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# Analysis of Influence of Sand Matrix on Properties of Moulding Compounds Made with Furan Resin Intended for 3D Printing

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## Abstract

Binder jetting (BJ) sand printing is a 3D printing process in which a sand mould or sand core is produced from an STL file. A single layer of a sand matrix consisting of one or more grains in height of sand is applied to a worktable, and then a liquid resin or binder is applied to bond the grains together. This process is repeated until the final result matches the CAD model.

The sand matrix is the main component of ceramic cores and moulds. The present study aims to demonstrate the influence of the matrix used on the properties of the resulting moulding sand.

Three types of sand matrices were selected for the study. The first was a quartz matrix for 3D printing with binder jetting; this is characterised by a sharp geometry that allows for proper layering during printing. Ordinary quartz sand was also used for the study; this type of sand is usually used for the production of sand cores in the hotbox process, among other things. The shape of this sand is irregular. The last matrix to be tested was Cerabeads sand; this was selected because its spherical geometry clearly distinguishes it from the other two matrices. The matrices were analysed for their grain sizes. Scanning electron microscope images were also taken to compare the geometries and chemical compositions of the respective matrices.

In presented research utilises a sand matrix for the production of self-curing compounds with furan resin dedicated for binder jetting 3D printing. The moulding masses were produced in a laboratory circulation mixer. The laboratory moulds were produced with wooden core boxes and pre-compacted by vibration. The samples from the matrix for the 3D printing were produced using the binder jetting method. The samples were produced to determine the flexural strength, tensile strength, gas permeability, hot distortion, and apparent density.

It was not possible to carry out tests for the Cerabeads sand, as the obtained moulds were too brittle to perform adequate tests. Tests with the other matrices have shown that the shape and size of the matrix affect the apparent density and gas permeability.

**Keywords:** Furfuryl resin, Foundry engineering, Sand moulds and cores, 3D printing, Binder jetting

## 1. Introduction

Additives technologies are playing an increasingly key role in today's industry. In recent years, many techniques related to additive manufacturing have developed dynamically. Additive manufacturing (also known as 3D printing) is the production of objects by applying successive layers of material based on a CAD model. Originally, 3D printing was intended for rapid prototyping; as the technology has advanced, however, the focus in the industry has shifted towards rapid manufacturing. Technologies, materials, and equipment are continuously improving, leading to the growing presence of additive manufacturing (AM) in the global market.

In the foundry industry, incremental techniques are used to produce metal parts as well as sand moulds and cores for traditional gravity casting; however, none of these techniques are currently being used on a large scale. The most common technique for the production of ceramic moulds is binder jetting (BJ); this consists of a ceramic matrix and a binder (mainly quartz sand and organic resins) that independently achieve the required strength when combined with catalysts or activators [1 - 4].

The course of the curing process depends on the applied binder technology. Currently, organic binders in the forms of furfuryl resins are most commonly used; these enable a mould to gain strength spontaneously when suitable activators/catalysts are used [1 - 3, 5].

At AGH University of Science and Technology in Krakow, research is being conducted into the technology of the additive manufacturing of moulds and cores using the binder jetting process. The first phase of the research involves analysing the properties of the materials that are used in the technology – ceramic matrix and furfuryl resin. Three different matrices were analysed: quartz sand used in traditional methods for the production of sand moulds and cores, the Cerabeads 400 synthetic matrix, and quartz sand that is intended for additive manufacturing technology (3D printing) using the binder jetting method (supplied by the ExOne company). The resin that was used in the research was also supplied by ExOne. The presented results of the preliminary investigations included an analysis of the grain size and apparent density of the tested sands, a strength analysis of the moulded sand that was produced from the materials, an analysis of the permeability, a microscopic analysis of the tested sand matrix, and checking for the presence of bridges among the grains [1, 3, 5].

The operating principle and components of the additive manufacturing system using the binder jetting process are shown in Figure 1. To start the 3D printing process, a file with the geometry of the target object is required. Uploading the spatial object into a device's software and positioning it on its virtual worktable is the first step of additive manufacturing; more than one object can be uploaded in order to reduce the working time of the device. The printing process begins with the application of the first layer of the ceramic matrix by the recoater. The layer can consist of one or more grains in height of the supplied material, whereby the sand is mixed with the hardener or activator in a mixer and then delivered to the recoater. When the entire surface of the worktable is covered with the ceramic matrix, the print head precisely applies the resin or binder. Figure 2 illustrates the printing process in the binder jetting 3D system. The sand layer is applied to the worktable with the recoater. A liquid binder is then sprayed over the layer by the injector; this binder sinks into the sand layer and surrounds it so that bridges form among the grains of the layer. Once the print layer has been created, the recoater applies another layer of sand, and the print head applies droplets of the binder. As soon as the print head has completed its task, the worktable lowers by a level that is equal to the height of the ceramic matrix layer. This process is repeated until the desired core or mould is produced. After the first curing, the unused sand is removed from the process [1, 2, 3, 4, 5].

