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Original Research Paper

Comparative experimental study of sand and binder for flowability and casting mold quality

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1. Introduction

Casting is one of the oldest metal manufacturing technique known to humans [1]. Among the many variants of casting, sand casting is the most prevalent worldwide because of the economics, flexibility and range of alloys it offers [2]. Although sand casting technology has evolved throughout time, the combination of sand and binder used for making of sand molds is still an open area of research. The aim in general is to find materials which allow for better mold qualities, improved manufacturing process, finished casting quality, more economical, sustainable process, etc. Gradual tightening of environmental restrictions also mean that alternative materials are always being sought for foundries even for long established foundry processes and materials [3]. As an example, prolonged exposure to the most widely used foundry sand, silica, causes silicosis in foundry workers [4]. Replacement of silica sands with other naturally occurring or synthetic sands can be reasoned also with mold-metal interactions, aimed at improving casting quality. There is also health concern due to harmful emissions from organic binders. The making of sand molds using additive manufacturing is also a field which is gaining more attention in recent times [5]. The repeated deposition of subsequent layers of sand in 3D printers require sand that flows better and interacts in a predictive manner with the binder. All these developments have intensified the research for not only the sand but also the binders used. Many different binders, both organic and inorganic, have been put to use in foundries successfully for many years now, each with their own set of challenges and advantages. A good comparison is therefore warranted for different binders too.

In this study, flow properties of six different types of foundry sand are studied and some properties are investigated on how these sands perform with three different binders in a mold. Data obtained from this study provides useful information on the performance of different types of sand and binder. Apart from that, it can also be used for comparison when new materials are being investigated for mold making or when the performance of reclaimed sand is being tested.

1.1. Flowability

In simple terms, flowability can be described as the ability of powder or bulk solid to flow [6]. A powder or bulk solid is said to be flowing if it deforms plastically when subjected to a force...
The magnitude of force required to make a powder flow could then become one parameter to measure powder flowability [7]. Flowability of sand plays an important role in determining how well the sand flows around a pattern and thus ensuring mold production of uniform hardness and density. Flowability also determines how easily sand is spread in additive manufacturing of sand molds or in the design of hoppers, mixers, silos etc. There are many established tests for testing powders for flowability, for example in pharmaceutical industries and powder metallurgy. These include simple tests like Hall flow, Hausner Ratio, static angle of repose and also more comprehensive tests like Powder Rheometer studies, shear tester, dynamic angle of repose, etc. [8,9]. In this study, relatively simple tests which can be carried out easily with inexpensive apparatus in foundries, are done.

In light of recent development of sand mold production using additive manufacturing, flowability plays a more crucial part in the need to deposit each layer of powder uniformly in a repeatable manner [9], along with the need to ensure the least variation possible in the mechanical motion during recoating of each layer. Although the intrinsic powder properties affect how a powder flows, it must also be noted that powder flow is also dependent on how the powder interacts with the equipment or the apparatus it is on, which makes accurate prediction of flowability with a single test almost impossible [9]. There are differing views on how well any of the tests could accurately predict flowability of powders for different applications but many of these are quite simple and easy to carry out. Hence, a combination of them could lead to a more accurate determination of flowability rather than depending on a particular one, which is why the following three flowability tests were done in this study to assess the comparative results: Hall flow, Hausner Ratio and static Angle of Repose.

### 1.2. Mold quality

A good mold is an absolute necessity to obtain a good cast product. To investigate how different combinations of sand and binder would perform, three different tests were carried out to determine the mold quality. These were the loss on ignition test, 3-point bending strength test and permeability test. Together they provide important information about mold performance. A good sand mold is usually one which is strong enough to withstand the molten metal pressure, has good dimensional stability, permeable to the gases generated during pouring, provides good collapsibility after solidification, resistant to molten metal penetration etc. Generally a higher binder content leads to greater mechanical strength [10]. However, if the strength is retained after pouring, it becomes difficult to break the mold after solidification of the metal. Also, a higher binder content leads to high gas generation [11] and high cost. A good mold, therefore, is a tradeoff between several different factors.

