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Effects of used sand recycling on the foundry properties of three-dimensional printed sand moulds and cores

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Abstract. Sand casting is one of the important metal casting processes that involves hard labour and patternmaking to produce sand moulds. However, it has evolved considerably since the adoption of rapid sand casting, a type of additive manufacturing. This advancement has reduced costs and improved lead time by eliminating tooling. Nevertheless, there are still some challenges that are being experienced, such as the recyclability of the waste sand produced by the foundry. With high costs of virgin sand and sand disposal, reusing the used sand is important. The objective of this paper is to evaluate the feasibility of adding new sand to the used sand during rapid sand casting. The results indicate that the semi-activated sand collected from the hopper can be reused to produce sand moulds and cores if new sand is added to it.

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1 Introduction

Sand casting is the manufacturing process whereby a molten material is poured into a sand mould cavity to produce a desired part [1]. Previous studies have found that moulding is a time-consuming process that requires skilled craftsmen to create each part of the pattern perfectly, taking into consideration the path of the molten metal, shrinkage allowances and the solidification process [2]. Therefore, in order to improve the lead times and costs while maintaining the quality of the castings, the foundry industry has introduced additive manufacturing.

One of the processes used to make sand moulds and cores is binder jet printing, a three-dimensional (3D) sand printing technology that uses binder polymers to bind particles together into a physical 3D model. This is used to produce either finished products, or moulds into which alternative materials can be poured. Recent 3D printers used for rapid sand casting include ZCast, ExOne and Voxeljet. The printers use a layer-by-layer printing process to create parts with complex internal and external geometries. The layers are defined by slicing the computer model from which the part will be constructed into thin sections. The sand particles, 140–200 µm, mixed with an activator, are bonded together by a binder, and solidified into a 3D shape [3]. The binder jet printing is best explained by Figure 1 below.

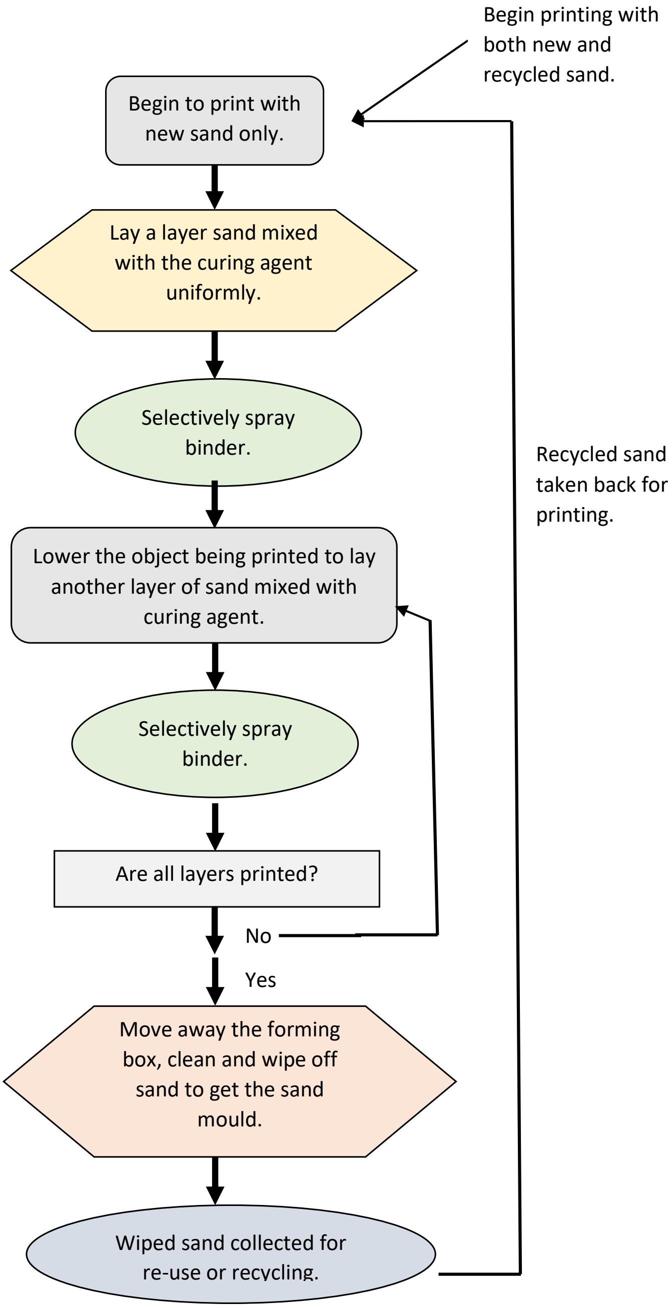

Fig. 1. Flow chart of 3D sand mould printing [4]

After printing the sand moulds and cores, any loose sand is carefully removed and disposed of or could be recycled and reclaimed [5]. The reclamation processes are normally mechanical and thermal reclamation. These reclamation processes are done after the moulds have been used during casting to carry the molten metal all the way through solidification.

Mechanical reclamation methods involve breaking up of lumps, separation of metals from sand particles, sieving and classifying the sand grains in order to remove the binder from the surface of the grains, cooling of sand grains to usable temperature. This effectively eliminates a substantial portion of the weakened or partially burnt binder. The degree to which the sand has been heated directly correlates with the efficiency of the sand reclamation process and up to 90% of reclaimed sand may be used. Motlhabane et al. [5] have studied the mechanical reclamation of the wasted sand generated by the 3D Printing. It was found that it could produce renewed sand complying with the specification of the Original Equipment Manufacturer, which is the Voxeljet VX1000. On the other hand, thermal reclamation involves heating the waste sand to about 800ºC in the oxidizing atmosphere in order to burn off the binder present on the sand particles. This method is capable of reclaiming 100% of the bonded sand [5][6][7]. However, during three-dimensional printing, the sand particles barely come in contact with the binder. This is because the binder is only sprayed on the geometry of the part to be printed [8]. Therefore, even though the loose sand removed from the printed part has the amount of resin present on the surface of the particles, the resin is inactive, which allows 2% of the resin to be added to the process during recycling.

