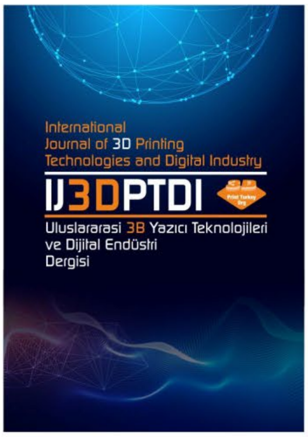

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INVESTIGATION OF MECHANICAL PROPERTIES OF SAND CASTING MOLDS PRODUCED BY BINDER JETTING 3D PRINTER

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ABSTRACT

The effective use of the additive manufacturing method in the casting industry plays an important role on rapid prototyping of casting samples. The production of negative-drafted and complex shaped casting parts, which cannot be produced with the classical modeling technique with sand-mold, can also be produced very easily with this method. On the other hand, it is very fast and effective, especially in terms of rapid production of prototype castings, which can be directly molded without the need for model production. In this study, a 3D Printer with binder jet technology was designed and produced. 3D Printer; It consists of 3 parts, the main chassis, the sand spreader and the spraying part. Sand mold samples were produced with different nozzle feed rates, different catalyst ratios and sand grain sizes. The consumables used in the production of sand molds are silica sand, furan resin and catalyst. The mechanical properties of the produced samples were determined by performing compression and gas permeability tests. The compressive strength was found in the range of 0,6471 MPa - 0,0472 MPa and the gas permeability was found in the range of 180 GP - 150 GP for the samples produced at different printing parameters. Afterwards, it was determined which of the produced samples were more suitable for a sand casting mold by comparing the results obtained from similar studies in the literature. In this study, a new printer was designed with direct spray technique without using cartridges and preliminary studies were carried out successfully.

Keywords: Binder Jetting, Casting, Additive Manufacturing, Sand Mold, Mechanical Properties, 3D Printer.

1. INTRODUCTION

A three-dimensional printer is a machine that produces three-dimensional solid objects from a three-dimensional CAD (Computer Aided Design) file prepared in the digital environment. These machines are similar in design to CNC (Computer Numeric Control) systems and work similar to them. Thanks to three-dimensional printers, models designed in digital environment can become objects that can be handled and examined in a short time. Three-dimensional printer technologies work with the technique of stacking layers on top of each other. But the methods of creating these layers may differ. The most widely known of these methods are those that form solid objects by melting plastic materials [1].

Process differences in 3D printer technologies are determined by the American Society for Testing and Materials (ASTM) depending on the machinery and materials used: 1- Vat Photopolymerization, 2- Material Extrusion, 3- Material Jetting, 4-Binder Jetting, 5- Powder Bed Fusion, 6- Directed Energy Deposition and 7- Sheet Lamination was made in seven main categories, including energy accumulation [2].

Today, 3D printers are used in a wide range of areas from aviation, automotive, medical and medical applications, molding applications, nano composite production, energy sector, construction industry, textile, food industry, education, art and hobby applications [3].

Ulkir et al. [4] investigated production of piezoelectric cantilever using MEMS-based layered manufacturing technology. The fabrication of the piezoelectric cantilever was made by Stereolithography (SLA), which is one of the additive manufacturing methods. This is an example of the uses of 3D printers.

There are several additive manufacturing methods used to produce casting sand molds. Some of these are Selective Laser Sintering, Stereolithography, Fused Deposition Modeling, Material Extrusion, Material Jetting, and especially Binder Jetting (3D Printing) are the most commonly used additive manufacturing methods for making casting sand molds and models [5].

The binder jetting process uses two materials; a powder based material and a binder. The binder acts as an adhesive between powder layers. The binder is usually in liquid form and the build material in powder form. A print head moves horizontally along the x and y axes of the machine and deposits alternating layers of the build material and the binding material. After each layer, the object being printed is lowered on its build platform. In Figure 1 show an example binder jetting method [6].

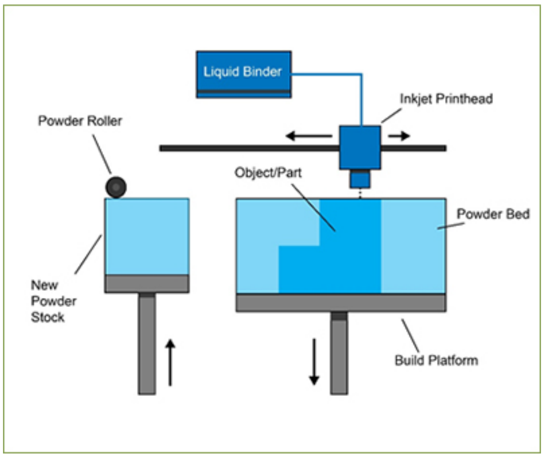

Figure 1. Binder jetting [6].