Figure 3 shows an example of a binder jetting print, which includes the AGH logo.

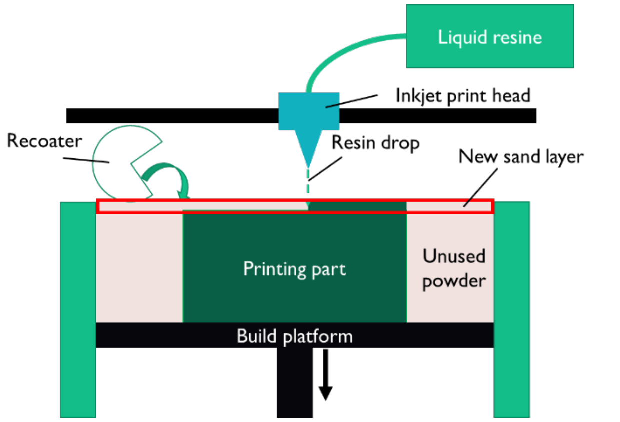


Fig. 1. Components of additive manufacturing system (printing) for moulds in binder jetting 3D system [1, 3]

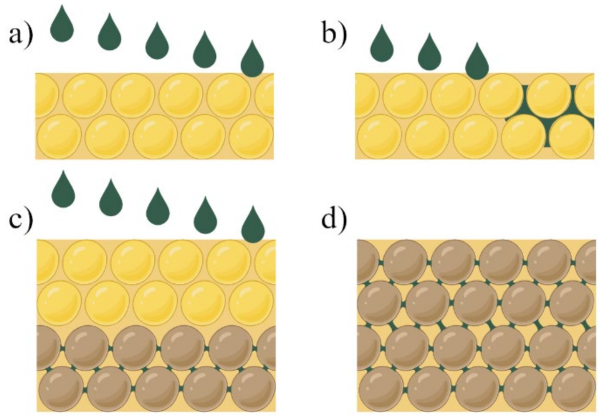


Fig. 2. Illustration of printing process in binder jetting 3D system: a) droplets of liquid binder are applied to layer of matrix; b) binder surrounds sand grains; c) droplets of binder applied to new layer of matrix; d) matrix grains connected by resin bridges [1, 3]


Fig. 3. Three-dimensional print of AGH University logo

## 2. Description of approach, work methodology, materials for research, assumptions, experiments, etc.

### 2.1. Aperture, materials, and methodology

The size of the matrix was determined in two ways:

- classic sieve analysis method: using laboratory shaker (LPzE-2e) and set of sieves that complied with PN-ISO 3310-1/ASTM E11 standard [5];
- laser particle sizer method: using ANALYSETTE 22 NanoTec laser particle sizer [8].

The moulding sands that were intended for the laboratory samples were produced in a planetary laboratory mixer from Morek-Multiserw. Samples were produced from the moulding sands using wooden cores and a vibrating compactor LUZ-2e from Morek-Multiserw. The moulding sands were produced from three types of matrices: standard quartz, the quartz that is used in the binder jetting technology, and Cerabeads 400. The binder that was used was a resin that was developed for binder jetting technology by ExOne. The strength tests of the moulding sands were carried out with the Morek-Multiserw LRu-2e device, while the permeability of the moulding sands was measured with the Morek-Multiserw LPiR-3e device. The phenomenon of high-temperature deformation and the course of the sample-breakage process were carried out with the LRu-DMA [6, 7, 8, 11]. The moulding sands that were used to determine the bulk density were prepared in a similar way as with the laboratory samples. The moulding sand was compacted using an automatic laboratory tamper (LUA-2e) by applying 1, 3, 5, or 10 impact impulses. The apparent density was determined by the gravimetric method by relating the sample mass to its volume after compaction at a given compaction energy [9, 10, 11].

Three series of tests were performed using the binder jetting (BJ) 3D printing method, including 40 specimens each for the bending strength, tensile strength, and cylindrical specimens (gas permeability, hot distortion, and apparent density). Scanning electron microscopy images were obtained using a Phenom Pro 10499-L microscope.

### 2.2. Aim of research

The general aim and main research question are focused on determining the influence of the type of ceramic matrix on the key technological properties of moulding sands as assessed under conditions that are similar to those occurring in the foundry process. The experiments were divided into three stages: the first involved an analysis of the ceramic matrix, the second consisted of preparing moulding sands from three types of ceramic matrices with the furfuryl resin that is used in binder jetting (tests were conducted for strength, permeability, and apparent density), and the third aimed to determine the influence of temperature on the moulding sands (including an assessment of the hot distortion and sintering losses).

