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Investigation on the Effect of Granulometric Features on the Permeability of No-Bake Resin Bonded Sand Cores

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Abstract

Foundry sand is the main element of sand mixtures from which molds or sand cores are made. Due to the continuous development of coremaking technologies, the selection of the right type of base sand becomes more and more important. The major features of foundry sand are determined by the following factors: chemical and mineralogical composition, sand grain size, grain size distribution, sand grain shape, and surface quality. The main goal of our research was to develop a qualification method that can be used to predict the characteristics of sand cores made from different sand types. Samples made from different types of foundry sand were used during the research whose properties were examined with a new qualification system, and then its connection with the gas permeability of sand cores was analyzed. Based on the research results, a strong correlation could be established between the suggested quality indicators: CQ_i (Core Quality Index), *CG* (Coefficient of Granulometry), and permeability.

Keywords: Foundry sand granulometry, Grain size, Grain morphology, Grain shape, Permeability

1. Introduction

The molding and core sand mixtures are complex and quite complicated systems. The sand mixture, which is used for manufacturing cores and molds, is made from base sand and a binder material, which can be organic or inorganic. Many parameters affect the mechanical and thermal stability of molds and cores. The strength and the permeability of cores are dependent on the granulometric features of the sand, the bonding agents (quantity, quality, different curing conditions), and the bulk density of the sand mixture [1-2].

The coremaking technologies utilize several different natural and, nowadays, more and more artificial base materials. The main constituent of the chemically bonded sand mixtures is the foundry sand which gives approx. 90-98 wt. % of the mixture. Due to this, the properties of the foundry sands determine the properties of sand cores. The characteristics of the sand depend on its chemical and mineralogical composition, particle-size distribution, and grain shape, as well as on the surface texture. All these features affect the gas permeability of the sand cores as well as their mechanical strength [3-8].

The properties of mold and core sand mixtures are mainly influenced by the granulometric parameters of the foundry sand, such as grain shape, surface quality, grain size, structure, and specific surface area. Even the slightest difference in granulometric features can cause a significant change in the permeability or strength characteristics of sand cores [9-14].

The aim of this research work was to create a comprehensive qualification method, which, for a given coremaking technology, can predict the mechanical properties and gas permeability of sand cores based on the granulometric properties of the sand. Since the current qualification methods of granulometric features are imprecise and not clearly quantified, the parameters of the cores and the different production parameters cannot be compared. The sieve analysis is one of the most basic granulometric investigation methods. In the case of sieve analysis, the source of error may be the clogging of the sieve holes, as well as the damage or rupture of the sieve mesh. During image analysis, the particles are measured in a random arrangement, which can cause differences in the results when measuring irregularly shaped particles [15-19].

The granulometric measurements are mainly based on the measurement of quartz sands; therefore, the specific surface values of sands with different material densities are different even for the same surface area. Due to the different material densities, the mass of the sample to be measured to determine the specific surface area must be corrected [20].

The comparison based on bulk density is inaccurate, as the results of the comparison of different sand types (e.g., comparing quartz with chromite). The reason for the error is the diverging densities of the different materials, which affect bulk density. In the case of sand cores with the same bulk density, different results can be obtained due to the different material densities. Our work aimed to correct this fault with the introduction of a new qualification parameter, which simultaneously characterizes the granulometric and bulk density parameters of the sand cores.

2. Materials and methods

2.1. Materials

Two types of quartz sand and two special foundry sand was used for our tests (GBM 45 from Badger, USA, SH 33 from Šajdikove Humence, Slovakia, Bauxite sand W55 and J-SAND). It was important to select foundry sands with similar average grain sizes but different grain shapes. Fig. 1. shows the stereo microscopic images of the grains of different sands.