Due to the method of binding, the material characteristics are not always suitable for structural parts and despite the relative speed of printing, additional post processing can add significant time to the overall process.

As with other powder based manufacturing methods, the object being printed is self-supported within the powder bed and is removed from the unbound powder once completed. The technology is often referred to as 3DP technology and is copyrighted under this name [6].

The Binder Jetting is capable of printing a variety of materials such as metal, ceramics and sand. Some materials, such as sand, do not require additional processing. Other materials often require additional treatments such as curing or sintering. In the additive manufacturing method, solid layers are produced, there is no need for a separate mold because the parts are supported with loose powder in production, very large sized and complex shaped parts can be produced, no permanent thermal stresses are created on the parts produced because no heat source is used during production, and it is more cost effective than other additive manufacturing methods. Cast core and sand molds can be produced by the additive manufacturing method with binder jetting [5].

Cast core and sand molds can be produced by the additive manufacturing method with binder spraying. They are given in the Figure 2.

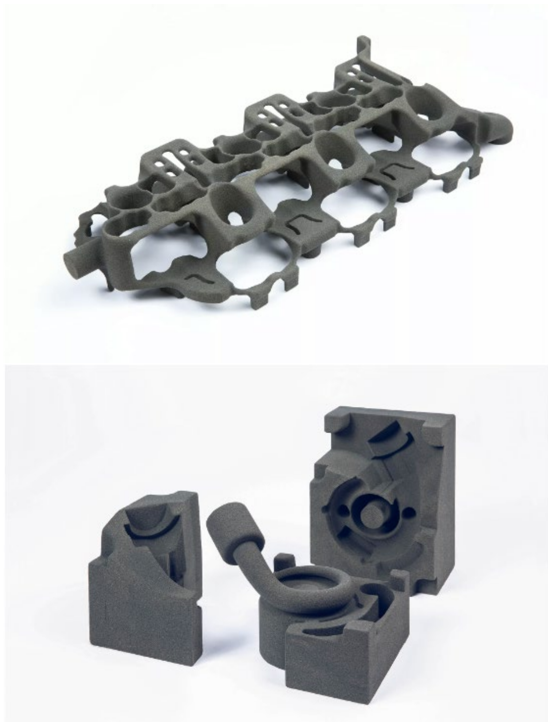

Figure 2. 3D printed sand casting cores and 3D printing molds for casting metal, respectively [7].

In this study, sand molds with different printing parameters that can be used for casting applications according to the binder jetting additive manufacturing method were produced and the mechanical properties of the produced molds were investigated. Thanks to this study, we aim to create the infrastructure for producing sand models ready for casting directly without using wood and aluminum models.

In this study, a 3D printer with a new spray nozzle system was produced with direct injection technique without using cartridges. Thus, sample production was provided in the 3D printer, which was produced with a more economical design.

2. MATERIAL AND METHOD

Sand mold samples were printed in a binder jetting 3D Printer, which was produced by designing a special spray system. Binder jetting 3D Printer is given in Figure 3. The building area dimensions of Binder Jetting 3D Printer are 320x345x300 mm. Axis motion speeds can be adjusted with the speed of the stepper motors used. Mach3 program was used as the software in the binder jet 3D printer.

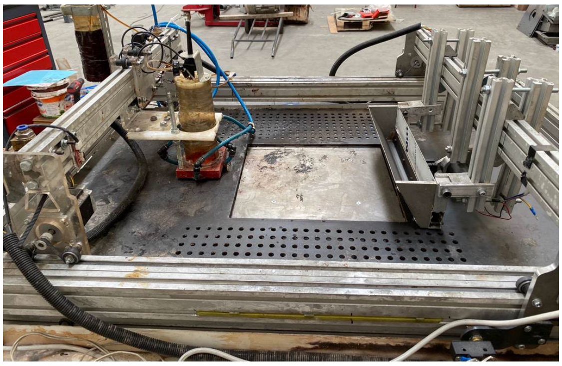

Figure 3. Binder jetting 3DP.

Afterwards, compression and gas permeability tests were carried out to determine the mechanical properties of the produced sand molds at different printing parameters. The work flow chart is given in Figure 4.

