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The Impact of Chamotte Sand on the Mechanical and Physical Characteristics of Ceramic Molds Made of Chromite Sand

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ABSTRACT

Casting flaws are common in the high-temperature steel casting process, particularly surface flaws and rough surfaces. One option to avoid these surface defects is to use sand with a higher melting point, like chromite sand. This study is an extension of the previous research, which found that chromite sand, a ceramic mold material, frequently fractures during the sintering process. Chamotte sand material of 3% and 5% by weight has been applied as a binder to chromite sand to improve this. With an ideal sintering temperature of 1,050°C, two ceramic sintering processes, the Shaw and the Unicast processes—have been used. To determine the chromite-chamotte sand mixture's potential as a ceramic mold material, tests for cold crushing strength (CCS), modulus of rupture (MoR), permeability, and refractory were conducted. The mixture with 3% wt chamotte sand with the Shaw sintering technique provided the highest results and was appropriate for ceramic mold.

Keywords: *Ceramic mold; chamotte sand; chromite sand; Shaw process; Unicast process.*

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ABSTRAK

Cacat pengecoran umum terjadi pada proses pengecoran baja suhu tinggi, terutama cacat permukaan dan permukaan kasar. Salah satu pilihan untuk menghindari cacat permukaan ini adalah dengan menggunakan pasir dengan titik leleh yang lebih tinggi, seperti pasir chromite. Penelitian ini merupakan perluasan dari penelitian sebelumnya, yang menemukan bahwa pasir chromite, bahan cetakan keramik, sering retak selama proses sintering. Bahan pasir chamotte sebesar 3% dan 5% berat telah diaplikasikan sebagai pengikat pada pasir chromite untuk memperbaiki hal ini. Dengan suhu sintering ideal 1.050°C, dua proses sintering keramik—proses Shaw dan proses Unicast—telah digunakan. Untuk menentukan potensi campuran pasir chromite-chamotte sebagai bahan cetakan keramik, pengujian untuk kekuatan hancur dingin (*cold crushing strength* - CCS), modulus pecah (modulus of rupture - MoR), permeabilitas, dan refraktori dilakukan. Campuran dengan pasir chamotte 3% berat dengan teknik sintering Shaw memberikan hasil tertinggi dan sesuai untuk cetakan keramik.

Kata kunci: Cetakan keramik; pasir chamotte; pasir Chromite; proses Shaw; proses Unicast.

INTRODUCTION

Chromite sand, in the steel metal casting industry, is generally only used as a coating on the core of the casting - this sand has been proven to work well as a heat release of the casting and strengthening certain parts of the casting mold - so that sand inclusions do not occur into the steel casting. Chromite sand is not commonly used as a raw material for sand molds even though it has very good capabilities, because the price of chromite sand is relatively higher than silica sand, so that the casting industry generally mixes it with silica sand, but this mixture reduces the heat-ability (refractoriness) due to the formation of fayalite ($2FeO.SiO_2$) [1]. Sand molds are widely used in the casting industry, given their ease of formation and recyclability, which can reduce production costs. Molding sand has a variety of sand types and binding materials, which will affect the quality of the casting [2]. In castings that require high pouring temperatures such as steel, not all types of sand can be used, only types of sand that have high heat capacity can be used, one of which is silica sand. Silica sand significantly reduces surface defects, especially for flat or simple castings. In curved castings, these surface defects using silica sand are still easy to occur. To minimize surface defects in curved castings (e.g., impellers), chromite sand is used, which has a high melting point. Chromite sand has high thermal conductivity and provides a cooling effect on the cooling process of the cast metal [3]. Chromite sand has low thermal expansion which helps eliminate expansion defects and better metal penetration resistance than zircon sand [4]. Behind these advantages, chromite sand has a softer grain size and lower binding strength compared to silica sand [5], so it requires a special binder (usually a synthetic binder). To minimize surface defects is to change the sand mold to a ceramic mold. Umam, et al. [5] have conducted research on the development of ceramic molds made from chromite sand to overcome surface defects in steel castings, but are hampered by the fact that the chromite sand molds are not perfectly bonded when undergoing a heat treatment process to become ceramic molds (production scale). To increase the binding capacity of chromite sand, it is necessary to provide a mixture of sand and a binder, namely chamotte sand. The chamotte sand acts as a crucial filler or aggregate, improving thermal stability, strength, and refractoriness in binders for high-temperature foundry molds, refractory bricks, and specialized cements. This study aims to test the mechanical properties of chromite sand, namely cold compressive strength (Cold Crushing Strength - CCS) and modulus of rupture (MoR) as well as testing physical properties including refractoriness tests and porosity tests. This characterization aims to determine the ability of chromite sand as a ceramic mold.