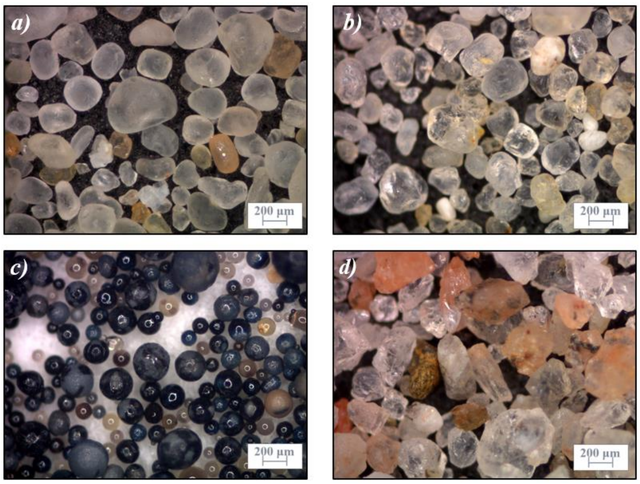

Fig. 1. Stereo microscopic images of the sands a) GBM 45, b) SH 33, c) Bauxite sand W55 and d) J-SAND at 20x magnification

2.2. Rating method

We introduced the so-called *Core Quality Index*, which includes the sand volume and surface, as well as the bulk density of the investigated sand core; therefore, it is eligible for the complex qualification of core parameters. The Core Quality Index, which also takes into account the granulometric properties of the base sand, can be calculated according to (Eq. 1):

$$CQ_i = Air\ quantity\ /\ SM \tag{1}$$

where CQ_i is the Core Quality Index [-], *Air quantity* is the percentage of air in the sand core [vol. %], and *SM* is the Sand Modulus [cm]. The *Air quantity* gives the total volume of porosity in the core. The *Sand Modulus* was calculated using Eq. 2:

$$SM\ =\ V_{sand}\ /\ (SA_{sand}) \tag{2}$$

where V_{sand} is the volume of sand in the sand core [cm^3], and SA_{sand} is the total surface area of sand in the sand core [cm^2], which can be calculated by knowing the specific surface area and the mass of the sand core.

The following data are required to define the value of *SM*:

- Volume of the sand core = V_{core} [cm^3],
- Mass of the sand core (sand) = m_{core} [g],
- Material density of the sand = ρ [g / cm^3],
- Specific surface area of the sand = A_{BLAINE} [cm^2 / g].

For each specimen, the mass was measured to thereby determine the *Air quantity*, the *SM*, and the CQ_i values. It is important to note that the mass of the binder was neglected.

2.3. Specimen preparation

The sand mixture used for the making of the specimens was made with phenolic no-bake resin (Furtolit 4003) and a catalyst as set by the recipe (Härter RS 20). The quantity of the phenolic resin was 1 wt. % of the sand quantity, the catalyst was 0.4 wt. % in respect to resin mass. In all cases, the sand mixture was stirred with a Multiserw-Morek laboratory mixer for 2×1 minute (1 minute stirring with the catalyst and 1 minute with the resin). After the preparation of the sand mixtures, standard Ø50 mm x 50 mm height cylindrical samples were made with a Multiserw-Morek compaction device with different compaction loads of 1, 3 and 5 MPa for 20 seconds. The specimen preparation was made at approx. 20-22 °C. The process of specimen production is illustrated in Fig. 2. These specimens were later subjected to gas permeability tests.

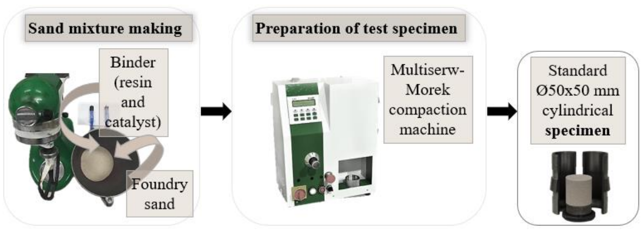

Fig. 2. Preparation of test specimens

In order to study the effects of the mixed grain size, the GBM 45 quartz sand was fractionated by sieving into the following size fractions:

- fine fraction – 100-200 μm,
- medium fraction – 200-315 μm,
- and coarse fraction – 315-630 μm.

Then, the fractionated sand samples were used to produce permeability test specimens.

2.4. Permeability test

This measurement gives information about the permeability of the standard cylindrical specimens. The permeability of the cured samples was measured with the apparatus shown in Fig. 3.

Fig. 3. DISA type permeability testing machine and accessory for measuring cores

The gas permeability can be calculated using the following Equation:

$$P = (V \times h)/(A \times p \times t) \quad (3)$$

where P is the gas permeability [-], V is the volume of air flowing through the sample [m^3], h is the height of the core sample [cm], A is the cross-sectional area of the sample [cm^2], p is the air pressure under the specimen [Pa], and t is the time needed for the V volume of air to flow through the sample [s]. The standard permeability test specimens made from different foundry sands are shown in Fig. 4.