The above reclamation methods, together with recycling, reduces the amount of used sand discarded, thus reducing the detrimental economic and environmental effects. The availability of dumping ground for used chemically bonded sand is becoming difficult day by day. The dumped sand, which is toxic, pollutes the atmosphere, as well as the ground water and soil resulting in long lasting harm to plants, human health, and the environment. Foundries continue to lose money buying new sand and paying for transport to disposal sites and the cost of disposal. Previous research has found that casting using sand moulds accounts for around 80% of global casting [9]. Therefore, recycling and reusing the sand is necessary because it reduces foundry costs, and environmental and health issues.

During recycling, a portion of new sand is added to the used sand to create the moulds and cores with the properties too close to the quality of the cores produced with new sand. Before adding the new sand, the waste sand is usually subjected to a low level of primary attrition which only breaks the lumps and removes some of the binder from the surface of the sand grains. In the casting process, waste sand can be recycled and reused multiple times until it becomes unreclaimable and is then discarded. Waste sand becomes unreclaimable when the residual levels of the furan resins, curing agents and other impurities that coat or penetrate the sand grains, increase to an unacceptable level. Large amounts of binder increase the amount of gas production during casting, resulting in poor quality casting due to defects [10]. Therefore, adding new sand to the waste sand dilutes the amount of impurities, such as binders, catalysts and curing agents in order to maintain the quality of the sand. As sand is repeatedly recycled, it breaks down, resulting in increased amounts of fine particles, which decreases the porosity of the moulds and cores. Adding new sand to the waste sand maintains the correct grain size distribution.

Nyembwe et al. [11] investigated the physical properties of waste sand produced using a Voxeljet VX1000 three-dimensional printer and traditional hand ramming. The sand test specimens produced were tested for tensile strength, bend strength, friability, hardness, surface finish and density. They mixed silica sand made up of 60% virgin sand and 40% used sand. Their tests were based on cured and uncured specimens. The results revealed that bend strength and tensile strength of uncured specimens produced by a three-dimensional printer were lower than the hand-rammed specimens. However, under cured condition, the strengths were equal. They also found that the hardness was the same, but the friability of 3D printed specimens was higher than that of hand-rammed specimens. Based on their results, they concluded that the post processing of 3D printing by heating changed the physical properties significantly. It improved the bend strength, tensile strength, and friability of the material, while the hardness remained unchanged.

It is important to critically balance the mould strength, porosity, and permeability to promote handling strength and off-gassing respectively. Factors such as sand particles, binder viscosity, droplet size, binder saturation and printing layer thickness affect the mechanical properties and surface quality of the 3D printed moulds and cores. For instance, particles that are too small do not spread properly due to a lack of flowability, or the press roller may over press the powder. On the other hand, if the grains are too large, they lack good strength, resulting in most parts lacking sufficient strength. Therefore, the correct sand particle size and shape should be utilized in order to achieve good strength and permeability [12].

The aim of this paper is to effectively optimize and analyze the effects of adding different ratios of new sand to used sand in order to promote the recyclability of 3D printing, which will increase its sustainability and reduce costs associated with purchasing new sand.

2 Methodology

This section explains the experimental work of the study. Figure 2 provides the steps of the methodology. It consisted of Sand Sampling, Sand Characterisation, Sand Dilution and Sand Testing.

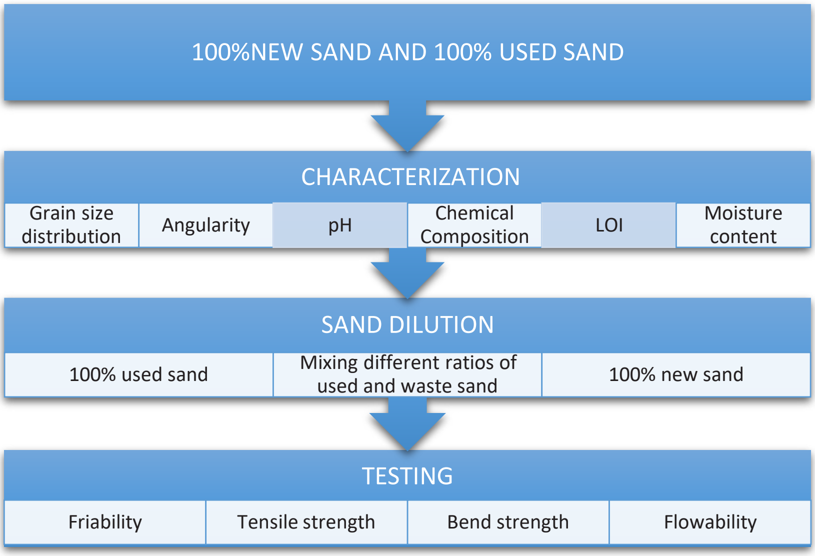

Fig. 2. Experimental procedure

2.1 Characterisation

Acharya et al. [13] and Nyembwe et al. [14] mentioned that it is important to characterize the sand before testing for foundry properties. Although there are several tests available for sand characterization, the most important tests to determine the performance and properties of furan no-bake, sand are: sieve analysis, LOI, pH tests, strength tests, acid demand value, chemical composition, bulk density, and grain shape. The Characterisation procedure to determine these properties follow the recommendations made by the American Foundrymen Society (AFS)[15].

Other tests include X-ray fluorescence spectroscopy (XRF) and scanning electron microscope analysis (SEM), which determines the chemical composition of the moulding material [16] and the shapes of the sand particles respectively. The chemical composition gives the reflection of the cleanliness of the material as well as the sense of how much silica is present in the moulding material. High refractory materials produce sand moulds which can withstand high temperatures during pouring without melting and mixing with the casting. While the shape of the material affects the amount of the resin and contributes to the strength of the material. The best foundry sand has round sand grains with medium to high sphericity which will give good strength with low additions of resin [17].