In this context, the goal of the article is to highlight the differences among the traditional methods and the additive manufacturing techniques for producing foundry cores and moulds using the binder jetting method as an existing (and prospective) alternative for manufacturing cores and moulds through spatial printing. Additive technologies in modern industry have had an increasing impact on industrial development – particularly in the production of custom and small-batch products with complex final product geometries.

## 3. Description of achieved results of own research

### 3.1. Investigation of size of quartz matrix and SEM images with chemical analysis

The bases for carrying out the investigation that is described here were analyses of selected types of ceramic matrices. The investigation began with determining the sizes of the individual matrices; a sieve analysis was carried out for this purpose. The sieve analysis method is described in Lewandowski's book and is commonly used to test sand matrices [5]. Laser particle analysis is an alternative method for testing sand matrices [8]. These results are shown in Table 1, while Table 2 contains the results of the laser grain-size measurements.

Table 1.
Sieve analysis of grain sizes

| Matrix | Sieve analysis | | |
|---|---|---|---|
| | Arithmetic mean | Geometric mean | Specific surface area |
| | [mm] | [mm] | [$cm^2$/g] |
| Quartz | 0.260 | 0.251 | 9428 |
| 3D printing quartz | 0.132 | 0.129 | 18119 |
| Cerabeads | 0.363 | 0.347 | 7113 |

Table 2.
Laser analysis of grain sizes

| Matrix | Laser grain measuring | | |
|---|---|---|---|
| | Arithmetic mean | Geometric mean | Specific surface area |
| | [mm] | [mm] | [$cm^2$/g] |
| Quartz | 0.240 | 0.214 | 2519 |
| 3D printing quartz | 0.133 | 0.109 | 3317 |
| Cerabeads | 0.332 | 0.252 | 10859 |

The next step consisted of scanning electron microscopy (SEM) analyses – the results of which are shown in the SEM images. The visual data allowed for a comparison of the shapes and relative dimensions of the analysed sand matrices. The standard quartz matrix is shown in Fig. 4, while the second type (which served as a quartz matrix for the 3D printing) had significantly smaller particle sizes (see Fig. 5); meanwhile, the Cerabeads matrix (shown in Fig. 6) was characterised by quasi-spherical grain shapes, the smallest values of diameters da and dg, and the greatest theoretical grain-surface area.

Scanning electron microscopy also made it possible to analyse the chemical compositions. Table 3 shows a comparison of the chemical compositions of three elements (oxygen, aluminium, and silicon) for each of the matrix types that were examined.

Table 3.
Chemical composition of sandy soils

| Quartz sand | | |
|---|---|---|
| Element Number | Element Symbol | Weight Conc. |
| 8 | O | 51.00 |
| 13 | Al | 3.00 |
| 14 | Si | 46.00 |
| 3D printing quartz sand | | |
| Element Number | Element Symbol | Weight Conc. |
| 8 | O | 56.50 |
| 14 | Si | 43.50 |
| ---- | ---- | ---- |
| Cerabeads | | |
| Element Number | Element Symbol | Weight Conc. |
| 8 | O | 42.50 |
| 13 | Al | 44.00 |
| 14 | Si | 13.50 |