Organic, no bake chemical binders like furan and phenol have been quite successfully used in foundries due to their ease of use, mold strength, production efficiency, good collapsibility and good sand reclamation [12,13]. However, at high temperature thermal decomposition occurs, which results in volatile organic emissions, some of which are harmful for human health [13]. Furan is also considered to be carcinogenic [14]. The gases produced might also lead to casting defects. The main reason for resuming interest in inorganic binders was health and environmental issues. In recent times however, the requirements of casting critical aluminum parts for automotive engine for better performance has also contributed to interest in modified sodium silicate inorganic binders [15]. Research is ongoing to improve the challenges originally faced with sodium silicate binders, mainly the shake out difficulty, poor reclamation properties, etc. [16,p. 927], along with exploring other new possibilities and advancements.

### 1.3. Silica sand alternatives

Silica is the most widely used sand for molding because of its availability, lower price and high melting point. The search for silica alternative is driven by many factors. As stated previously, one of the reasons is the disease ‘silicosis’, caused by a prolonged exposure to silica. As a result, the use of silica sand in foundries is coming under increased scrutiny in many countries. Additionally, the expansion of silica during alpha to beta transition at 573 °C could result in mold expansion in the range of 1.1–1.6% [17], which results in a loss of casting accuracy. The problem of large nonlinear expansion of silica is worse in ferrous castings, especially when virgin sand is used. Silica sand is usually mined in large numbers from coastal regions. This causes environmental degradation and the impacts have a long recovery time [18]. Apart from foundries, silica is also an essential raw material for glass industries, ceramics industries, many silicon based chemical products, construction work, etc. [19]. With the demand for silica sand increasing and mining sites coming under increased scrutiny due to stricter environmental laws, the price of silica is also seeing an upward trend. All these factors have intensified the search for silica sand alternatives for foundry use.

The expansion related problem of silica sand is not shared by zircon and chromite sand. Zircon and chromite sand have low thermal expansion but good thermal conductivity which is responsible for their excellent chilling properties [16, pp. 920–921]. However, these are much more expensive and heavier than silica. Bauxite is an abundant mineral but not much in use in foundries currently. It has the prospect of resolving some issues encountered with silica sand and ferrous casting as it has lower thermal expansion than that of silica. The density of bauxite is also less than that of zircon and chromite. This decreases many indirect production costs incurred during the use of zircon and chromite due to their high densities [16,p. 921]. Apart from natural sands, interest is also growing for artificial sands. Cerabeads are engineered synthetic sand made by sintering of mullite granules [20]. They have very uniform spherical shape and low thermal expansion [20]. Cerabeads cost less than chromite and zircon, and are sometimes marketed as an alternative to zircon.

There has not been a study that incorporates the flowability tests done here on different sand types. Apart from providing the result on flowability, this study also shows whether all these tests come to the same conclusion on flowability. In literature, extensive study on silica sands and different types of binder can be found in separate studies. The mold production method differs a lot which makes it hard to directly compare results between different studies. There exists a gap where many different types of sand and many different types of binder are tested in a single study that ensures a fair comparison. This study aims to bridge a small gap in the wider picture and facilitate the choice of mold materials as well as help in the search for alternative and/or better mold materials.

### 2. Material and methods

#### 2.1. Material

Six different types of sand were used in this study. These are silica, bauxite, Cerabeads 400, Cerabeads 1450, zircon and chromite. Silica sand provides a good benchmark for comparisons with other sands due to the widespread use and knowledge about its use. Bauxite is mainly aluminum oxide and is heavier than silica. Two types of Cerabeads are tested in this study, the 400 and 1450 variant. For simplicity, these two will be referred to as CB 400 and CB 1450, respectively. Chromite sand...
is a mixture of several oxides. The principal constituent was chromium oxide, followed by iron, aluminum and magnesium oxides. Zircon is light in colour, usually consisting of very small rounded grains, and has a high bulk density almost equal to that of aluminium [16,p. 921].