2.1.1 Grain size distribution/grain fineness number

Good grain distribution is needed to produce high quality sand moulds. The grain size distribution controls both the surface area and the packing density of the mould, in addition, it also determines the amount of resin and catalyst to be added during the printing of sand moulds and cores. To determine the grain fineness number, 100 g of sand was passed through several sieves which were assembled in an ascending order with the pan placed at the bottom and a lid on top. The properly stacked sieves were placed on the mechanical shaker, with the shaker's lid tied to the sieves to ensure that the sieves did not come loose during the vibration process. The mechanical shaker was set to shake/vibrate for 15 minutes. After 15 minutes of sieving the sand, the sieves were removed from the shaker and the retained sand in each sieve was weighed separately and recorded.

2.1.2 The grain shapes

The grain shape contributes to the amount of sand surface area. If the surface area of the sand increases, the amount of bonding material must also increase for the sand to be bonded properly. The grain shapes are either round, compound, angular or subangular. The angular grain shapes have the greatest surface area and therefore need more bonding material while the round grain shapes have the lowest surface area, which uses less bonding material. The grain shapes were determined by SEM (scanning electron microscope) analysis in secondary electrode (SE) mode.

2.1.3 The pH

The chemical property is determined by the pH value of the sample which gives the water-soluble level of alkalinity or acidity of the sand. A pH close to neutral, which is 7, means that the sand is less reactive, and is the best for moulding and core production. The pH of both sands was tested before the sample preparation took place. The pH was obtained by mixing 25 g of sand with 100 ml of distilled or deionized water adjusted to a pH of 7. The sand and water were stirred for five minutes using the magnetic stirrer. The pH of the mixture was then measured, using the pH meter. The sand that had been used for 3D printing will have a lower pH because it is precoated with an acid activator.

2.1.4 Chemical composition

The chemical composition indicates the refractoriness of the sand. The higher the percentage of silica present in the sand, the higher the refractoriness. Sand samples can be sent to a certified laboratory for analysis by an X-ray fluorescent spectrometer.

2.1.5 Loss on ignition (LOI)

Loss on ignition is a procedure used to measure the amount of binder and impurities present in the sample. It is represented by the amount of combustible materials that have been burnt off from the sample. The LOI was determined by placing 10 g of sand into six crucibles. The crucibles containing the sand were then placed inside the muffle furnace and heated for two hours at 1000 °C. After heating, the total weight was taken and the LOI was calculated using equation 1.

$$\%\mathrm{LOI}=(\text{initial weight-final weight})/(\text{initial weight})\times 100 \tag{1}$$

2.1.6 Moisture content

Moisture content is the amount of water present in the sand. This was determined by transferring 100 g of sand to each pan and heating the pans with the sand in the furnace for two hours at 105 °C. After cooling, the sand samples were weighed again, and the moisture content was determined using equation 2.

$$\%MC=\frac{initial\,weight-final\,weight}{initial\,weight}\times 100 \tag{2}$$

2.2 Sand dilution

Table 1 below summarizes the dilution ratios used during recycling of the waste sand together with the foundry properties tested after the recycling of each sand type.

Table 1: Summary of dilution rates for foundry properties testing

Sand Type	Foundry Properties
100% used sand	• **Friability** • **Bend strength** • **Tensile strength** • **Flowability**
80% used sand + 20% new sand	
60% used sand + 40% new sand	
40% used sand + 60% new sand	
20% used sand + 80% new sand	
100% new sand	

To produce the laboratory test specimens, 3 kg of used sand was poured into a 5 kg laboratory sand mixer and the mixer was started. While mixing, 2% furan resin, as recommended by Voxeljet process, was added slowly to avoid spillage. The furan resin and sand were mixed for 5 minutes, once all the resin had been added. Immediately after mixing, the moulding sand was transferred into the appropriate wooden patterns and hand-rammed for tensile strength, bend strength and friability testing specimens. The sand specimens were left to set for 24 hours at room temperature before putting them into the oven to bake at 110 °C for two hours to eliminate the excess moisture which may be present on the sand samples. The samples were then allowed to cool to room temperature before being tested.

The above procedure was used with the 80% used sand + 20% new sand, 60% used sand + 40% new sand, 40% used sand + 60% new sand and 20% used sand + 80% new sand, and lastly 100% new sand. Five specimens were produced from all sand samples for each test, this enabled us to get the average results for each test.

2.3 Testing for foundry properties

The laboratory specimens were tested for tensile strength, bend strength, flowability and friability. The specimens of the waste sand and diluted sand were compared to specimens produced using 100% new sand.

2.3.1 Friability

The friability test determines the resistance of the mould and core surface erosion during the pouring of molten material.

Fig. 3. Friability patterns with friability tester on the right

Two specimens were first weighed and put inside the rotating cylindrical screen with the wire mesh cage as shown in figure 3. The specimens were rotated, scratching against each other, for 5 seconds. After rotating, the sand samples were weighed for the second time, and the friability was calculated using equation 3. High moulding sand friability means the bonded sand is not strong enough to withstand sand erosion and, in addition, could result in sand inclusion during casting.

$$\%F=(\text{initial weight-final weight})/(\text{initial weight})\times 100 \qquad (3)$$

2.3.2 Bend strength and tensile strength

Strength determines if the mould or core can withstand the handling operations and metallostatic pressure during casting. These are the bend and tensile strengths, and they are measured using a universal strength machine.