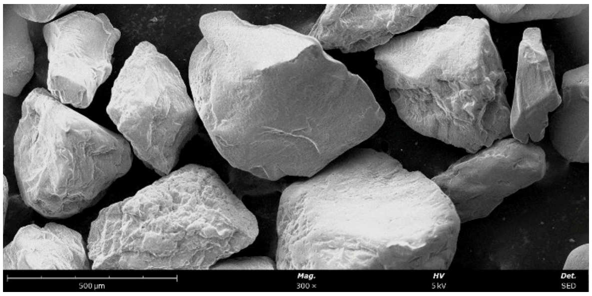

Fig. 4. SEM – standard quartz matrix

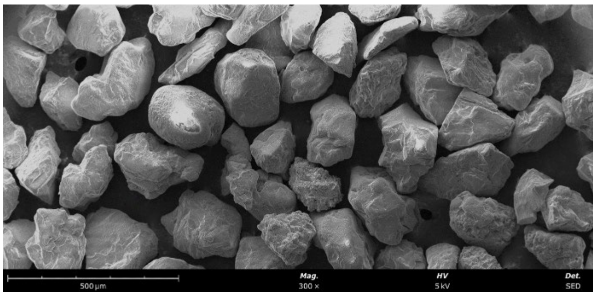

Fig. 5. SEM – quartz matrix using in additive manufacturing

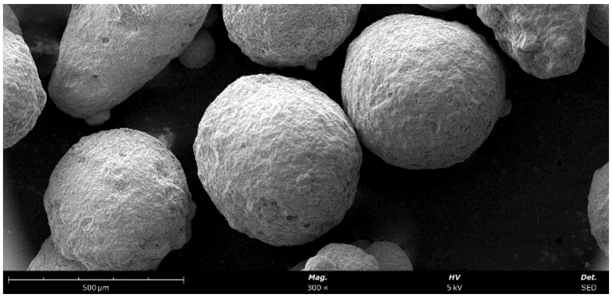

Fig. 6. SEM – Cerabeads 400 matrix

## 3.2. Flexural and Tensile Strength Studies

After analysing each of the ceramic matrices that were designated for the study, strength tests were conducted. The specimens were prepared for flexural strength tests according to the scheme that is presented in Fig. 7 and for tensile strength tests according to the scheme in Fig. 8. The specimens for each type of ceramic matrix were produced using self-cured furan-based resin and a hardener that is used in additive manufacturing by the binder jetting method. The binder of the moulding sand consisted of 1% resin and 0.3% hardener.

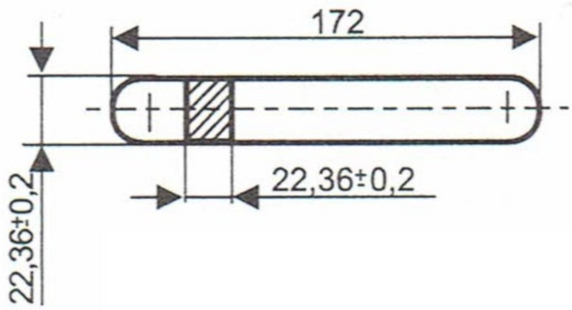


Fig. 7. Scheme of bending test specimen [5]

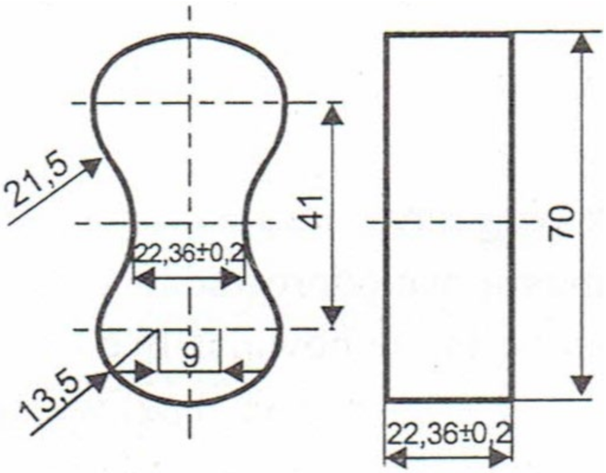


Fig. 8. Scheme of tensile dog-bone test specimen [5]

Using binder jetting 3D Printing technology, specimens were produced according to the schemes that are presented in Figs. 7 and 8 for a result comparison [5, 11, 12]. A total of 40 specimens for flexural strength tests and 40 specimens for tensile strength tests were produced using the conventional self-cured moulding method with a quartz matrix. Additionally, 20 specimens for flexural strength and 20 specimens for tensile strength were produced using the binder jetting 3D printing method. Graphical summaries of the obtained results are presented in Figs. 9 and 10.

The Cerabeads matrix could not be tested. The specimens produced with the Cerabeads matrix proved to be fragile. They did not achieve sufficient strength for the tests. This could be due to the insufficient amount of resin used. The Cerabeads matrix has a larger grain size and a higher weight compared to the other two matrices.

The arithmetic means of the flexural strength results were as follows:

- self-cured moulding method with quartz matrix – 2.804 MPa;
- binder jetting 3D printing specimen – 3.297 MPa.

The arithmetic means of the tensile strength results were as follows:

- self-cured moulding method with quartz matrix – 1.102 MPa;
- binder jetting 3D printing specimen – 1.181 MPa.

A data analysis indicated that the alternative use of binder jetting technology resulted in an approximately 20% increase in the flexural strength when compared to the self-cured moulding method for the same type and composition of the tested sand matrix. A similar comparison for the tensile strength showed slightly greater strength for those specimens that were produced using the 3D printing technology (about 7.5%) [5, 11, 12].

