08$A_1A_2A_3$ + 21,214.58$A_1A_2A_4$ + 241.2444$A_1A_3A_4$ + 19,061.11$A_2A_3A_4$ + 11,386.93$A_1A_2(A_1$-$A_2)$ − 14.7333$A_1A_3(A_1$-$A_3)$ − 68.1778$A_1A_4(A_1$-$A_4)$ − 8691.67$A_2A_3(A_2$-$A_3)$ − 9511.11$A_2A_4(A_2$-$A_4)$ − 19.4444$A_3A_4(A_3$-$A_4)$	91.44%
B_2 (N/cm^2) = 764.517A_1 − 9347.93A_2 − 872.24A_3 + 1.483A_4 + 78.898A_1A_2 − 8.318A_1A_4 + 82.749A_2A_3 + 93.936A_2A_4 + 8.812A_3A_4	46.55%
B_3 (mmWS) = 2687500A_1 − 24854500A_2 − 4255720A_3 − 210.72239A_4 − 527991A_1A_2 + 7210.15A_1A_3 − 41,980.95A_1A_4 + 878233A_2A_3 + 409363A_2A_4 + 64,875.58A_3A_4 + 6116.17835A_1A_2A4 − 7656.51$A_2A_3A_4$ + 6691.20$A_1A_2(A_1$-$A_2)$ − 152.59A_1 A_4 $(A_1$- $A_4)$ + 1610.43$A_2A_4(A_2$- $A_4)$ + 222.92A_3A_4 $(A_3$- $A_4)A_3$	75.36%

mmWS gas permeability, which is desired and accepted in the literature [24]. That is, there is a good match between the results obtained from the mathematical model and the actual results, excluding gas permeability data.

3.2. Effects of experimental variables on the physical properties of casting sand

The effects of moisture, bentonite and coal dust percentages on green compression resistance are shown in Figure 1. Along with the decreasing moisture level between 4.275% and 3.9%, the amount of bentonite increased clearly and the green compression strength increased. These results are in line with previous studies by Saikaev et al. and Kundu et al., but in this study, a decrease in green compression strength was observed after 3.9% humidity [12,25]. The increase in the green compression strength is explained by the active bentonite bonding the sand particles together. In addition, when the moisture was higher than 3.9%, green compression strength was reduced. This moisture value is considered to be the upper limit for the activation of bentonite. The binding capacity of bentonite increases up to a certain point in the humidity, but worsens at higher humidity. On the other hand, it is seen that the amount of coal has no effect on the green compression strength. The work of Kul et al. in 2018 supports this data [13].

Figure 2 shows the effects of % moisture, bentonite and coal dust on shear strength. When the effects of experimental parameters on shear strength were examined, results similar to those observed in green compression strength were obtained. Although the shear strength results are in fact parallel to the results made by Abolarin et al. in 2010, due to the increased up to 10% humidity in their study, decrease has been observed after 4% humidity [10]. In this study, when

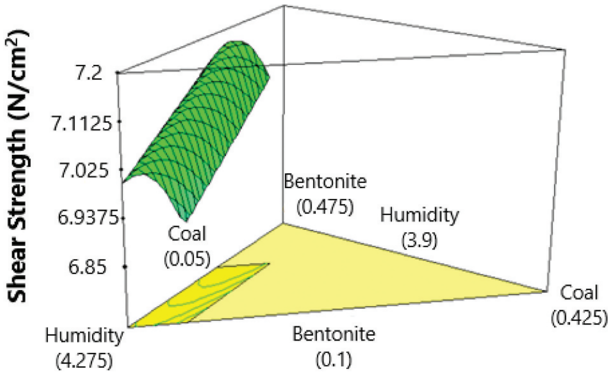

Figure 2. 3D response-surface graph for the effects of variables on the shear strength.

the amount of moisture and bentonite increases, the shear strength increases.

The effects of moisture, bentonite and coal dust percentages on gas permeability are shown in Figure 3. As the amount of coal increases, the gas permeability starts to decrease due to the small pores of the coal and the pores are closed. It was observed that the gas permeability was maximum when the humidity level was minimum as seen in Figure 3. This result was found to be compatible with the work of Kaminska et al. in 2020 [4]. In addition, considering the relationship of moisture with bentonite, the gas permeability value drops significantly when the humidity and bentonite increase together to a certain level. The decrease in gas permeability has decreased with the increase in the humidity rate after the mentioned value of 4.1%. Due to the high water content seen here, the gas permeability is reduced again as the residual water, which is not absorbed by bentonite, occupies the pores encapsulated among the sand particles. These results are consistent with Kul et al. study in 2018 [13]. This can be defined as the saturation point in the moisture value required for the activity of bentonite. Activation of bentonite is reduced at low humidity rates, so sand particles are

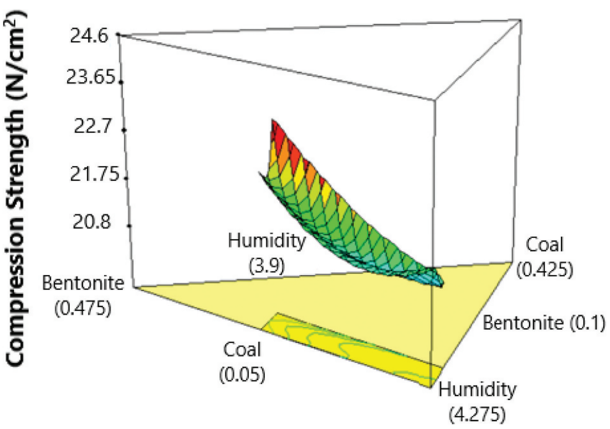

Figure 1. 3D response-surface graph for the effects of variables on the compressive strength.