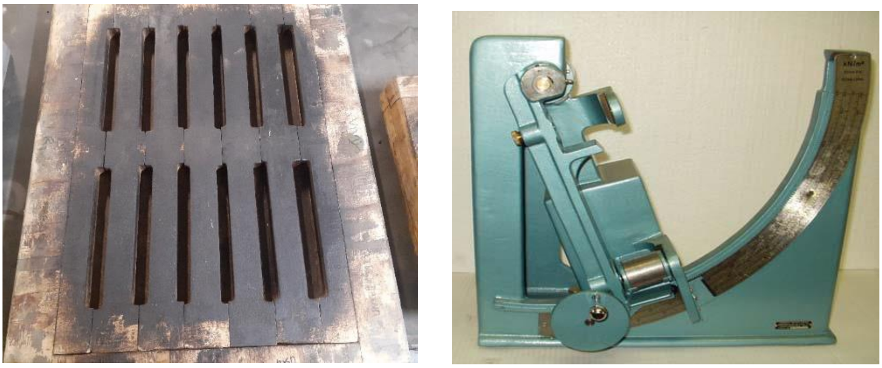

Fig. 4. Bend strength pattern with bend strength tester on the right

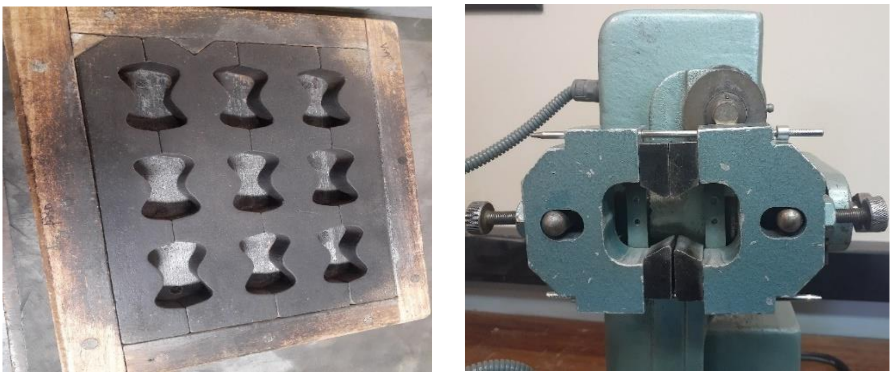

Fig. 5. Tensile strength pattern with tensile strength tester on the right

2.3.3 Flowability

The sand hopper of the Voxeljet VX1000 has a small opening at the bottom through which sand flows to the build chamber. The flowability is determined by measuring the angle of repose which is measured from the horizontal base of the sand pile, as shown in Figure 6. The sand sample has to meet the specifications of the recoater in order to avoid defects. Therefore, flowability is used to validate if the coated sand will be suitable for use in the Voxeljet VX1000 recoater system.

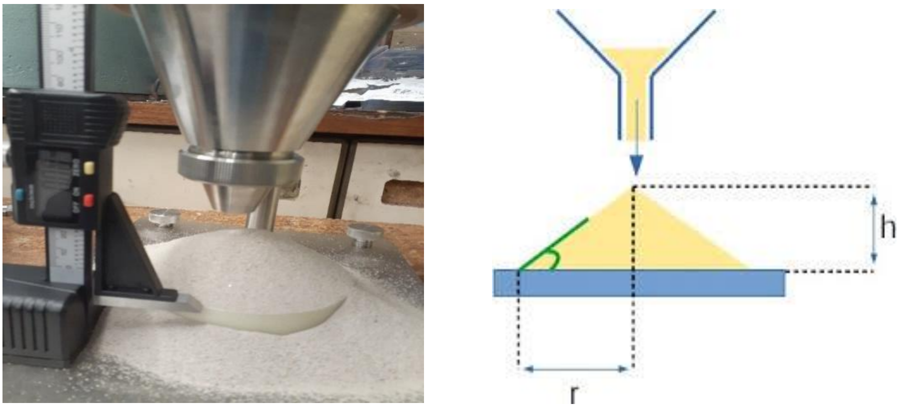

Fig. 6. Flowability tester with the method for calculating the angle of repose on the right.

Table 2 shows the relationship between the angle of repose and the flowability [18].

Table 2: Flowability

Flowability	Angle of repose (°)
Excellent	**25–30**
Good	**31–35**
Fair	**36–40**
Passable	**41–45**
Poor	**46–55**
Very poor	**56–65**
Extremely poor	**>66**

3 Results and Discussion

This section presents the test results of the study. It explains in detail the results obtained during the characterization and the testing of the foundry properties.

3.1 Characterisation results

Table 3 summarises the Characterisation test results. The trends and the discussion are presented in the sections below.

Table 3: Summary of characterization results

Sand Parameter	**Used Sand**	**80%W + 20%V**	**60%W + 40%V**	**40%W + 60%V**	**20%W + 80%V**	**Virgin Sand**
AFS GFN	66.57	64.72	64.24	61.42	56.64	49.27
LOI (%)	0.7	0.65	0.6	0.54	0.4	0.4
%SiO_2	85.81					85.25
%Fines	7.46	7.46	7.76	5.54	2.84	0.06
pH	3.53	3.37	3.13	2.98	2.84	2.79

3.1.1 Grain size Distribution/ Grain Fineness Number

Figure 7 shows the grain size distribution which illustrates the distribution profile of the addition rates together with the 100% new and used sand. It also influences the mould packing density by controlling the permeability and the strength of the moulds. Coarse grains increase the permeability of the sand moulds which may result with metal penetration and poor surface finish, while finer grains give better surface finish but decreases the permeability of the sand moulds which might results with gas defects in castings. As it can be seen in figure 7, the sand distribution of the used sand together with the dilution ratios appears to be widely spread as compared to the new sand which is narrowly spread. Van Tonder et al. [18] mentioned that most foundries prefer sand in which 10% or more of the sand sample is retained in the 3 to 5 individual screens. The figure show that all sand types have more than 10% of the sand retained in 5 screens, meaning that they meet the requirements although it also depends on the preference of the foundry. The moulds and cores produced from these sand types will have almost the same surface finish although the ones produced using the new sand will have a rougher surface finish than the one produced from the used sand.