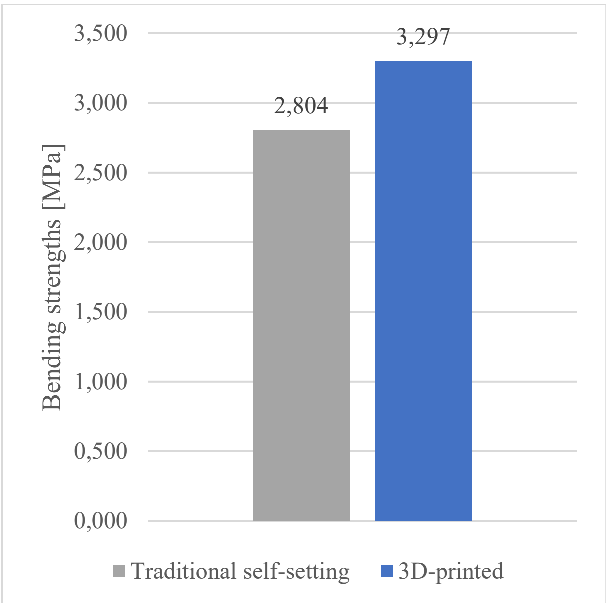

Fig. 9. Comparison of average bending strength

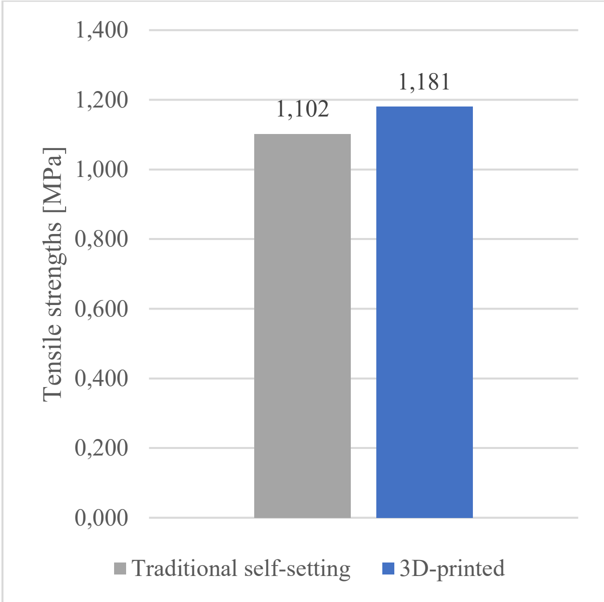

Fig. 10. Comparison of average tensile strength

## 3.3. Study of Apparent Density and Permeability

A study was conducted to compare the apparent density and permeability of cylindrical specimens made by the traditional self-cured moulding method with a standard quartz matrix and a matrix that is used in binder jetting as well as additively manufactured specimens [11, 13]. The traditional specimens were additionally subjected to standardised impact impulses using a rammer; for each matrix, these were single, triple, quintuple, and decuple compaction impulses [5, 8, 10]. To determine the apparent density, the heights of the specimens were measured. The apparent density was calculated by measuring the ratios of the masses of the specimens to their volumes [14]. These results are presented in Table 4.

Table 4.
Apparent density of moulding sands with various matrices

| Matrix | Number of strokes | | | |
|---|---|---|---|---|
| | 1 | 3 | 5 | 10 |
| | $g/cm^3$ | $g/cm^3$ | $g/cm^3$ | $g/cm^3$ |
| Quartz | 1.454 | 1.490 | 1.515 | 1.540 |
| 3D-printed quartz | 1.366 | 1.396 | 1.410 | 1.464 |
| Additive manufactured | 1.369 | | | |
| Cerabeads | - | - | - | - |

The average results of the gas permeability measurements have been graphically presented for the standard quartz matrix (Fig. 11) and for the matrix that was used in the 3D printing, along with the average permeability of the additively manufactured specimens

(Fig. 12). A summary of the gas permeability results is provided in Table 5.

Table 5.
Gas permeability of moulding sands with various matrices

| Matrix | Number of strokes | | | |
|---|---|---|---|---|
| | 1 | 3 | 5 | 10 |
| | $m^2/(MPa \times s)$ | | | |
| Quartz | 30.367 | 28.033 | 25.133 | 24.033 |
| 3D-printed quartz | 12.900 | 11.433 | 10.933 | 8.600 |
| Additive manufactured | 13.833 | | | |
| Cerabeads | - | - | - | - |

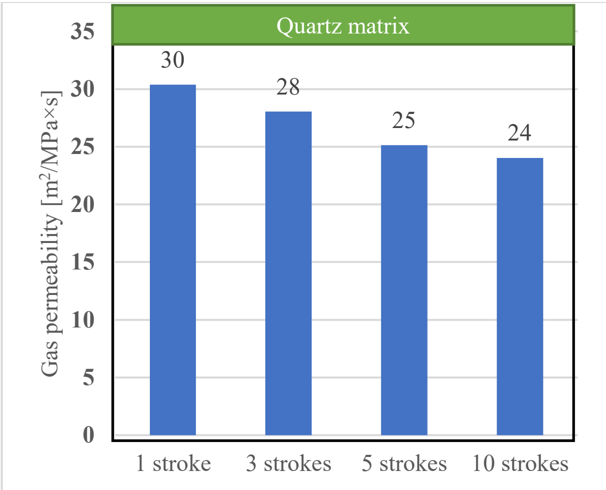


Fig. 11. Comparison of gas permeability test results for moulding sand with standard quartz matrix