CAD-Three Dimensional Part Design

CAM and G Code Generating

Determining Printing Parameters
- Sand particle size,
- Catalyst ratio,
- Printhead feedrate

Sand + Catalyst Mixture

Sample Production
- Laying the sand+catalyst mixture
- Spraying the resin

Mechanical Tests
- Compression Test
- Gas Permeability Test

Figure 4. Work flow chart.

For the production of sand molds, sand and catalyst were mixed homogeneously at certain mixing ratios and filled into the vibrating sand chamber. In order to form the base layer and prevent the part from sticking to the part of the building area, the hopper was moved back and forth in the Y-axis direction to form 3 layers. Then, the spraying process was carried out by selectively moving the sprayer head on the sand layer for the CAD design, CAM and G codes of the sample to be produced. Afterwards, a sand spreading layer was laid and the sprayer part was moved again. These processes continued until the last layer was finished and the sample was produced. Afterwards, the sample was kept in the printer for a certain period of time to cure at room temperature, and then the sample was removed. Then, the mechanical properties of the 25x15 mm and 50x20 mm cylindrical samples, which were printed on a binder-jet 3D printer, were determined by performing the compression test and gas permeability test. Silica sand, furan resin and catalyst were used as consumables for the production of sand molds. Consumables are given in Table 1.

Table 1. The consumables.

Material	Specifications	Density(gr/cm3)
Foundry Sand	Silica Sand	2,65
Furan Resin	Furanol CS470	1,14-1,16
Furan Catalyst	Furanol Serter CS30-80	1,22-1,27

Sand particle size, catalyst ratio and printhead feedrate were used as printing parameters in sample production. The printing parameters are given in Table 2.

Table 2. The printing parameters.

Parameters	Specifications
Sand particle size	Fine sand (125-250 µm) Coarse sand (250-500 µm)
Catalyst ratio (by weight of sand)	%0,5-0,6-0,7
Printhead feedrate	F300-F400-F500 mm/min

3. EXPERIMENTAL RESULTS

25x15 mm cylindrical samples were printed for each parameter in the binder jet 3D printer. Compression test was performed on the printed samples with a special apparatus (loadcell) mounted on the CNC vertical processing machine. Precise results were obtained with the load and displacement data obtained from the CNC and recorded in the Labview Program. Two samples were tested for each parameter and the average was taken. Figure 5 shows the sample in the compression test. Test results are given in Figure 6-7.

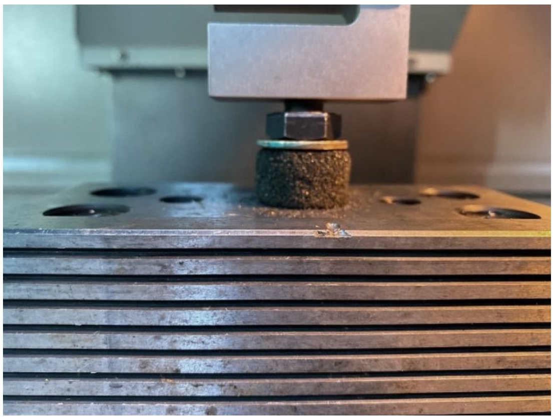

Figure 5. The sample in the compression test.

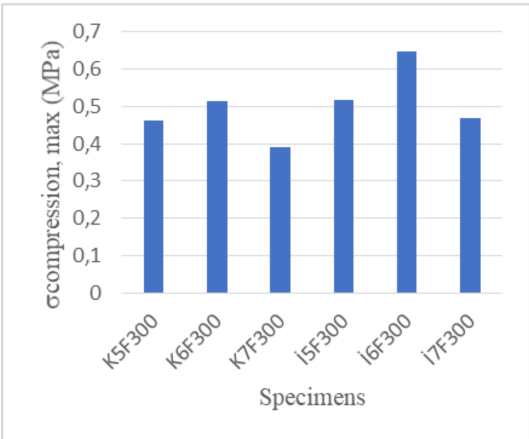

Figure 6. Coarse-fine particle sand size, different catalyst ratio and same printhead feedrate.

According to Figure 6, F=300 mm/min for coarse sand (250-500 µm). It is seen that the compressive strength increases as the catalyst ratio increases up to a certain amount at the printhead feedrate, and then it decreases. It is seen that the highest compressive strength is in the K6F300 sample with 0,6% catalyst ratio. This is thought to be due to the appropriate resin catalyst saturation ratio. That is, since the amount of resin in the structure is constant, the catalyst ratio that will react with the resin in that ratio is important. If the catalyst ratio is more or less than it should be, the compressive strength is lower than the maximum.