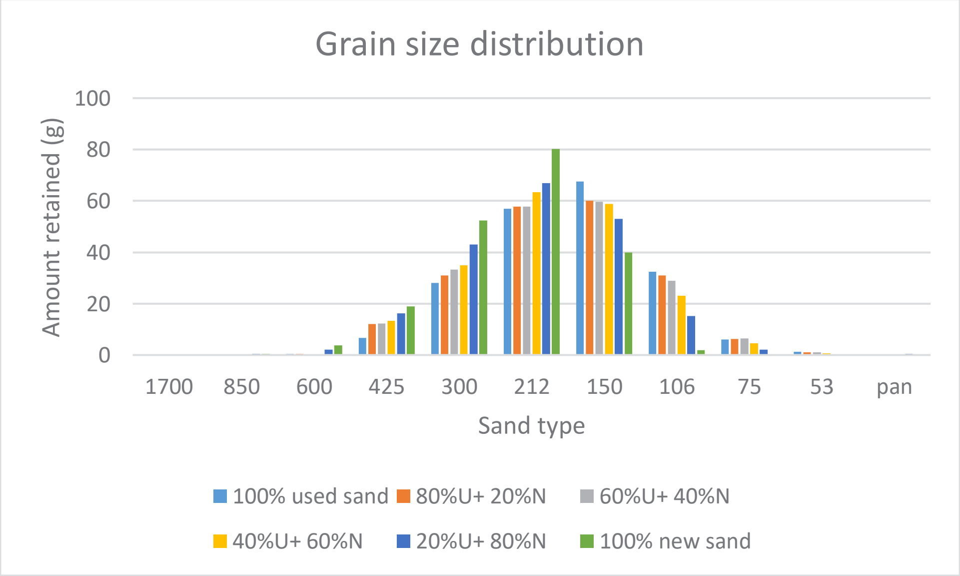

Fig. 7. Grain size distribution

Figure 8 shows the grain fineness number of used sand, addition ratios and new sand. The grain fineness number of the used sand is visibly higher, with a value of 66,57 and decreases with the addition of new sand. The high grain fineness number means that the refractory material is finer, and the lower grain fineness number means that the refractory material is rougher. This means that used sand is finer than the new sand, meaning that used sand will produce moulds and cores with smoother surface finish as compared to the moulds produced using 100% new sand. This agrees with the distribution profile in figure 8. Van Tonder et al. [18] stated that that foundries have the option of specifying the grain fineness number range in order to obtain a specified surface finish, although the grain fineness number which ranges between 50 and 60 is most common because it requires less binder and offers good surface finish.

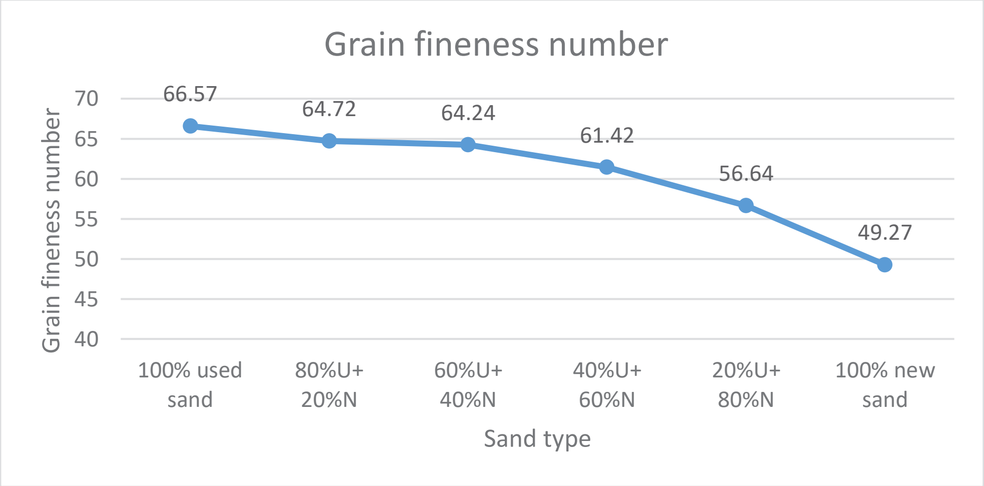

Fig. 8. Grain fineness number

3.1.2 Grain shapes

Figure 9 shows the grain shapes of both the new sand and the used sand respectively. As it can be seen, the grain shapes of both sands are a mixture of subangular and round shapes. Given that spherical grains require less binder and have a smaller surface area, these sand grains provide good flowability and permeability. In addition, the presence of subangular grains with large surface area has high binding ability which will results with good compaction and good strength. The grain sizes of the new sand are visibly larger than the grains of the used sand which concurs with the grain fineness number in figure 8.

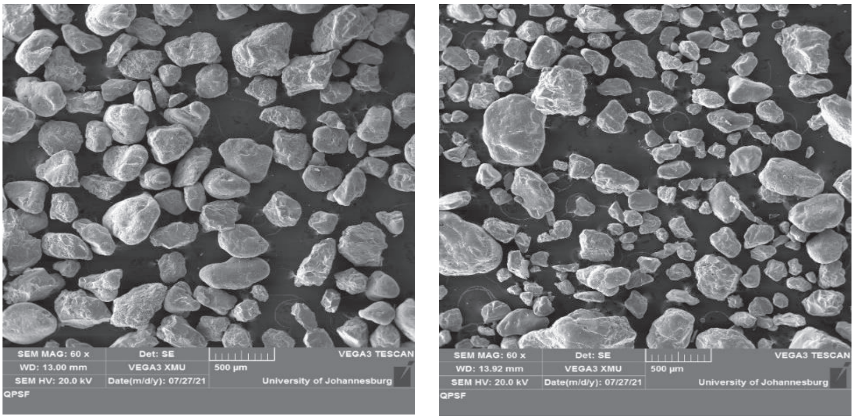

Fig. 9. Scanning Electron Microscope Micrograph: with new sand on the left and used sand on the right**.**

3.1.3 Sand pH

Figure 10 indicates the pH of the sand samples. The pH of the used sand was found to be 3,53 which is higher than the specification of 3,4 and decreased with the addition of new sand. The low pH promotes hardening and has a strong effect on the curing rate. Moulds produced from the used sand would be expected to take longer to cure as compared to the moulds produced from the new sand. The addition of new sand to the used will enhances the curing rate and consequently promote strength.