LITERATURE REVIEW

Chromite sand is composed of iron spinel oxide and chromium ($FeCr_2O_4$) with Cr_2O_3 greater than 37%, has a melting point of 2,180°C and a density of 4.3-4.5 g/cm3 [6]. Chromite sand has an AFS (Average Fineness Number - American Foundrymans Society) between 50 and 80 [7]. This sand has a higher acid requirement, so it requires a larger amount of acid catalyst if using furan resin as a binder [8]-[9]. Chamotte sand is calcined clay containing a high amount of alumina. This clay is produced by firing in a rotary kiln at temperatures between 1,400°C and 1,600°C, before being ground and sieved to a specific particle size. Chamotte sand, also often called mulite sand, is a type of high-quality casting sand made from high-quality kaolinite minerals. Its main crystal phase is mulite. This clay has good performance in terms of lower thermal expansion rates, uniform expansion, better anti-vibration, good hardness, etc. This clay is excellent for use in precision casting. Chromite provides superior resistance to metal penetration and a strong chilling effect due to its high thermal conductivity. Chamotte shares high thermal properties but is less effective than chromite. Blending has an impact on the mold's overall thermal behavior, which influences defect generation and solidification rates.

Ceramic molds are metal casting molds made of ceramic, which is a combination of plaster mold casting and investment casting. The process of making ceramic casting molds is generally through the Shaw process or the Unicast process. Ceramic molds are generally used to make tools, or as die casting molds, injection molds, extrusion molds, glass molds, and stamping molds [10].

The Shaw process, named after its inventor Osborn-Shaw, is a two-stage ceramic firing process. First, the green mold is heated at a temperature of 200-400°C to remove volatile substances and second, firing at a temperature of 980-1,050°C to remove the remaining volatile substances. This process is often referred to as the sintering process, where changes occur in minerals into ceramics as shown in Figure 1. The Unicast process is a direct-firing process for ceramics, like the Shaw process (see Figure 2), except that it does not require a pre-firing mold. After drying, the green mold is then fired (sintered) in a kiln at a temperature of around 1050°C. The Shaw process makes the mold immune to severe thermal shocks during casting and resulting in extreme accurate parts, where the Unicast process allows the mold to be less robust for certain extreme high-temperature metal casting. The Shaw process has sintered longer time led to higher production cost per part, and the Unicast process has lower initial installation and manufacturing cost, as it can utilize traditional foundry equipment.

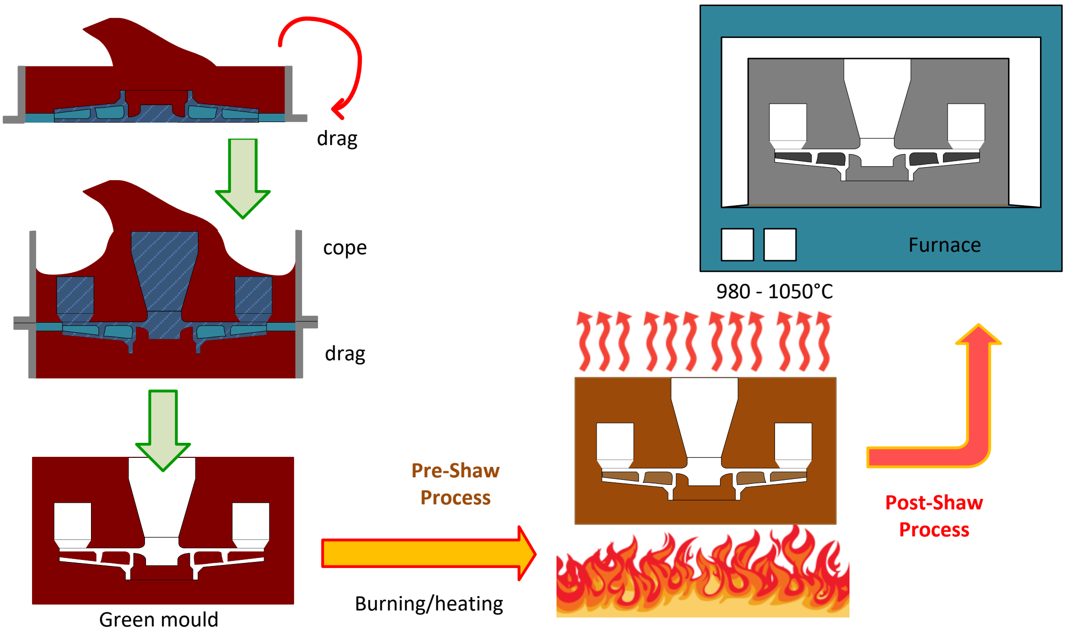

Figure 1. Shaw sintering process.