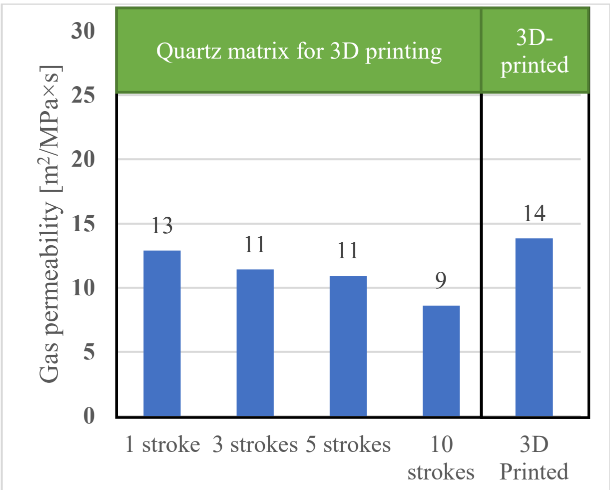


Fig. 12. Comparison of gas permeability test results for moulding sand with quartz matrix designed for binder jetting technology and for specimen that was printed using binder jetting technology

## 3.4. Hot distortion

In the casting process where sand cores and moulds are used, they are subjected to high temperatures. The degree of any deformation and/or distortion affects the final quality of castings. Deformation can result in surface and dimensional defects. Using the LRu-DMA device, tests were conducted on three specimens. Three sets of specimens for the tested sand matrices were produced by the self-cured moulding method using a resin and hardener that were designed for 3D printing [6, 7, 15]. Figure 13 presents a deformation graph over time.

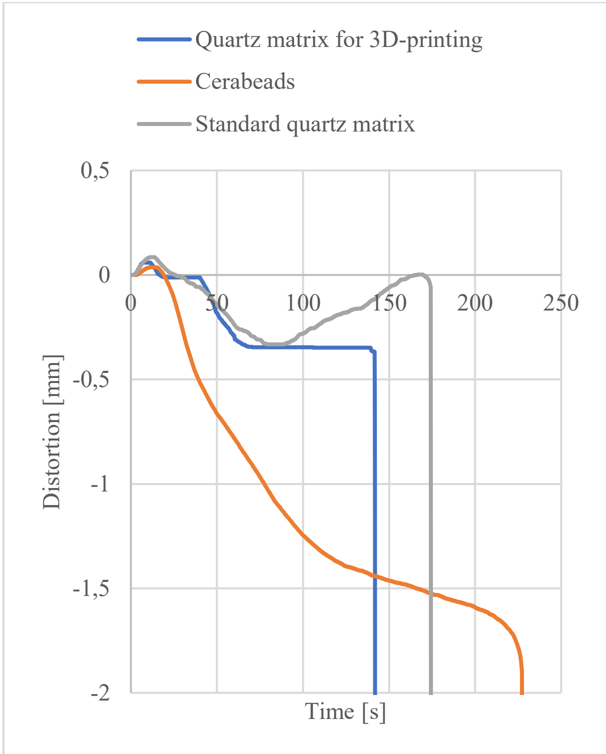


Fig. 13. Thermal deformation graph for specimens produced by self-cured moulding method with three different sand matrices

# 4. Conclusions and discussion

The use of an additive mould and core technology brings rapid prototyping and series production to a higher level. Not only is it possible to produce prototypes without the need for costly core boxes, but it is also possible to mass-produce moulds and cores of varying (and often complex) shapes. However, this poses challenges to which the authors of the article paid particular attention; these are strength, apparent density, permeability, and thermal deformation. These properties were investigated in terms of the influence of the sand moulding sand matrix.

Analysing the microscopic images, it is possible to see visual differences in the studied matrices. The quartz sand that was used in the additive manufacturing was characterised by small grain sizes and homogeneity. The standard quartz sand showed a greater variation in the grain sizes. The grains were visually larger in the standard quartz sand than they were in the matrix grains that were used in the additive manufacturing. The Cerabeads matrix grains were visually the largest; what drew our attention was their spherical shapes.

The microscopic images were complemented by sieve and laser analyses of the sizes of the tested matrices. The quartz sand for the additive manufacturing showed the greatest fractional homogeneity; the average grain size is 0.133 mm. The small grain size and the homogeneity of the fraction allowed for a uniform distribution on the printer's working field; however, this may have resulted in the reduced permeability of the printed casting mould. The grains of the standard matrix were less homogeneous; the average grain size was 0.240 mm (1.80 times larger than the matrix for AM). The average size of Cerabeads was 0.332 mm, which was 2.5 times larger than the matrix for AT and 1.38 times larger than the standard quartz matrix. It also had the least homogeneous fraction of the warps that were tested.