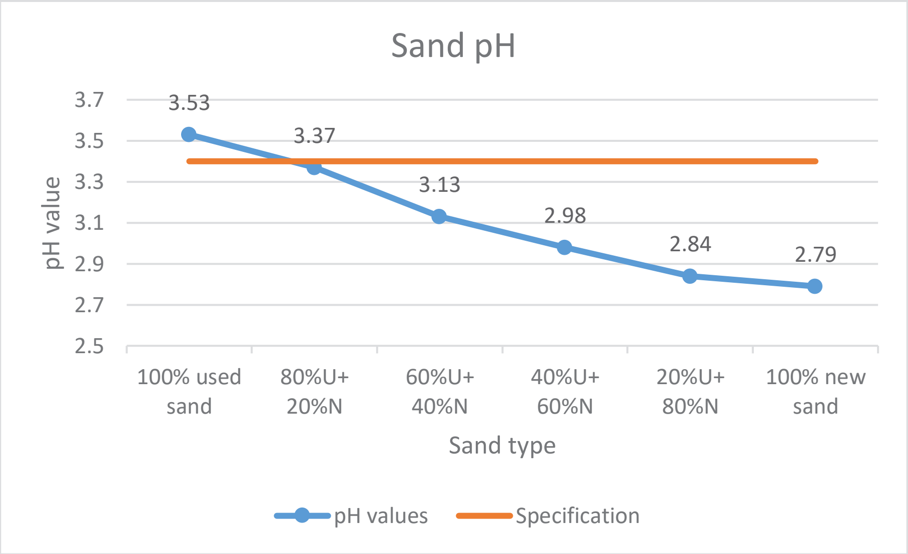

Fig. 10. Sand pH

3.1.4 Chemical composition

Chemical composition has a direct effect on the pH and the sintering temperature of the moulding material. The higher the silica content, the more refractory of the sand. As indicated in table 3, both the used sand and the new sand have the silica content of 85, 81 and 85, 25 respectively. This means that they will have the same effect on the protection of the mould wall since the refractory of silica sand is directly proportional to silica content.

3.1.5 Loss on ignition

Figure 11 shows the LOI of the sand samples which measures the amount of volatiles such as the combined mass of water, resin, catalyst, and volatile impurities. High values of loss on ignition means that the material had high impurities. In this case, the used sand has a high loss on ignition of 0,70 and it decreases with the addition of new sand which the lowest LOI of 0,40. This could be explained by the fact that the used sand has the presence of the binder on the surface of the particles since it was some of the particles were brushed off or vacuumed from the moulded components. During heating, all impurities and volatile material evaporate leaving the clean sand. Usually less than 3.5% is acceptable for iron while 3% or less is acceptable for non-ferrous and steel. Although used sand has high LOI, it is still acceptable, and means that the presence of the binder will not affect the properties of the moulds and cores negatively.

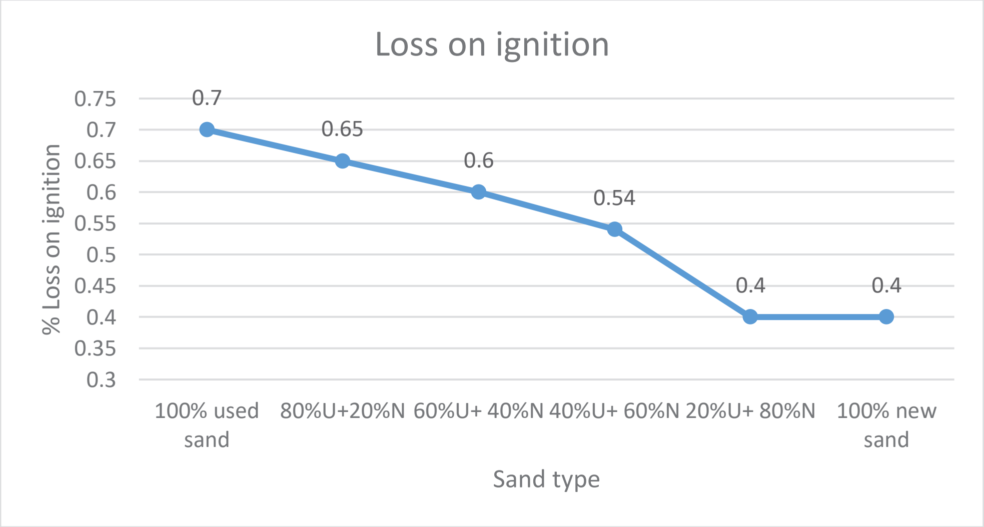

Fig. 11. Loss on ignition

3.1.6 Moisture content

Figure 12 presents the moisture content of the sand samples. The moisture of the used sand is lower than the moisture of the new sand and it increases with the increasing additions of the new sand. This could be explained by the fact that new sand has a high amount of sulphonic acid which resulted in a lower pH value as seen in figure 10. However, the recommended moisture content for 3D printing sand is 0,2% or less. The hardening process, which is called polycondensation, releases water due to the exothermic process taking place during drying. If there is a high amount of water present on the sand sample, the curing takes long, the bonds between sand particles becomes weaker and the strength of the moulds reduces. This is because moisture has a direct effect on the curing rate, the strength and the flowability of the material during the printing process.