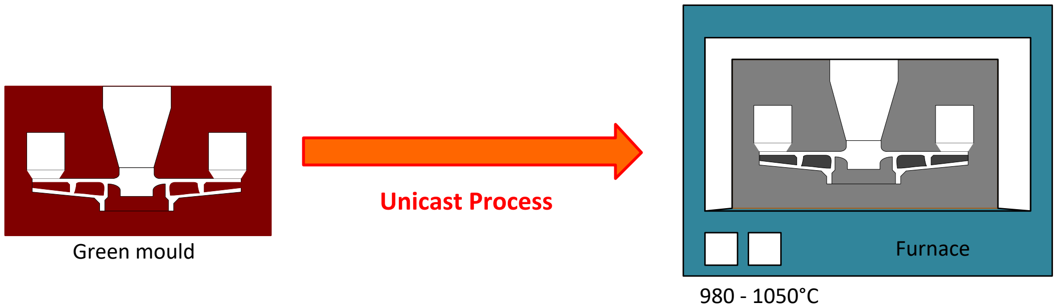

Figure 2. Unicast sintering process.

The main advantages of using ceramic molds are excellent surface finish, small dimensional tolerances, and the ability to cast castings with thin cross-sections or complex shapes. The main disadvantages are: relatively high cost, which is not suitable for large-scale production and single-use molds. Ceramic molds are often used in high-temperature casting of ferrous and non-ferrous materials, with weights varying from 100 grams to several tons. Cross-sections as thin as 1.3 mm are possible to cast and typical tolerances are 0.1 mm for the first 25 mm and 0.003 mm per additional mm. The surface finish obtained ranges from 2–4 μm RMS (Root Mean Surface) [11].

Ceramic molds made of chromite sand with a resin binder have been made by Umam, et al. [5] using the Shaw and Unicast processes. Both ceramic mold sintering processes have advantages and disadvantages, both economically and technically. Figure 3 shows the weak binding strength of chromite sand causing the mold to not bond perfectly after the sintering process. Therefore, it is necessary to study the effect of additional binders (outside of resin) on chromite sand so that when the sintering process is carried out, it will bond perfectly and still meet the requirements as a ceramic mold.

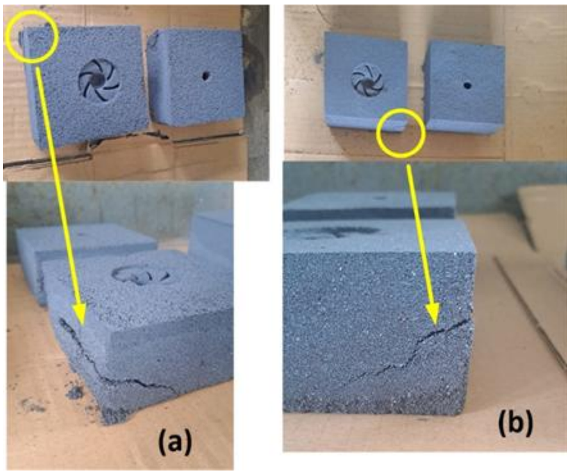

Figure 3. Mold of the results of the Shaw process (a) and the Unicast process (b) [5].

The fundamental characteristics of molding sand, such as adhesiveness, density, green strength, permeability/porosity, refractoriness, collapsibility/modulus of rupture, dry strength/cold crushing strength, and flowability, must be considered to obtain an appropriate casting mold. The capacity of sand to stick to foreign surfaces, such mold frame walls, is known as adhesiveness. For ceramic molds to be manufactured and handled, they need to be strong and durable enough. For the sand grains to adhere to the side of the mold frame, they must be adhesive, meaning they must be able to adhere to other objects. Additionally, the capacity of sand grains to adhere to one another is known as density. In addition to preventing erosion of the mold wall surface during the flow of molten metal, this cohesive quality makes it simple to remove the pattern from the mold without causing damage to the mold.

Green strength is the binding ability of sand in sand molds, generally influenced by the binder. Green strength also depends on the shape and size of the grains, as well as the amount and type of binder. When molten metal is poured into the mold, the hot metal will evaporate the moisture in the sand layer it touches and this dry sand layer must have sufficient strength to maintain its shape (dry strength) to avoid erosion of the mold walls during the flow of molten metal, while also preventing the mold cavity from enlarging due to the metallostatic pressure of the molten metal. Flowability or plasticity is the ability of sand to solidify and behave like a fluid. When impacted, sand will flow uniformly throughout the pattern and disperse its impact pressure equally in every direction. In general, sand particles are difficult to maneuver around projections or corners [12]. Sand's flowability rises as green strength decreases and vice versa, as sand grain size decreases. Numerous elements, such as clay and water content, affect the flowability of sand [1]. The mold must be able to collapse as soon as the molten metal inside it solidifies to avoid the contracting metal ripping or shattering. The dry strength and the shattering mold are measured by CCS and MoR tests, respectively.