In addition, F=300 mm/min for fine sand (125-250 µm). It is seen that the compressive strength increases as the catalyst ratio increases up to a certain amount at the printhead feedrate, and then it decreases. It is seen that the highest compressive strength is in the İ6F300 sample with 0,6% catalyst ratio. This is thought to be due to the appropriate resin catalyst saturation ratio. That is, since the amount of resin in the structure is constant, the catalyst ratio that will react with the resin in that ratio is important. If the catalyst ratio is more or less than it should be, the compressive strength is lower than the maximum.

Guo et al. [8] show that when the resin content is constant, the tensile and flexural strengths of the sand mold initially increase and then decrease with the increase in the curing agent content. When the curing agent content is constant, the tensile and bending strengths of the sand mold increase with the increase in the resin binder content. According to the analysis, the main factors affecting the strength of the sand mold are resin binder content, hardener content and sand mold density. The higher the resin binder content, the higher the strength of the sand mold. The curing agent increases the degree of crosslinking of the resin binder, thereby increasing the strength of the sand mold. Since three-dimensional printing on the sand mold requires mixing the curing agent and the sand particles, the curing agent content directly affects the fluidity of the sand particles. The higher the hardening agent content, the lower the fluidity of the sand particles and the lower the compactness of the sand layer.

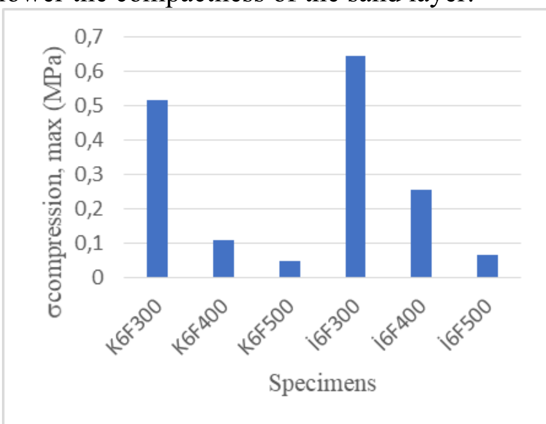

Figure 7. Coarse-fine particle sand size, same catalyst ratio and different printhead feedrate.

According to Figure 7, for coarse sand (250-500 µm) at a constant (0,6%) catalyst ratio, it is seen that the compressive strength decreases as the printhead feedrate increases. It is seen that the highest compressive strength is in the K6F300 sample, which has a feed rate of F300 mm/min. It is thought that the reason for this is that the increase or decrease in the print head advance speed affects the amount of resin. As the amount of resin decreases, the chemical bond between the sand particles decreases. Thus, the compressive strength also decreases.

In addition, for fine sand (125-250 µm) at a constant (0,6%) catalyst ratio, it is seen that the compressive strength decreases as the printhead feedrate increases. It is seen that the highest compressive strength is in the İ6F300 sample with a feed rate of F300 mm/min. It is thought that the reason for this is that the increase or decrease in the print head advance speed affects the amount of resin. As the amount of resin decreases, the chemical bond between the sand particles decreases. Thus, the compressive strength also decreases.

Khandelwal et al. [9] on the other hand, the effects of sand grain size, binder percentage and curing time on mechanical properties as well as dimensional changes of chemically oven-free, chemically bonded molds and cores were investigated by laboratory experiments. As a result of the study, the compressive strength of the mold properties for different test parameters was found to be in the range of 4,08 kg/cm2-16,16 kg/cm2 (0,400 MPa- 1,584 MPa). Optimum mold properties were obtained in 2,4% binder, 40 GFN grit and after 4 hours of curing, and optimum compressive strength of 14,80 kg/cm2 (1,451 MPa) was obtained.

Motoyama et al. [10] examined the validation of thermal stress analysis, including the furan sand mold used to predict the thermal stress in castings. In addition, in the study, the compression test result graph of the sample produced using silica sand and 1,2% furan resin was given and it was seen that the maximum compressive stress was in the range of 0,8-1,0 MPa.

Said et al. [11] investigated the optimization of the mold composition to improve the quality of sand casting. They aimed to optimize the composition of silica sand, bentonite, water and coal dust in green sand to reduce defects in foundry products. In the study, the effect of parameters on compressive strength was investigated. As a result of the study, the green compression strength of the samples was determined in the range of 30-100 kN/m2 (0,03-0,1 MPa).