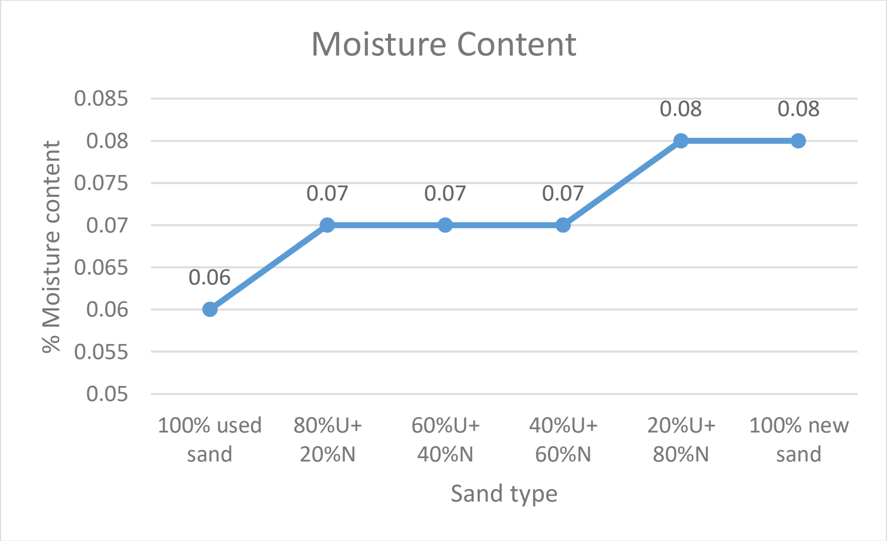

Fig. 12. Moisture content

3.2 Foundry properties results

3.2.1 Friability

Figure 13 shows the friability, which is the ability of the sand moulds and cores to withstand pressure with erosion of the sand particles. The friability of the waste sand is evidently higher than the rest of the sand samples with 6,2%. Since the pH and the moisture content of the used sand were higher, the affected the curing rate which resulted with weaker bonds between the sand particles. However, the friability started improving with the addition of new sand with much better results with the addition of 40% new sand. Low percentage of friability means goof friability since the specification of friability should be less than 10%.

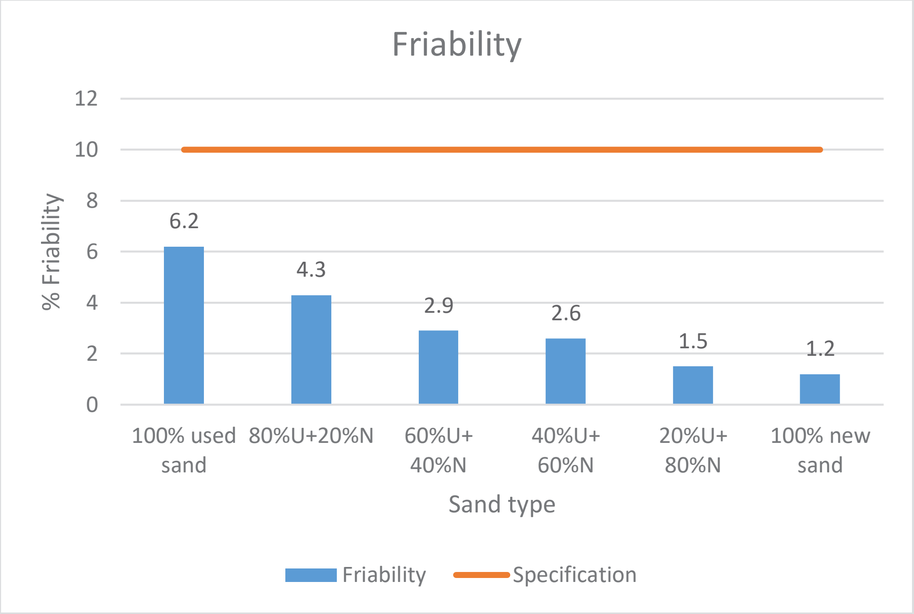

Fig. 13. Friability

3.2.2 Bend Strength

Figure 14 demonstrates the bend strength of the sand samples. The average bend strength of the used sand is visibly lower than the average bend strength of the new sand and the dilution ratios. Nevertheless, all results are within the minimum required bend strength specified by Voxeljet, which is 220 N/cm^2. The reduced strength of used sand can be explained by the fact that, as shown by the high pH value of the used sand in figure 10, the pH increases during storage, which tends to delay the polycondensation process, resulting in less strength [19]. If there is a high amount of water present in the sand sample, the curing takes long, the bonds between sand particles become weaker and the strength of the moulds and cores reduces. In addition, the strength results appear to indicate that the used sand had a lower strength possibly due to the presence of inactive binder that has reacted on the surface of sand grains. That is why reclamation could be a better process because it removes all reacted binder mechanically or thermally.