The permeability or porosity of the mold is required for the escape of air, gas or water vapor present or produced in the mold when the molten metal is poured into it. All gases produced during the pouring and solidification process must escape otherwise; there will be defects in the form of burst bubbles on the surface or empty cavities in the casting. Aminnudin [13] explained that permeability is a function of grain size, grain shape, and binder content in the mold. The sand ramming area has an impact on the permeability of ceramic molds, which can be improved by employing ventilation rods to enlarge the vents. The ability of molding sand to endure high temperatures without melting or being damaged is known as refractoriness, and it makes it simpler to produce appropriate castings. A rough casting surface can be produced by molding sand with low refractoriness burning on the surface. There is a limit to how much refractoriness can be enhanced.

The refractoriness level depends on the amount of high-melting-point (heat-resistant) minerals and the shape and size of the particles. The higher the heat-resistant mineral content and the course the grain volumetric composition, the higher the refractoriness. Heat-resistant properties are measured by the sand's sintering point, not its melting point. Refractoriness is measured by the pyrometric cone equivalent (PCE) test.

METHOD

The materials utilized were SK36 chamotte sand from the market and chromite sand from PT. Baralogam Multijaya. These were combined with Fenotec 810 resin, which had been supplemented with Fenotec Hardener H40 catalyst from PT. Foseco Indonesia [14]. Figure 4 depicts the tools and procedures utilized.

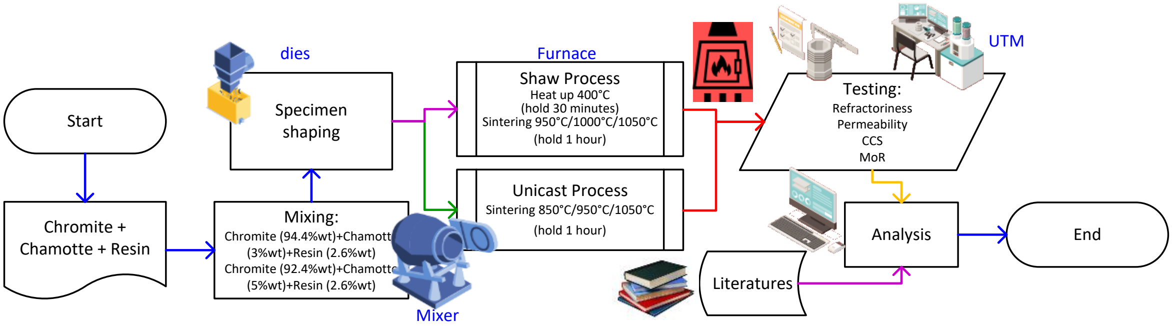

Figure 4. Flow diagram of the research process and equipment used.

The chromite sand was first cleaned of impurities before being combined with chamotte sand and binder. The composition of the chromite sand, chamotte sand, Fenotec 810 resin, and its hardener, Fenotec H40, is 94.4%:3%:2%:0.6% (wt) and 92.4%:5%:2%:0.6% (wt). During the mixing process, no extra solvent or dispersing agent was utilized. Permeability, refractory, MoR, and CCS specimens are formed once the sand and binder have been thoroughly combined. The specimen will thereafter undergo two processes: the Unicast Process, which does not require preheating but is directly sintered (850°C, 950°C, 1,050°C) with 1 hour holding time, and the Shaw Process, which uses preheating (400°C – 30 minutes hold) followed by sintering (950°C, 1,000°C, 1,050°C) with 1 hour holding time. The specimens were then tested including porosity (ASTM C 20), refractoriness (ASTM C 24), CCS (ASTM C 133) and MoR (ASTM C 133). The number of specimens for each variable was 10, examples of MoR and CCS specimens are shown in Figure 5. The test data were then analyzed and discussed so that a conclusion could be drawn.

The porosity (permeability) test used 50 x 50 x 50 mm specimens, were heated to 816°C and then exposed to water as a saturation media. The PCE (refractoriness) test used 6.91 x 16.38 x 27,46 mm cone specimens were heated with 150°C/h and then removed at 1000°C. The softening of the cone (as a PCE) will be indicated by the top bending over and the tip touching the plaque. The CCS and MoR specimens used 51 x 51 x 51 mm and 228 x 51 x 51 mm bars specimens, respectively. The specimen CCS and MoR were loaded to failure using a mechanical testing machine. The maximum applied load is recorded as total maximum load (W) for CCS or maximum applied at rupture (P) for MoR. Calculate the CCS and MoR using equivalence (1) and (2), respectively:

$$S = \frac{W}{A} \qquad \text{...... (1)}$$

$$MOR = \frac{3PL}{2bd^2} \qquad \text{....... (2)}$$

Where:
S = CCS (MPa)
W = total maximum load indicated by the testing machine (N)
A = average of areas of the top and bottom of the specimen perpendicular to the line of application of the load (mm^2)
MOR = MoR (MPa)
P = maximum applied at rupture (N)
L = span between supports (mm)
b = breadth or width of specimen (mm)
d = depth of specimen (mm)