According to the literature research, it has been seen that many printing parameters affect the compression test results. When the compression test results obtained according to the selected compression parameters in our study were examined, it was seen that it was lower than the results of other studies in the literature. The reason for the low compression strength is thought to be due to the use of sand, resin and catalyst used in traditional casting in production with a 3D printer. However, when we look at the literature as the green compression strength of the traditional casting sand mold, it shows that the compression strength result of the samples produced in the study is sufficient for the sand mold.

50x20 mm cylindrical samples were printed for each parameter in a binder-jet 3D printer. Gas permeability test was performed on the printed samples. Gas permeability results were found for a 50x50 mm cylindrical sample using the equation below, since the test sample is 50 mm in diameter and 50 mm high, and the gas permeability measuring device gives the results according to the standards accepted by AFS (American Foundry Association) for gas permeability. Two samples were tested for each parameter and the average was taken. Calculation of gas permeability is given in Equation (1). Figure 8 shows the sample in the gas permeabilitiy test and the samples produced. The test results are given in Figure 9-10.

$$GP = V.H / A.P.t \qquad (1)$$

In this place; GP: Gas permeability number, V: The volume of air passing through the test sample (cm^3), H: Height of test specimen (cm), A: Cross-sectional area of the test specimen (cm^2), P: air pressure (gr/cm^2), t: Time for air to pass through the test sample (min).

Figure 8. K7F300 gas permeability sample and the sample in the test tube, İ6F400 compression test sample, respectively.

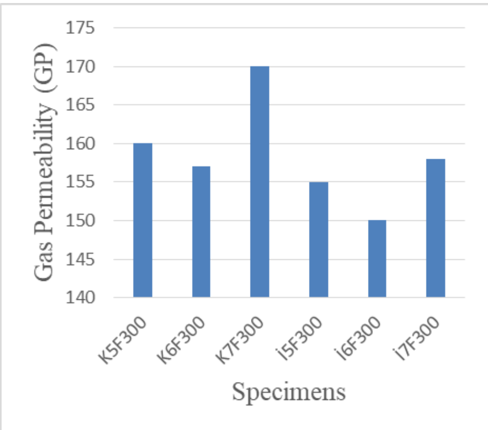

Figure 9. Coarse-fine particle sand size, different catalyst ratio and same printhead feedrate.

According to Figure 9, it is seen that the gas permeability decreases as the catalyst ratio increases up to a certain amount at the printhead feedrate of F=300 mm/min for coarse sand (250-500 µm), and then increases. It is seen that the highest gas permeability is in the K7F300 sample with 0,7% catalyst ratio. This is thought to be due to the appropriate resin-catalyst saturation ratio. That is, since the amount of resin in the structure is constant, the catalyst ratio that will react with the resin in that ratio is important. If the catalyst ratio is more or less than it should be, the gas permeability is higher than the minimum.

In addition, for fine sand (125-250 µm), it is seen that gas permeability decreases as the catalyst ratio increases up to a certain amount at the printhead feedrate of F=300 mm/min and then increases. It is seen that the highest gas permeability is in the İ7F300 sample with 0,7% catalyst ratio. This is thought to be due to the appropriate resin-catalyst saturation ratio. That is, since the amount of resin in the structure is constant, the catalyst ratio that will react with the resin in that ratio is important. If the catalyst ratio is more or less than it should be, the gas permeability is higher than the minimum.

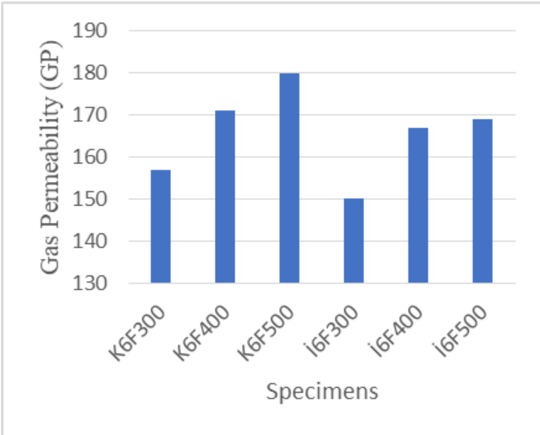

Figure 10. Coarse-fine particle sand size, same catalyst ratio and different printhead feedrate.