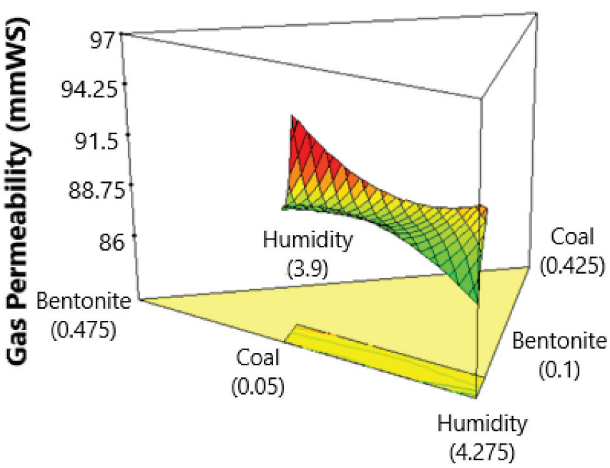

Figure 3. 3D response-surface graph for the effects of variables on the gas permeability.

Table 4. Estimated and experimental results for optimum values obtained by mixture design method.

Humidity %	Coal %	Bentonite %	Recycled sand %	Comp. strength (N/cm^2)	Shear strength (N/cm^2)	Gas Perm. (mmWS)	Estimated Comp. Strength	Estimated Shear Strength	Estimated Gas Perm.
3.90	0.1	0.30	95.69	22.8	7.7	90	22.99	7.57	93.82
3.90	0.05	0.10	95.95	23.1	7.5	89	22.94	7.45	92.47
3.92	0.05	0.30	95.73	22.1	7.6	91	22.59	7.59	91.26

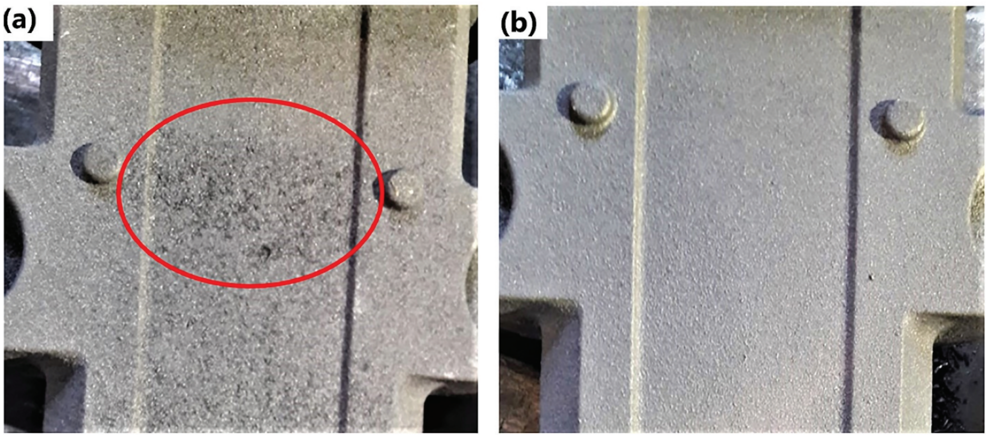

Figure 4. (a) The casting part before the optimisation work. (b) The casting part after the optimisation work.

weak or poorly bonded to each other. Since the activation of bentonite is low, it is thought that more space is formed in order to remove the gas formed between the sand grains and finally the gas permeability value increases. Since we use recycled sand, it has been observed that the coal dust we use in a very small amount reduces the gas permeability to a small extent. This result is consistent with the work of Sahoo et al. in 2017 [14].

Optimum conditions that maximise compressive strength, shear strength and gas permeability are determined by Design Expert software. The results of the validation experiments performed under optimum conditions are shown in Table 4. Experimental and simulated values were found to be consistent with each other. It is seen that the model gives significant results at the intervals determined for the humidity rate% (A_1), coal dust% (A_2), active bentonite% (A_3) and recovered sand% (A_4). In other words, by using this model, estimates can be made about the intervals between green compression strength, shear strength and gas permeability.

Figure 4 shows the casting parts before and after the optimisation work. It is clearly seen that there is an interaction between the weak moulding sand and the liquid metal before the optimisation study (Figure 4 (a)). The surface of the cast parts after optimisation has been found to be cleaner (Figure 4(b)).

4. Conclusion

Within the scope of the study, the most efficient recycled mould sand composition ranges were determined by optimising the inverse proportion between gas permeability, green compression and shear strength values in mould sands, mixture design (MD) optimisation method. The results of the experiments and the software estimation results were compared and evaluated.

Preliminary studies were carried out for the optimisation study of recycled sand, and the limit values of the components forming the sand were determined. Then, these values were determined as ($3.90< A_1 < 4.40$), ($0.05< A_2 < 0.10$), ($0.10< A_3 < 0.30$), ($95.20< A_4 < 95.95$). So, with subsequent detailed optimisation, 22.8 N/cm^2 compression strength, 7.7 N/cm^2 shear strength and 90 mmWS gas permeability values were obtained.

Ultimately, by increasing the gas permeability value, the gas formed in the mould is released more easily and the gas-borne errors are tried to be prevented, and the physical compression of the mould against the liquid metal is increased by increasing the green pressing and cutting strength. As a result of this study, it was seen that it was contributed both environmentally and economically by increasing the efficiency of the mould sands of ESTAS Company.

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Disclosure statement

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