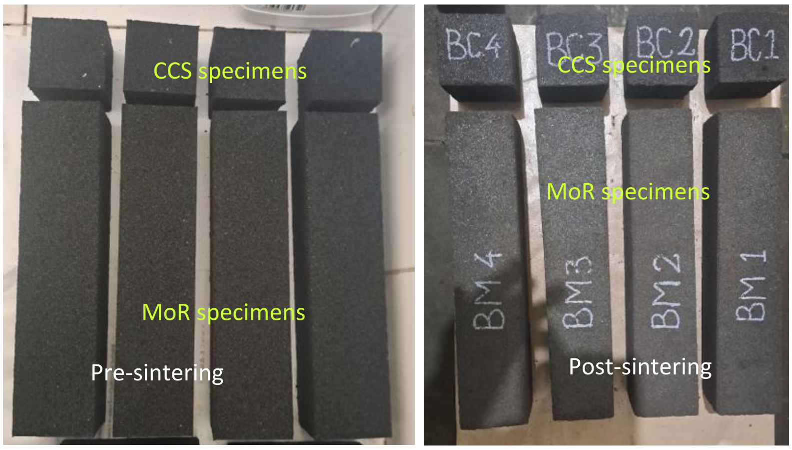

Figure 5. CCS and MoR specimens before and after sintering.

The research was conducted at the Materials Testing Laboratory, Mechanical Engineering Department, AKPRIND Indonesia University as a place for specimen making and CCS testing, as well as the Center for Ceramics and Non-Metallic Minerals, Bandung, as a place for refractoriness, porosity, CCS and MoR testing as shown in Figure 5. The processing of test result data uses standard statistical calculations (mean and standard deviation) where the graphs obtained are analyzed to see the trends.

RESULTS AND DISCUSSION

Two sintering process conditions, the Shaw and Unicast processes—are used to display the test results. The outcomes of this study are compared with research data from Umam et al. [5] using secondary data (chromite). Figures 6 and 7 illustrate the impact of sintering temperature with the Unicast process on the CCS and MoR properties. The CCS and MoR properties for a mixture of chromite sand with chamotte (3% and 5%) exhibit a higher tendency than pure chromite sand, where the CCS and MoR values increase with increasing sintering temperature. In the meantime, Figures 8 and 9 illustrate how the Unicast process's sintering temperature affects the specimen's porosity and refractory qualities. The property values for chromite sand with chamotte (3% and 5%) are typically lower than those for pure chromite sand. On the other hand, chromite-chamotte sand's refractory and permeability qualities are greatly increased by raising the sintering temperature. Compared to 3% chamotte, 5% chromite-chamotte sand has greater CCS, MoR, refractoriness, and permeability values.