Sieve analysis was done on the samples to reveal the size distribution of particles in the samples. Analysis was done according to test procedure AFS 1105-12-S [21]. Mass of sample measured for each analysis was determined by bulk density. Higher mass of sand was used for sand type with higher bulk density. All the flowability tests were done using virgin sand and no additives added.

Three different binders were used with the six different types of sand to conduct the mould quality tests. Two of the binders were organic: furan no bake binder and alkaline phenolic ester cured no bake binder. Both the organic binders used in this study were two-part binder systems. The third binder is a modified version of inorganic sodium silicate binder. The sodium silicate binder traditionally used in foundries usually require CO₂ or heat for curing. The modified version used in this study is a two-part binder system, consisting of a solid promoter and a liquid binder and required heat for curing. For simplicity, this binder will be referred to as MSS (modified sodium silicate) throughout the rest of the paper.

### 2.2. Hall flowmeter test

In the hall flow test, a particular quantity of bulk material is allowed to fall through the hall funnel and the time taken to do so is noted. The hall funnel was made according to standard ISO 4490 [22], which is used for flow tests of metal powders. The hall funnel has an orifice with a diameter of 2.5 mm. For metal powders, the standardized test measures the time taken for 50 g of powder to fall through the funnel. However, this process is best suited for powders which have very similar densities. If the density difference is high, this test tends to favor materials with the higher density. Therefore, in this experiment, the volume of the sand was kept constant rather than the mass. In mold making, a ‘particular volume’ is filled up using sand, rather than a ‘particular mass’. In additive manufacturing of sand molds as well, the notion holds true as a particular volume of sand is required for spreading in each layer. Therefore, 25 ml of sand is allowed to flow through a hall funnel made of aluminium and the time taken to do so is measured. For each sand, the test is carried out three times and the average calculated.

### 2.3. Hausner Ratio (HR)

Hausner Ratio is defined as the ratio of tapped density to bulk density [23]. The change in volume of bulk materials on tapping is a complex combination of the powder morphology, surface area, inter particle attraction, moisture content, etc. Loose sand has many void spaces, which reduces on tapping as the particles pack closer together and results in a higher tapped density than bulk density. In this experiment, the Hausner Ratio is measured using a 100 ml graduated cylinder, filled with a carney funnel between the 80 ml and 100 ml mark. The cylinder was then tapped using a sieve shaker for 1 min. The new tapped volume and mass of sand was recorded using a balance. The experiment was done three times and average value calculated. As the mass remains constant, the ratio of initial apparent volume to the final tapped volume gives the desired Hausner Ratio. The lower the value of Hausner Ratio, the better the particle flows. Table 1 shows the relation between flow behavior and Hausner Ratio.

### 2.4. Angle of Repose (AOR)

Another most widely used test for flowability is the angle of repose. Non-cohesive powder is normally used in this test. The test can be done in different ways, but in its simplest form, free flowing bulk solid is allowed to fall and form a cone with the base. The angle of repose is then the steepest angle made by the unconfined material without collapsing, measured from the horizontal base on which the pile of material rests [24]. Consequently, to measure the angle of repose, the height can be kept fixed and the diameter measured, or the diameter is kept fixed and the height is measured. There are several methods of measuring angle of repose, a summary of these methods could be found in [25].