The chemical analysis showed that oxygen and silicon were the main matrix elements for AT (O: 56.5% Si: 43.5%) and the standard quartz matrix (O: 51%; Si: 46%). The standard quartz sand also consisted of 3% aluminium. The chemical composition of the Cerabeads matrix was different: 44% aluminium, 42.5% oxygen, and 13.5% silicon. The aluminium had a higher density (2.7 g/cm3) than the silicon did (2.33 g/cm3). The lower proportion of oxygen and the density of the aluminium indicates a higher matrix mass; this may result in the need for more bonding components to make the moulding compound.

The mouldings that were prepared using the Cerabeads matrix for the strength, apparent density, and permeability tests proved to be too brittle to conduct the tests. As mentioned in the chemical analysis, this may have been due to the insufficient resin content. However, it was possible to use the shapes to conduct the thermal deformation test.

The average flexural strength of the additively manufactured specimens was 3.297 MPa, which was 15% greater than those that were made using the self-cured moulding method with the standard quartz matrix (whose average strength was 2.804 MPa). It is worth noting that masses with the furfuryl resin that is used in 3D printing achieve high flexural strength. An analysis of the literature indicated that self-cured moulding masses with furfuryl resins have reached up to approximately 2.5 MPa [11, 16, 17, 18].

The obtained tensile strength results showed slight differences between the printed and self-cured moulding made specimens (1181 and 1102 MPa, respectively). The tested printed specimens also had 7% greater strengths. The literature reports that additively manufactured figure-eight specimens can reach strengths of above 1.5 MPa, whereas eighth-form specimens that are made using the self-cured moulding method achieve strengths that are below 1 MPa. The strength of a moulding compound is influenced by the matrix that is used and the correct proportions of the bonding components. A moulding compound with a quartz matrix with 1% resin and 0.3% hardener achieves values that are similar to binder jetting [13, 15].

Gas permeability is a property that allows the amount of gas flow through moulding sand to be determined. During the solidification process of a metal in a mould, gases can be formed by the evaporation of water, the decomposition of organic components in the sand, or the burning of admixtures in the moulding sand. Low gas permeability can cause several casting defects (such as porosity). The tests conducted on moulding sand indicated the significant effect of grain size on its gas permeability. self-cured moulding sand with a standard quartz matrix reached a value of more than 30.4 m2/(MPa×s) with a single impact pulse. In contrast, the gas permeability values of the printed specimens and the self-cured moulding mass with a dedicated AM matrix were 13.8 m2/(MPa×s) and 12.9 m2/(MPa×s), respectively (both after one impact pulse). The tests showed that gas permeability is loosely related to apparent density. The data in Tables 4 and 5 show the relationship between density and gas permeability. Despite the higher density of the mass with the standard quartz matrix, it had more than twice the permeability of the mass with the matrix that was dedicated to AM. This was due to the grain size of the matrices that were tested. A more important aspect is the porosity of the moulding mass; the larger the matrix grains, the larger the spaces between them that allow gas to flow [4, 5, 9, 13, 19, 20].

Exposing a moulding compound to high temperatures causes deformation. Figure 13 shows how the masses with the different matrices reacted to high temperatures. The thermogravimetric studies showed that both the AM-dedicated matrix and the standard quartz matrix were not overly prone to heat distortion. However, the small amount of the resin may cause it to burn out more quickly, making the specimens last a relatively short time when compared to the literature data [6, 7, 11, 13]. The shapes made from the Cerabeads matrix compound lasted the optimum amount of time but showed significant deformations; the reason for this may have been the density of the matrix that was discussed in the chemical analysis.

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# References

[1] Mostafaei, A., Elliott, A.M., Barnes, J.E., Li, F., Tan, W., Cramer, C.L., Nandwana, P. & Chmielus, M. (2020). Binder jet 3D printing – process parameters, materials, properties, and challenges. *Progress in Materials Science*. 119, 100707. DOI: https://doi.org/10.1016/j.pmatsci.2020.100707.

[2] Le Néel, T.A., Mognol, P. & Hascoët, J.-Y. (2018). A review on additive manufacturing of sand molds by binder jetting and selective laser sintering. *Rapid Prototyping Journal*. 24(8), 1325-1336. https://doi.org/10.1108/RPJ-10-2016-0161.

[3] Gibson, I., Rosen, D. W., Stucker, B., Khorasani, M. (2021). Additive manufacturing technologies. Cham, Switzerland: Springer. DOI:10.1007/978-3-030-56127-7.

[4] Upadhyay, M., Sivarupan, T., & El Mansori, M. (2017). 3D printing for rapid sand casting—A review. *Journal of Manufacturing Processes*. 29, 211-220. https://doi.org/10.1016/j.jmapro.2017.07.017.