Fig. 4. Standard permeability test specimens

3. Results and discussion

3.1. Granulometric analysis results

Foundry sands with diversely shaped grains shown in Fig. 1. were studied in this work. The grain size distribution bar chart and the cumulative curve evaluated by sieve analysis are shown in Fig. 5.

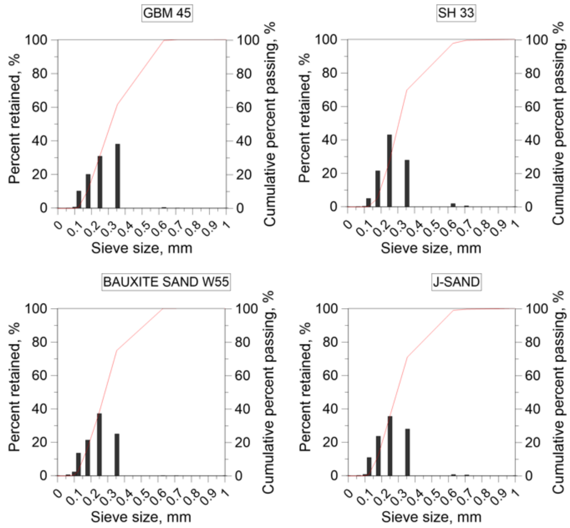

Fig. 5. Grain size distribution diagrams of the investigated sands

Based on the results of the granulometric analysis, it can be determined how many major fractions the applied sands contain and whether the grain size distribution of the investigated sands is different. The studied sand types typically consist of three major fractions in the size range of 0.355–0.18 mm. On the other hand, the grain size distributions within these fractions are quite different (Fig. 5).

The results of the complete granulometric analysis are shown summarized in Table 1.

Table 1.
Granulometric measurement data of the investigated sands

		GBM 45	SH 33	Bauxite sand W55	J-SAND
Average grain size (d_{50})	[mm]	0.31	0.32	0.29	0.30
AFS grain fineness number *(AFS)*	[-]	44	44	48	46
Homogeneity degree (*GG*)	[%]	52	61	57	59
Coefficient of angularity (*E*)	[-]	1.29	1.33	1.05	1.34
Specific surface (A_{BLAINE})	[cm^2/g]	115	115	130	150
Density	[g/cm^3]	2.65	2.6	3.1	2.66
Bulk density (dry)	[g/cm^3]	1.6	1.56	1.63	1.47
Grain shape	[-]	sub-rounded	sub-rounded	rounded	angular

An aspect of the selection of base sands was to have sands with different grain shapes and similar average grain sizes; as a result, the effect of the different grain shapes on the parameters of the core could be investigated. Based on the average grain size results shown in Table 2, the difference between the different sands is not significant considering the average grain size. The two quartz sands (GBM 45 and SH 33) are extremely similar regarding their granulometric characteristics. The AFS grain fineness number of the quartz sands is the same, and their average grain diameter is almost the same. The angularity coefficient of the sands also has a similar value.
The Bauxite sand W55 has a rounded grain shape and high sphericity. On the other hand, J-SAND has the highest surface area since it has the most angular sand grains.

3.2. Permeability test results

The permeability and CQ_i values of the specimens from fractionated GBM 45 quartz sand are shown in Fig. 6. The measurement results are given by the average of 3 measurements.

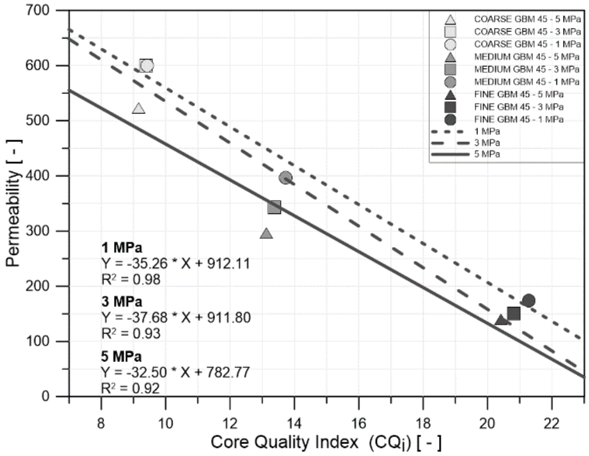

Fig. 6. The permeability test results as a function of CQ_i in the case of the fractionated GBM 45 quartz sand