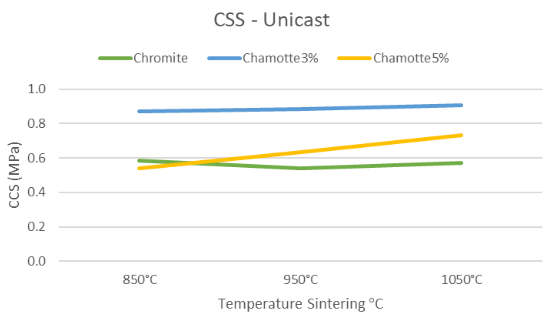

Figure 6. Unicast CCS

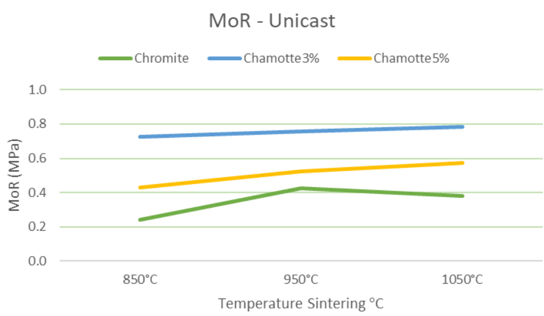

Figure 7. Unicast MoR

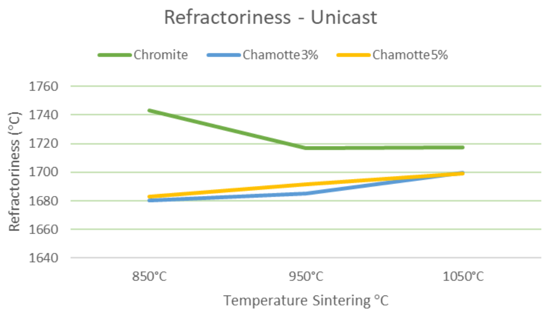

Figure 8. Unicast refractoriness

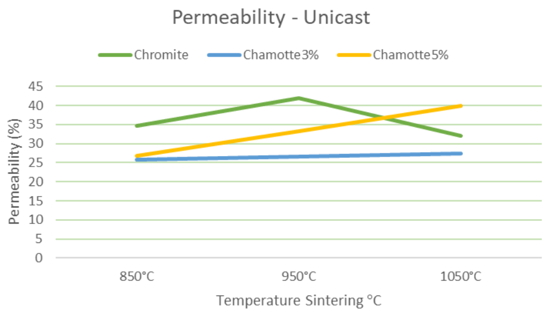

Figure 9. Unicast permeability

In the meantime, Figures 10 and 11 illustrate the impact of sintering temperature using the Shaw process on CCS and MoR characteristics, where there is a trend for these qualities to rise as sintering temperature increases. The CCS and MoR values of chromite – chamotte sand are higher than pure chromite sand, where the 3% chamotte mixture is higher than 5% chamotte in this Shaw sintering method. The refractory and permeability properties following the Shaw sintering process are illustrated in Figures 12 and 13, where the results increase dramatically with increasing sintering temperature, however the refractory and permeability values of chromite – chamotte sand are below pure chromite sand. Although the values and permeability have not revealed any appreciable variations between the two combinations, the refractory value of the 3% chamotte mixture seems to be higher than that of the 5% chamotte mixture.

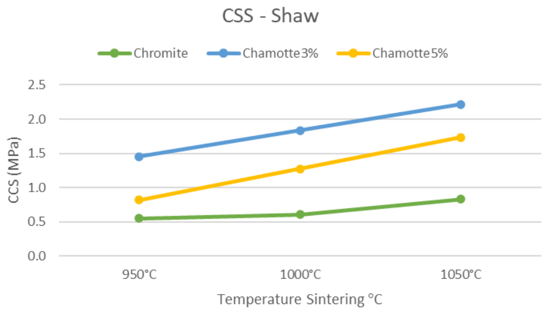

Figure 10. Shaw CCS

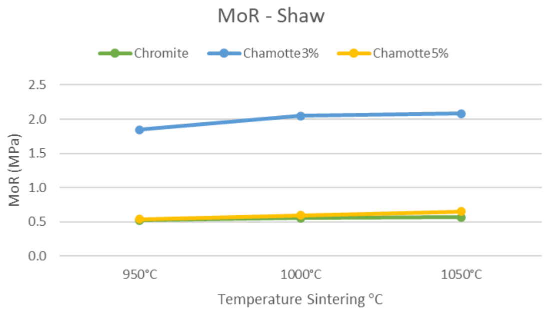

Figure 11. Shaw MoR

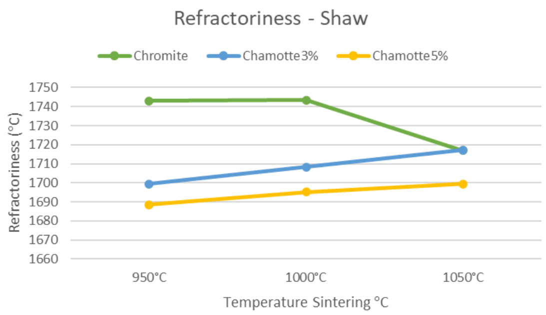

Figure 12. Shaw refractoriness

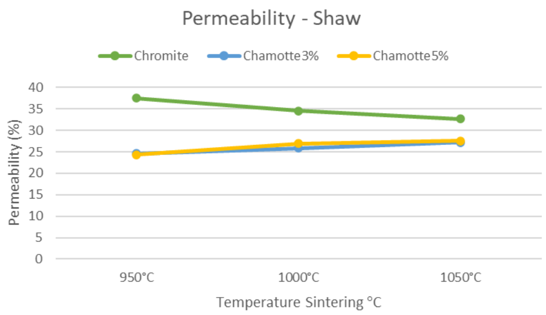

Figure 13. Shaw permeability

Using both Unicast and Shaw sintering techniques, the CCS and MoR values of chromite-chamotte sand (3% and 5%) are generally greater than those of pure chromite sand. The sand mold is nonetheless classified as being in the SK32-33 or super duty category even though the refractory and permeability qualities of chromite-chamotte sand (3% and 5%) are typically lower than the values of pure chromite sand for both sintering processes [15]. CCS values for 3% and 5% chromite-chamotte sand are compared in Figures 14 and 15, where the Shaw method yields greater values than the Unicast procedure. This is because the residue from the resin binder has been greatly reduced using the Shaw procedure [5].