In this study, an adapted version of standard ASTM C1444 [26] was used for measuring the angle of repose with some changes in the apparatus used. The angle of repose was measured by allowing the sand to flow through a carney funnel with an outlet diameter of 5 mm. The outlet was adjusted to sit 48 mm above a white paper. A laboratory retort stand, clamp and boss head were used to hold the funnel in place. Straight lines were etched on to the paper at different angles, that cross each other at the center. With a stopper in place, the funnel was completely filled with sand. The stopper was then removed to allow the sand to fall by gravity onto the paper, while still feeding sand into the funnel at the same rate of discharge until the top of the sand pile reaches the tip of the funnel. The diameter of the sand pile was then marked on the straight lines in the paper as close as possible to the base of the pile, 3 diameters are marked in each trial which is then averaged. The setup for measuring angle of repose is shown in Fig. 1. For each sand, the test was carried out three times and the angle of repose

![Fig. 1. Setup for measuring angle of repose.](image)

<table>
<thead>
<tr>
<th>Hausner Ratio</th>
<th>Flow Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00–1.11</td>
<td>Excellent</td>
</tr>
<tr>
<td>1.12–1.18</td>
<td>Good</td>
</tr>
<tr>
<td>1.19–1.25</td>
<td>Fair</td>
</tr>
<tr>
<td>1.26–1.34</td>
<td>Passable</td>
</tr>
<tr>
<td>1.35–1.45</td>
<td>Poor</td>
</tr>
<tr>
<td>1.46–1.59</td>
<td>Very poor</td>
</tr>
<tr>
<td>&gt;1.60</td>
<td>Non-flowable</td>
</tr>
</tbody>
</table>
is measured by averaging the result in degrees correct to 1 decimal place. The angle of repose was measured using Eq. (1).

\[
\text{Angle of repose} = \tan^{-1}\left(\frac{2H}{D - d}\right)
\]

(1)

where \(H\) (48 mm) is the height of sand pile, \(D\) is the average of three diameter measurement of sand pile and \(d\) (5 mm) is the internal diameter of the funnel. A high angle of repose means low flowing powder. The Carr classification for flow behavior and angle of repose is shown in Table 2.

### 2.5. Sand mixture preparation for mold quality tests

In the AFS test procedures [21] for preparing sand mixture, the binder is taken as a mass percentage of the sand. However, because of the high density difference between six different sands used in this study, a fair comparison cannot be done if the amount of binder used is based on the mass of sand. Sands with higher densities get more binder content per unit volume. In such cases, this results in very high strength. Hence, to ensure a fair comparison, a fixed ‘volume’ of sand and a fixed volume of ‘binder’ was used. Since most binders are optimized for silica sand, 1000 ml of silica sand was weighed, and the mass of binder required for this volume of silica is calculated. For all the other types of sand, the same 1000 ml container is used to measure specific volume of sand and same amount of binder is used. In this way, the amount of binder per unit volume of sand was kept constant for all sand types, therefore, ensuring a proper comparison.

1.5%, 1.0% and 2.0% by mass of silica sand were used for phenolic, furan and MSS binders respectively. For phenolic binder, the dosing amount was selected according to AFS test procedure AFS 3335-04-S. For furan and MSS binder, manufacturer recommended dosing amount was used. For mixing purposes, a standard laboratory mixer was used. The sand was first mixed properly with the first part of the binder (which is the catalyst, promoter or activator, depending on the binder type), followed by a thorough mixing with the second part, the main component. From each batch, test bars were made for bending strength test using metal mold, and cylindrical samples were made for permeability tests. Samples were cut out from bars to use in the loss on ignition tests.

### 2.6. Bending strength test

Standard bars measuring 22.4 mm × 22.4 mm in cross section and a length of 172 mm are made. In a 3-point bending strength tests, the bar rests on two supports from below and an increasing pressure is applied at the midpoint from above. The pressure required to break the bar is then recorded by the tester. The strength test results indicate whether the mold is strong enough to withstand the pressure from molten and solidifying metals. An optimum strength depends heavily on the application, however, if the mold is too strong then it becomes increasingly difficult to break the mold after the metal has solidified. Also, a high strength of mold can also increase shrinkage and distortion [28]. For phenolic and furan binders, the tests were carried out from 24 h of mixing and nothing additional was done to accelerate the curing by heat or other methods, as is the practice with no bake binders. For MSS, the strength was measured after 3 h of curing at 160 °C.