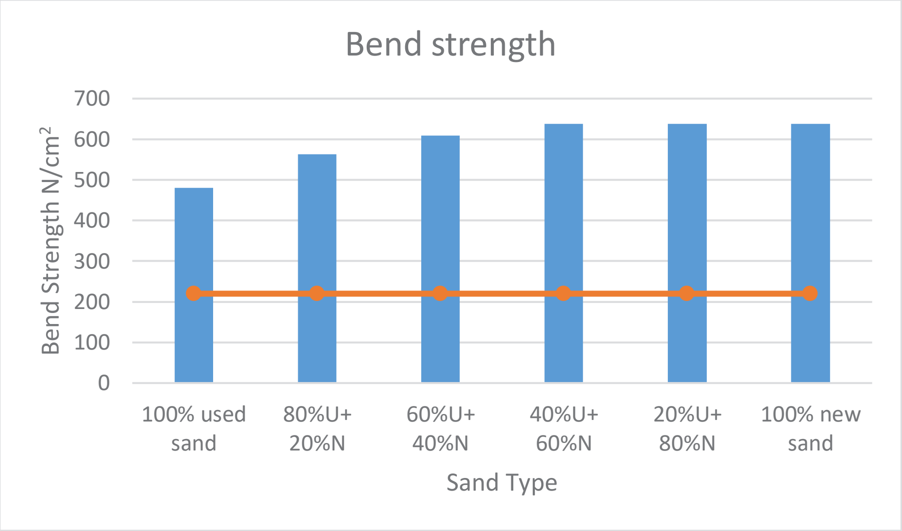

Fig. 14. Bend strength

3.2.3 Tensile strength

Figure 15 stipulates the tensile strength which was measured with a dog bone pattern shown in the methodology section 2.3.2 in figure 5. It is defined by the ability of the sand mould to maintain its shape during handling and pouring of the molten metal. Sufficient strength prevents pouring casting defects [20]. In addition, it the strength is too strong, it may reduce the collapsibility of the material after solidification. If castings are constrained from shrinking naturally, it can lead to issues such as casting hot tears, cracks, or distortion[21]. The tensile strength of the used sand, which had the highest pH value 3,53, produced samples with the lowest tensile strength of 195 N/cm^2 .As mentioned in subsubsection 3.1.3 and 3.2.2 , the pH of the sand has a massive influence on the strength of the sand moulds and cores. High pH results with prolonged curing time which results with lower strength and weak bonds between the sand particles. The strength of the sand samples increases with the increasing addition of the new sand during mixing. This is because the used sand with the high pH value increases and dilutes the pH of the new sand.

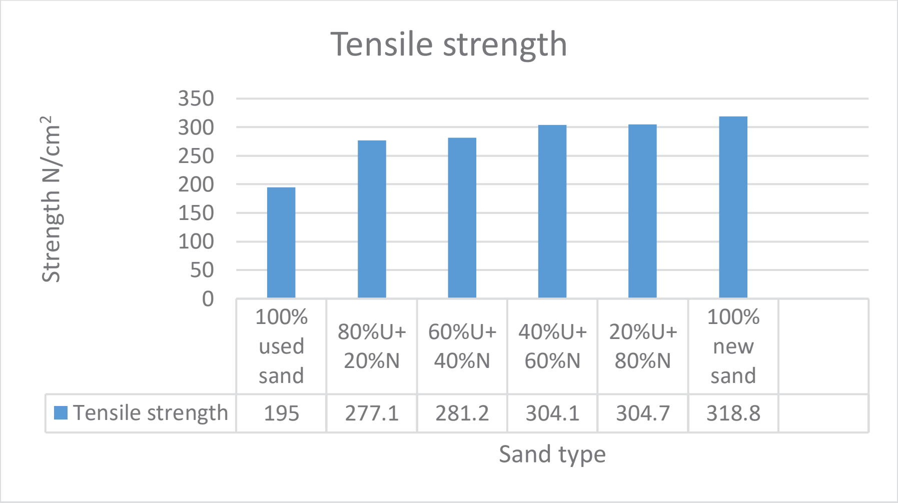

Fig. 15. Tensile strength

3.2.4 Flowability

Figure 16 represents the flowability of the sand samples. The angle of repose for both the virgin sand and the used sand on figure 16 are 27.30^o and 23.24^o respectively. The low flowability of the used sand is supported by the low moisture content of the used sand in figure 12, and the fact that low moisture content improves the flowability of the material. The flowability becomes higher with the addition of the new sand. The lower the angle of repose, the better the flowability. However, it can be concluded that the flowability of all the sand samples are acceptable because their angle of repose falls under the excellent category as illustrated in table 2.

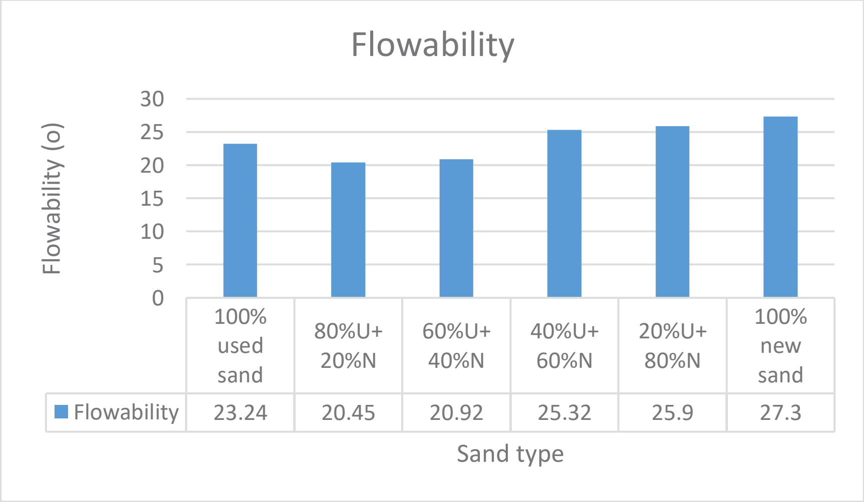

Fig. 16. Flowability

4 Conclusion

The purpose of this paper was to investigate how sand mixing of fresh sand with used sand during the three-dimensional printing affected the foundry properties of moulds and cores produced on a Voxeljet VX1000 3D printer. The results indicate that it is possible to reuse waste sand to large extent in terms of percentage addition during binder jetting process while maintaining adequate mechanical properties of the printed moulds and cores in line with the OEM's specifications. The study paves the way for the reduction of the running costs in terms of fresh sand use related to the binder jetting process. The study also contributes to better management of waste sand generated during rapid sand-casting process in line with the achievement of United Nation Sustainable Development Goals 9 and 13, respectively on Innovation and Infrastructure, Responsible Consumption and Production. Future studies on the sand recycling will compare the efficiency of the use sand recycling method with the transitional thermal and mechanical foundry sand reclamation methods.

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