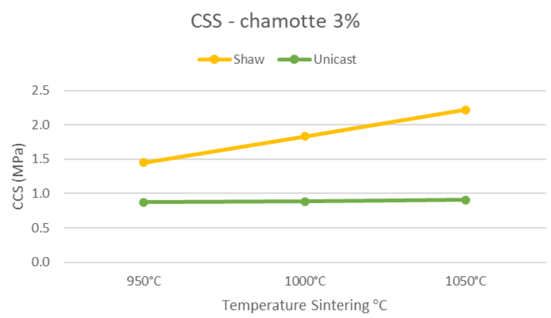

Figure 14. CCS chromite-chamotte 3%

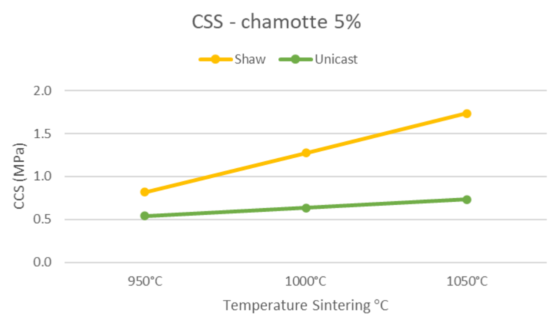

Figure 15. CCS chromite-chamotte 5%

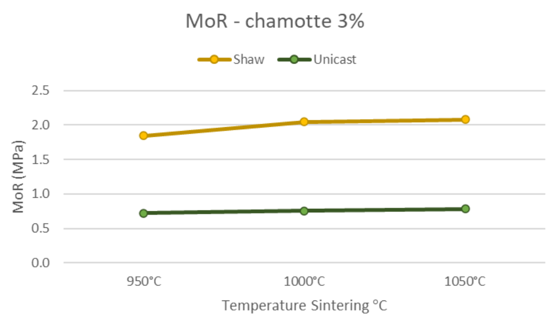

Figure 16. MoR chromite-chamotte 3%

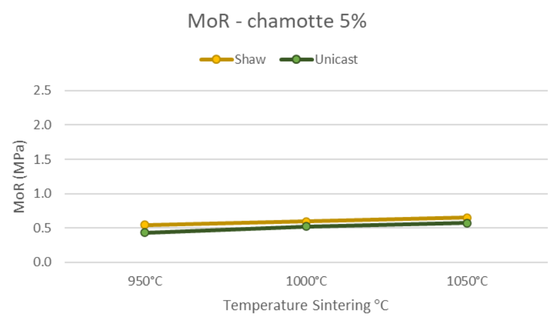

Figure 17. MoR chromite-chamotte 5%

As shown in Figures 16 and 17, the MoR value generated by the Shaw sintering process is higher than the Unicast process in accordance with the CCS value. However, the increase in MoR for a mixture of 5% chromite - chamotte sand is not as high as the results of 3% chromite - chamotte sand, this requires further review related to inappropriate manufacturing procedures or whether the binding ability of 5% chamotte sand to chromite sand has reached saturation. The refractory property value is likewise in line with the CCS and MoR, where the results of the Shaw sintering method show higher than the Unicast process (see Figures 18 and 19).