The Morek Multiserw Universal Strength Tester LRu-2e/w was used for the strength measurements. Fig. 2a shows test bars made with phenolic binder and the different types of sand. Three samples were tested for each combination.

### 2.7. Loss on Ignition (LOI)

Loss on ignition test measures weight loss of a sample when fired to a high temperature, which creates a similar effect as when molten metal is poured into sand molds. The loss is an indicator of weight loss due to gas generation, loss of chemically bound water and some weight gain due to oxidation when the test is not carried out in inert atmosphere. The tests were done in two steps. Samples were cut from test bars into small cuboids having mass between
20 g and 30 g and placed in ceramic bowl as shown in Fig. 2b. The difference in weight of the samples before and after heating, expressed in percent of initial weight is the loss on ignition. As the MSS binder required curing to harden at 160 °C, the test was modified to acquire comparable results with all the binders. Hence, all the samples were first heated at 160 °C for 1 h in a drying oven.

Fig. 3. Sieve Analysis of the sands.

followed by at 915 °C for 2 h in a muffle furnace. Measurement was taken before and after putting the samples in each oven and loss of ignition in this experiment was calculated with the difference in weight before and after taking it out of the 915 °C muffle furnace. Smaller loss on ignition values are desirable as it means smaller amount of gas generation. Fig. 2b shows cuboids cut out for the loss on ignition test. The test was carried out in duplicate and the average value reported.

2.8. Permeability tests

Sand molds must be permeable, as the gas evolved from burning binder must pass through the porous structure of cores and molds. Permeability of the molds depend on particle size and shape of the sand, compaction of the mold and also, the amount of binder used in the mold. Smaller particles cause the interparticle space to become smaller and the presence of binder bridge between particles is expected to reduce permeability of molds as well [28]. 50 mm × 50 mm cylindrical specimens were made according to AFS standard as shown in Fig. 2c. The permeability was measured using a Digital Absolute Permmeter. The reading ranged between 0 and 999, with 0 being not permeable, and 999 being the highest permeability. The instrument provides a numerical permeability number which indicates the volume of air that passes through a test tube of 1 cm² cross section and 1 cm in height when the air pressure is kept constant at 1 g/cm² [29]. The higher the number, the higher the permeability the mold possesses. The test was carried out in duplicate and the average value reported.

3. Results

The sieve analysis of the six sands are presented in Fig. 3. The distribution is shown along with the mean particle size. Bauxite and chromite had a wider distribution, while chromite also had the largest mean particle size of 0.387 mm. CB 1450 had the lowest mean particle size of 0.130 mm, followed very closely by zircon at 0.132 mm. Silica had a mean particle size of 0.264 mm. Very little or no dust was present in the sand samples.

3.1. Flowability tests

Table 3 documents the results obtained from the hall flow test. The total time taken for 25 ml of sand to flow through the funnel is documented, along with the mass of the 25 ml sample. The last two columns show flow in terms of volume flow rate, Q and mass flow rate $m$ respectively. Hall flow time is shown in Fig. 4 along with error bars at one standard deviation. The least time was taken by CB 1450 (56.43 s), followed very closely by zircon (56.91 s). Silica and bauxite took similar times at 72.12 s and 74.11 s respectively. The highest time was taken by chromite sand (85.13 s). The lower the time, the more flowable the sand is. From the results it was seen that the higher the mean particle size, the higher was the time taken.

Results from AOR is shown in Fig. 5, with error bars at one standard deviation. Silica exhibited quite high Angle of Repose (AOR) of 33.8°, more than all the other sands except chromite (34.7°). Similar to the hall flow, the lowest AOR was exhibited by CB 1450 (30.2°) followed by zircon (31.9°). All the sands were within ‘free flowing’ range. Results for Hausner Ratio is shown in Fig. 6, with error bars at one standard deviation. As with the AOR, the two lowest values were from zircon and CB 1450. Unlike AOR, bauxite had the highest HR value, followed by chromite. Silica had a HR value of 1.133. All the sands were within the ‘good’ flow range according to HR values.