[5] Lewandowski, J.L. (1997). *Materials for casting molds*. Krakow: Akapit. (in Polish).

[6] Jakubski, J. & Dobosz, S. M. (2007). The thermal deformation of core and moulding sands according to the hot distortion parameter investigations. *Archives of Metallurgy and Materials*. 52(3), 421.

[7] Ignaszak, Z., Popielarski, P. & Strek, T. (2011). Estimation of coupled thermo-physical and thermo-mechanical properties of porous thermolabile ceramic material using Hot Distortion Plus® test. *Defect and Diffusion Forum*. 312-315, 764-769. DOI:10.4028/www.scientific.net/DDF.312-315.764.

[8] Dańko, R. (2017). Influence of the matrix grain size on the apparent density and bending strength of sand cores. *Archives of Foundry Engineering*. 17(1), 27-30. DOI:10.1515/afe-2017-0005.

[9] Sundaram, D., Svidró, J.T., Svidró, J. & Diószegi, A. (2022). A novel approach to quantifying the effect of the density of sand cores on their gas permeability. *Journal of Casting & Materials Engineering*. 6(2), 33-38. DOI:10.7494/jcme.2022.6.2.33.

[10] Wisniewski, P., Sitek, R., Towarek, A., Choinska, E., Moszczynska, D., & Mizera, J. (2020). Molding binder influence on the porosity and gas permeability of ceramic casting molds. *Materials*. 13(12), 2735, 1-13. DOI:10.3390/ma13122735.

[11] Dobosz, S.M., Grabarczyk, A., Major-Gabryś, K. & Jakubski, J. (2015). Influence of quartz sand quality on bending strength and thermal deformation of moulding sands with synthetic binders. *Archives of Foundry Engineering*. 15(2), 9-15. DOI:10.1515/afe-2015-0028.

[12] Multiserw-Morek (2014) *Device for testing the strength of molding sands.* Retrieved October 15, 2023, from http://multiserw-morek.pl/products,urzadzenia_do_badania_mas_formierskich_i_rdzeniowych,urzadzenie_do_badania_wytrzymalosci_mas_formierskich-1. (in Polish).

[13] Bobrowski, A., Kaczmarska, K., Drożyński, D., Woźniak, F., Dereń, M., Grabowska, B., Żymankowska-Kumon, S. & Szucki, M. (2023). 3D Printed (Binder Jetting) Furan Molding and Core Sands—Thermal Deformation, Mechanical and Technological Properties. *Materials*. 16(9), 3339, 1-17. DOI:10.3390/ma16093339.

[14] Multiserw-Morek (2014) *Device for measuring the permeability of molding sands.* Retrieved October 15, 2023, from http://multiserw-morek.pl/products,urzadzenia_do_badania_mas_formierskich_i_rdzeniowych,urzadzenie_do_pomiaru_przepuszczalnosci_mas_formierskich. (in Polish).

[15] Multiserw-Morek (2014) *A universal device for testing hot-distortion phenomena and bending strength*. Retrieved October 15, 2023, from http://multiserw-morek.pl/products,urzadzenia_do_badania_mas_formierskich_i_rdzeniowych,uniwersalny_aparat_do_badania_zjawisk_hot-distortion_oraz_wytrzymalosci_na_zginanie. (in Polish).

[16] Kamińska, J., Puzio, S., Angrecki, M. & Łoś, A. (2020). Effect of reclaim addition on the mechanical and technological properties of moulding sands based on pro-ecological furfuryl resin. *Archives of Metallurgy and Materials*. 65(4), 1425-1429. DOI: 10.24425/amm.2020.133709.

[17] Major-Gabryś, K. (2019). Environmentally friendly foundry molding and core sands. *Journal of Materials Engineering and Performance*. 28, 3905-3911. DOI:10.1007/s11665-019-03947-x.

[18] Mitra, S., Rodríguez de Castro, A. & El Mansori, M. (2018). The effect of ageing process on three-point bending strength and permeability of 3D printed sand molds. *The International Journal of Advanced Manufacturing Technology*. 97, 1241-1251. DOI:10.1007/s00170-018-2024-8.

[19] Sundaram, D., Svidró, J.T., Svidró, J. & Diószegi, A. (2021). On the relation between the gas-permeability and the pore characteristics of furan sand. *Materials*. 14(14), 3803, 1-14. DOI:10.3390/ma14143803.

[20] Łucarz, M., Drożyński, D., Garbacz-Klempka, A., Jezierski, J., Bartocha, D., Wróbel, T., Kostrzewa, K., Feliks, E. (2022). Influence of weather conditions and mechanical reclamation on molding sand with alkali-phenolic binder for manganese cast steel. *Materials*. 16(1), 71, 1-18. DOI:10.3390/ma16010071.