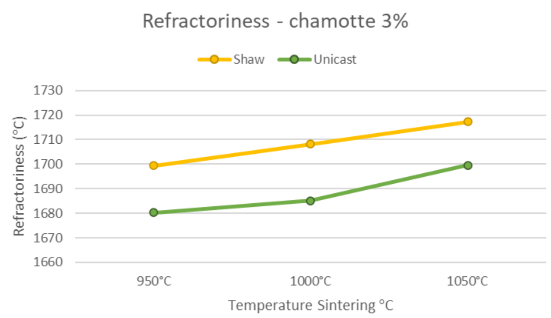

Figure 18. Refractoriness chromite-chamotte 3%

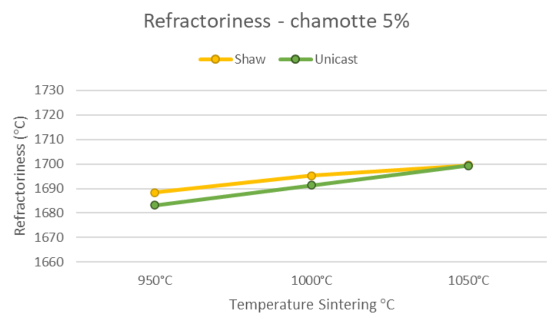

Figure 19. Refractoriness chromite-chamotte 5%

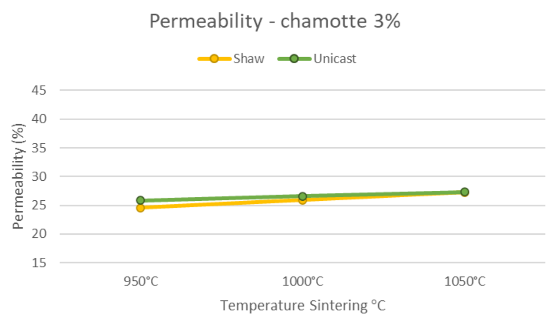

Figure 20. Permeability chromite-chamotte 3%

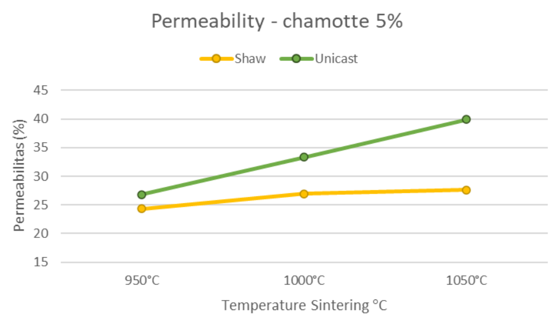

Figure 21. Permeability chromite-chamotte 5%

The permeability characteristics of the Unicast sintering process are higher than those of the Shaw method, as seen in Figures 20 and 21. Permeability is a combination of grain form and size, as well as the binding ability, in this case chamotte sand and resin. So, it needs more examination utilizing SEM on this mold. The CCS test results of chromite sand - chamotte both Shaw and Unicast methods are substantially superior to the test findings of Widianto, et al., [16] which are 0.14 - 0.45 MPa. In general, the Shaw process sintering results produce higher CCS, MoR and refractory properties than the Unicast process sintering on a mixture of chromite sand - chamotte 3% and 5%, with the permeability of the 5% chamotte mixture Unicast process reaching the highest value. Increasing permeability generally reduces mechanical strength, and vice versa. Both properties are largely determined by the material's pore structure, which is controlled during the fabrication process.

The results of CCS, MoR, refractoriness and permeability tests were subsequently validated by creating ceramic molds from 3% and 5% chromite-chamotte sand which were sintered using the Shaw and Unicast methods with a maximum temperature of 1050°C. The chromite-chamotte sand mold prior to sintering is depicted in Figure 22.

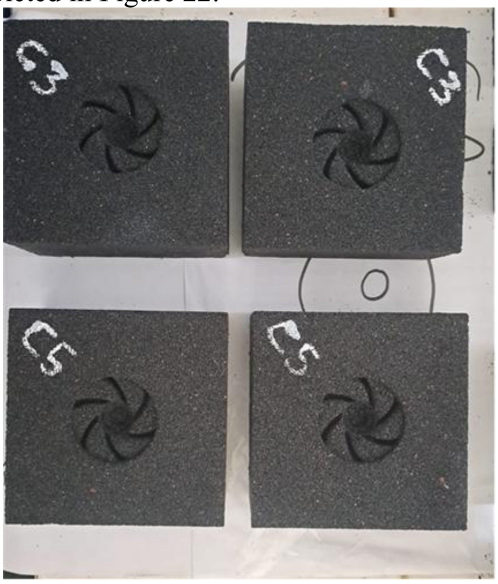

Figure 22. Chromite – chamotte sand mold before Shaw and Unicast processes.

Figures 23 and 24 show ceramic molds made of 3% chromite-chamotte sand after sintering with the Shaw and Unicast processes at a final sintering temperature of 1,050°C. No cracks are seen in the ceramic mold, indicating that the chamotte sand binder works well, thus improving the ceramic molding ability of pure chromite sand. Figures 25 and 26 show ceramic molds made of 5% chromite-chamotte sand, which are also denser than the 3% chamotte mixture. According to the findings of the permeability test of 5% chromite-chamotte sand using the Unicast technique, which has a higher value than the others, Figure 26 appears to have more porosity than the other ceramic molds. In order to prevent the gases produced by the reaction between the molten metal and the molding sand from becoming trapped in the metal solidification and creating cavity flaws, this permeability is crucial.

Figure 23. Shaw chromite-chamotte 3%

Figure 24. Unicast chromite-chamotte 3%

Figure 25. Shaw chromite-chamotte 5%

Figure 26. Unicast chromite-chamotte 5%

CONCLUSION

When compared to pure chromite sand as a ceramic mold material, the inclusion of 3% chamotte sand with the Shaw Process sintering has been shown to have better CCS, MoR, refractoriness, and permeability values. While the addition of 5% chamotte sand indicates a considerable decrease in permeability, the ceramic mold forming did not reveal any cracks. It should be mentioned, though, that the Shaw method is more expensive than the Unicast method.

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