<table>
<thead>
<tr>
<th>Sand type</th>
<th>Volume (ml)</th>
<th>Mass (g)</th>
<th>Time (s)</th>
<th>Q (ml/s)</th>
<th>m (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>25</td>
<td>39.1</td>
<td>72.12</td>
<td>0.35</td>
<td>0.54</td>
</tr>
<tr>
<td>Bauxite</td>
<td>25</td>
<td>53.2</td>
<td>74.11</td>
<td>0.34</td>
<td>0.72</td>
</tr>
<tr>
<td>CB 400</td>
<td>25</td>
<td>40.2</td>
<td>81.40</td>
<td>0.31</td>
<td>0.49</td>
</tr>
<tr>
<td>CB 1450</td>
<td>25</td>
<td>43.3</td>
<td>56.43</td>
<td>0.44</td>
<td>0.77</td>
</tr>
<tr>
<td>Zircon</td>
<td>25</td>
<td>74.9</td>
<td>56.91</td>
<td>0.44</td>
<td>1.32</td>
</tr>
<tr>
<td>Chromite</td>
<td>25</td>
<td>69.9</td>
<td>85.13</td>
<td>0.29</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Fig. 4. Hall flow test, error bars with one standard deviation.

Fig. 5. Angle of Repose, error bars with one standard deviation.

Table 3
Hall flowmeter test data.
3.2. Mold quality tests

Results from the bending strength tests, the loss on ignition tests and the permeability tests are shown in Figs. 7, 8 and 9 respectively. No measurable strength was obtained with the combination of furan and each of the Cerabeads as the samples did not have enough strength to hold its shape, which is why these values are missing in Figs. 7 and 9. The error bars are drawn at one standard deviation in Fig. 7. For phenolic binder, only zircon exhibited more strength than silica. The rest were less than silica, while the least was obtained with CB 400. The 3 h cured MSS obtained the highest strength with all sand types when compared with phenolic and furan binders. With MSS, zircon achieved the highest strength, followed by chromite and bauxite.

Furan produced the highest loss on ignition, followed by phenol and MSS with all sand types as can be seen in Fig. 8. The combination of silica and furan had the highest loss on ignition. A negative loss on ignition was obtained with the chromite sand, when combined with phenolic and furan binders. With MSS, zircon achieved the highest strength, followed by chromite and bauxite.

The difference in permeability for different binders on the same sand was little as can be seen in Fig. 9. Only zircon and CB 1450 exhibited lower permeability than silica. The highest permeability was seen with CB 400. Bauxite and chromite showed similar permeability between 250 and 300.

4. Discussion

The three flowability tests done here do not share a common unit, hence a quantitative statement about flowability in an universal ‘flowability’ scale is not attained. Rather, all of them had a separate numerical indicator. For example, the value of the Hausner Ratio or the angle in angle of repose, or the time it took for a particular volume of sand to flow in the Hall flow test gives some indication about the flow properties of the sand. It could be seen from Table 3 that using a fixed volume of sand ensures a better comparison for the purpose of this study, rather than a fixed mass, as higher density of the sand tends to give a more optimistic result if it is based on mass. This can also be confirmed from Table 3 which shows a very high mass flow rate for high density sands zircon and chromite. Also, there was a huge difference between zircon and CB 1450 in terms of mass flow rate due to density difference, although these two exhibited quite similar characteristics in the other flow tests. From the Hausner Ratio and Angle of
Repose results, all the sands fall within the ‘good’ flow range as per Tables 1 and 2. In order to further differentiate between the sands for flowability, more sophisticated methods can be used like powder Rheometry or shear tests etc. Although the three flowability tests did not agree on the same rank of the sands according to flowability, CB 1450 and zircon exhibited better results than the other four sands. The tests also indicate that particle size is a dominant factor. Both Cerabeads 1450 and zircon have similar mean particle size and size distribution and both of these have shown comparatively the best flow properties among all the different types and also their results are very close to each other. Also, a marked difference can be seen in the results of CB 400 and CB 1450. The tests here were done with virgin sands, the behavior is expected to change if the sands are mixed with any portion of the binder systems or with any other additives, for example in 3D printing the sand could be mixed with the activator/co-reactant first and binder is selectively deposited on the premixed sand. The little difference in flowability between the types could be desirable from the point of view of silica replacement. Little changes need to be accommodated if foundries are changing the sand types.