Despite the fact that samples made from different fractions possess almost equal porosity (*air quantity*), that is, there is no significant alteration in their bulk density; their permeability can vary due to the different shapes of channels (voids) among the sand grains.
The results indicate that the permeability of the specimens made from the coarse sand fraction was the highest - the value exceeded the measurement threshold limit (which is 600 [-]) - while this fraction possessed the lowest CQ_i value. The lowest permeability was measured on the core samples made from the fine sand fraction. In the case of samples made from different sand fractions, the air volume fraction is nearly the same, so there is no significant difference in their bulk density.

Based on the measurement results, it can be verified that the permeability of sand cores made with the same production parameters - same quantity and quality of binder, same bulk density - is higher when the coarse sand fraction is used. When the grain structure is mixed, various permeability values can be measured due to the inhomogeneous distribution of smaller grains compared to the systems with homogeneous grain sizes [5].

The results of the permeability test of the fractionated GBM 45 quartz sand are shown summarized in Table 2. The CQ_i and permeability values of the specimens made from the four different sands with different compaction forces are shown in Fig. 7. As can be seen, an unequivocal conclusion cannot be drawn from the results. Certainly, in the case of fractioned sands, the effect of grain size is excluded, and the grain shape is also the same if the same sand fractions are compared.

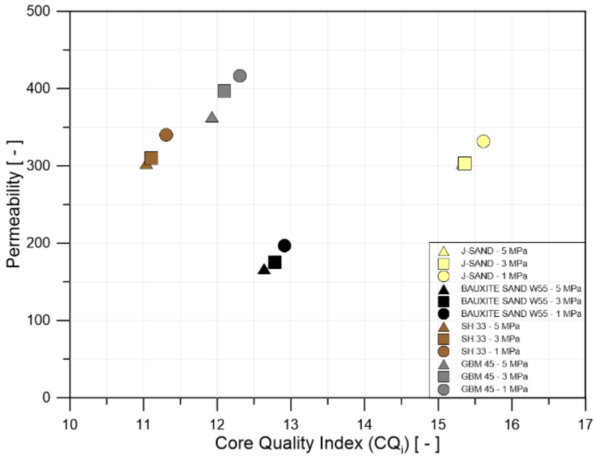

Fig. 7. The permeability test results as a function of CQ_i in the case of the investigated sands

Table 2.
The permeability test results of the fractionated GBM 45 quartz sand

Permeability [-]		**Mass of the specimen [g]**	**Bulk density of the specimen [g/cm³]**	**Volume of the sand in the sand core [cm³]**	**ΣArea of the sand grains in the sand core [cm²]**	***Air quantity* [vol. %]**	***SM* [10⁻³cm]**	***CQᵢ***	***CG***
GBM 45 Fine fraction									
1 MPa	173	150.32	1.50	56.72	27809	43.40	2.04	21.28	14.73
3 MPa	150	151.33	1.52	57.11	27996	42.45	2.04	20.81	10.08
5 MPa	140	154.57	1.55	58.33	28595	41.65	2.04	20.42	8.53
GBM 45 Medium fraction									
1 MPa	397	150.93	1.51	56.95	18112	43.16	3.14	13.73	14.73
3 MPa	343	153.11	1.54	57.78	18373	42.05	3.14	13.37	10.08
5 MPa	297	155.21	1.56	58.57	18625	41.29	3.14	13.13	8.53
GBM 45 Coarse fraction									
1 MPa	600	152.50	1.54	57.55	12962	41.82	4.44	9.42	14.73
3 MPa	600	153.43	1.55	57.90	13041	41.70	4.44	9.39	10.08
5 MPa	523	155.69	1.57	58.75	13234	40.68	4.44	9.16	8.53

However, in the case of the results shown in Fig. 7, the grain shape (i.e., angularity) and grain size distribution have an overwhelming effect on the permeability. Because the permeability of the cores is mainly influenced by the granulometric characteristics of the base sand, it is necessary to use a metric, which contains these parameters together. This suggested index-number is the *Coefficient of Granulometry*. The Coefficient of Granulometry can be calculated using Eq. 4:

$$CG = (AFS \times GG)/E \quad (4)$$

where *AFS* is the AFS grain fineness number [-], *GG* is the degree of homogeneity [%] and, *E* is the angularity coefficient of the sand [-]. The permeability and *CG* values of the specimens made from different foundry sands are shown in Fig. 8.