According to Figure 10, it is seen that the gas permeability increases as the printhead feedrate increases at a catalyst rate of 0,6% for coarse sand (250-500 µm). It is seen that the highest gas permeability is in the K6F500 sample with a feed rate of F500 mm/min. It is thought that the reason for this is that the increase or decrease in the printhead feedrate affects the amount of resin. As the amount of resin decreases, the chemical bond between the sand particles decreases. Thus, the gas permeability also increases.

In addition, for fine sand (125-250 µm), it is seen that gas permeability increases as the printhead feedrate increases at a catalyst rate of 0,6%. It is seen that the highest gas permeability is in the İ6F500 sample with a feed rate of F500 mm/min. It is thought that the reason for this is that the increase or decrease in the printhead feedrate affects the amount of resin. As the amount of resin decreases, the chemical bond between the sand particles decreases. Thus, the gas permeability also increases.

Coniglio et al. [12] they calculated the gas permeability of the sand mold samples produced from silica sand and furan binder. In the production of the molds, average sand particle size (140 μm), activator content (0.18% of sand weight), magnesium inhibitor (0,4% weight of sand), heating temperature (305 K) were kept constant. Samples were produced with the values of sand spreader speed (between 0,130-0,286 $m.s^{-1}$), sand layer thickness (280 μm), printing resolution (120-140 μm). According to the test results, the gas permeability, which is an important property of the sand mold for casting, varied within a wide range from 70 to 160 GP.

Martinez et al. [13] on the other hand, sand molds were produced by choosing round or round-cornered silica sand with a grain fineness number (GFN) of 65 and six different binder deposition settings with a binder content between 1% and 3%, and gas permeability was calculated. Permeability values at different resin ratios were found to be approximately 130-190 AFS. The permeability measurements confirm the hypothesis that increased difficulty in degassing will occur with the increase in binder concentration during casting.

According to the literature research, it was seen that many printing parameters affect the gas permeability test results. In this study, when the gas permeability test results obtained according to the selected printing parameters were examined, it was seen that they were in parallel with the results of other studies in the literature.

4. CONCLUSION

Sand mold production for complex shaped, reverse angled and especially prototype products is important for the casting industry. In recent years, the use of additive manufacturing has increased in the casting industry. In particular, the production method with a binder-jet 3D printer is one of the areas open to development for the casting industry. For this reason, this study is important for the production of sand molds in the casting industry. In this study, cylindrical samples were produced as the mechanical properties of the produced sand molds were investigated.

The study shows that for both sand grain size ranges (coarse-fine) and F=300 mm/min. at the printhead feedrate. It is seen that the compressive strength increases as the catalyst ratio increases up to a certain amount at the printhead feedrate, and then it decreases. It is seen that the highest compressive strength is in the İ6F300 sample with 0,6% catalyst ratio. This is thought to be due to the appropriate resin catalyst saturation ratio. That is, since the amount of resin in the structure is constant, the catalyst ratio that will react with the resin in that ratio is important. If the catalyst ratio is more or less than it should be, the compressive strength is lower than the maximum.

In Addition, for both sand grain size ranges (coarse-fine) and at a constant (0,6%) catalyst ratio. it is seen that the compressive strength decreases as the printhead feedrate increases. It is seen that the highest compressive strength is in the İ6F300 sample, which has a feed rate of F300 mm/min. It is thought that the reason for this is that the increase or decrease in the print head advance speed affects the amount of resin. As the amount of resin decreases, the chemical bond between the sand particles decreases. Thus, the compressive strength also decreases.

It is seen that the gas permeability decreases as the catalyst ratio increases up to a certain amount at the printhead feedrate of F=300 mm/min for both sand grain size ranges (coarse-fine), and then increases. It is seen that the highest gas permeability is in the K7F300 sample with 0,7% catalyst ratio. This is thought to be due to the appropriate resin-catalyst saturation ratio. That is, since the amount of resin in the structure is constant, the catalyst ratio that will react with the resin in that ratio is important. If the catalyst ratio is more or less than it should be, the gas permeability is higher than the minimum.

In Addition, it is seen that the gas permeability increases as the printhead feedrate increases at a catalyst rate of 0,6% for both sand grain size ranges (coarse-fine). It is seen that the highest gas permeability is in the K6F500 sample with a feed rate of F500 mm/min. It is thought that the reason for this is that the increase or decrease in the printhead feedrate affects the amount of resin. As the amount of resin decreases, the chemical bond between the sand particles decreases. Thus, the gas permeability also increases.

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