The bending strength results show comparable strength attained with each type of sand and binder. The values can be different and tweak upon in several ways like using differing amount of binders, increasing waiting time after mixing with binder, changing the compaction method or changing curing time and temperature for MSS etc. To avoid random variation, the process and apparatus was kept constant during this experiment so that the results obtained are comparable. For furan, the highest strength was obtained with silica. All the other sands showed lower strength and both the Cerabeads type possessed very little strength. The values can be differentiated if foundries are changing the sand types.

With all types of sand, furan has shown to be having the highest strength, followed by phenol and the least is obtained with the MSS. Both the Cerabeads type exhibited similar LOI profile to silica, across all binder types. The reported values were an average of two repeats, since the LOI results do not vary much, two samples were tested and the average reported. An improvement to the LOI test could be to perform the test in a reducing atmosphere in the absence of oxygen, although such an atmosphere does not exist in foundries.

Bauxite, chrome and CB 400 had higher permeability than silica, CB 400 being the highest. Large particle size, round uniform shape of the CB 400 results in hollow spaces which in turn results in the highest permeability. A very low permeability of CB 1450 and zircon sand were also seen. Different binder type did not affect the permeability much with the dosing amount used in this study, which could be a good thing if foundries are considering a switch from one binder to the other. It was rather the type, size and shape distribution of the sand particles which affected permeability more. If the size distribution is wider, the smaller grains take up the spaces between larger grains, resulting in a reduced permeability. This was seen in the difference in permeability of CB 400 and chrome. Although they have a similar mean particle size, the narrower size distribution and more uniform spherical shape of CB 400 resulted in a much higher permeability. Low strength and high permeability of CB 400 indicates suitability for core making. Differences in compaction during mold making can also affect permeability. However, in this study the procedure and compaction method was kept consistent to ensure as little variation in compaction as possible. Similarly, a much higher or lower amount of each binder could affect the permeability more but testing that remains beyond the scope of this study.

5. Future work

Testing novel materials for flow and mold quality becomes an automatic successor to this work. Apart from that, since a quantitative statement about sand flow is not obtained with the simple tests, it is necessary to correlate the comparative findings of this study with specific applications in foundries. Of special interest is how existing and novel foundry sands perform in powder bed and binder jetted additive manufacturing printers, both in terms of flow and also their interaction with different binders.

6. Conclusion

A good sand mold is a tradeoff between several factors, there is no single combination that is perfect for all applications. Apart from ensuring a good quality mold, the costs involved and other constraints like supply chain could play a major part in the ultimate choice of sand and binder for sand casting foundries. In this study, virgin zircon and CB 1450 sands exhibited superior flow properties than other sand types based on the 3 flow tests. Although, all the tested sands fall within the good flow range, further investigations are needed to establish any connections between the flow tests done here to actual applications, for example in 3D printing. Little effect is noticed of binder type on the permeability. A very low permeability of CB 400 resulted in a much higher permeability. Low strength and high permeability of CB 400 indicates suitability for core making. Differences in compaction during mold making can also affect permeability. However, in this study the procedure and compaction method was kept consistent to ensure as little variation in compaction as possible. Similarly, a much higher or lower amount of each binder could affect the permeability more but testing that remains beyond the scope of this study.
well as provide reference data in the search for novel mold materials.

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**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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