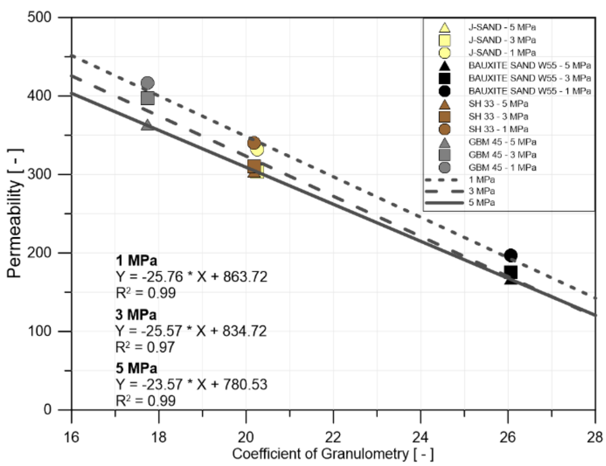

Fig. 8. The permeability test results as a function of *CG* in the case of the investigated sands

The results indicate that the permeability of the specimens made from the GBM 45 sand mixture was the highest, and at the same time, this sand type possessed the lowest *CG* value. The lowest permeability was measured on the sand cores made from Bauxite sand W55. The results of the permeability test of the investigated sands are shown summarized in Table 3.

Based on the measurement results, it can be verified that the permeability of the sand cores made with the same production parameters (same content and quality of binder, same compaction) can be determined from the granulometric parameters, and the introduced granulometric index-number, the Coefficient of Granulometry, *CG*.

4. Conclusion

The main purpose of the presented research was to reveal the correlation between the Core Quality Index (CQ_i), Coefficient of Granulometry (*CG*), and the permeability of sand cores.

Sand core samples made from various foundry sands (GBM 45 quartz sand, SH 33 quartz sand, Bauxite sand W55 and J-SAND) were used during the investigation, whose features were analyzed with a new qualification method and newly introduced metrics, whose relationship with the permeability of cores were also examined.

Based on the results, there is a strong correlation between the newly introduced metrics and the permeability values. Different foundry sands can be easily compared with the suggested qualification method. Otherwise, the different density values would make the comparison difficult (due to the different bulk densities). The new type of qualification method makes it possible to prognosticate the permeability of sand cores containing different base sands.

Table 3.
The permeability test results of the investigated sands

Permeability [-]		Mass of the specimen [g]	Bulk density of the specimen [g/cm^3]	Volume of the sand in the sand core [cm^3]	ΣArea of the sand grains in the sand core [cm^2]	*Air quantity* [vol. %]	*SM* [10^{-3}cm]	CQ_i	*CG*
GBM 45									
1 MPa	417	158.06	1.59	59.65	18335	40.03	3.25	12.31	17.74
3 MPa	397	159.85	1.61	60.32	18543	39.35	3.25	12.10	17.74
5 MPa	363	161.72	1.62	61.03	18759	38.81	3.25	11.93	17.74
SH 33									
1 MPa	340	152.42	1.57	58.62	16766	39.53	3.50	11.31	20.18
3 MPa	310	156.58	1.59	60.22	17224	38.83	3.50	11.10	20.18
5 MPa	303	158.87	1.60	61.10	17475	38.59	3.50	11.04	20.18
Bauxite sand W55									
1 MPa	197	189.29	1.61	61.06	20632	38.23	2.96	12.92	26.06
3 MPa	175	193.05	1.62	62.27	21042	37.82	2.96	12.78	26.06
5 MPa	167	193.49	1.63	62.42	21090	37.39	2.96	12.64	26.06
J-SAND									
1 MPa	332	147.44	1.46	55.43	19168	45.15	2.89	15.61	20.25
3 MPa	303	147.91	1.48	55.60	19228	44.41	2.89	15.36	20.25
5 MPa	303	149.28	1.48	56.12	19406	44.33	2.89	15.33	20.25

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