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Evaluation of Sodium Metasilicate Pentahydrate as a Solid Binder for Foundry Sand

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Abstract

Sodium silicates are among the most widely used inorganic binders in sand moulding for metal casting, yet significant differences in handling, curing, and final casting performance persist across available forms. Liquid sodium silicate binders dominate in current foundry practice, but they pose challenges in transport, storage, and mixing uniformity. To address these limitations, dry silicate powders like sodium disilicate powder have been researched in prior studies, demonstrating favourable moulding and final casting characteristics. Building on this approach, the present study examines sodium metasilicate pentahydrate ($Na_2SiO_3 \cdot 5H_2O$) as an alternative binder for sand moulding applications. Experimental mixtures were prepared using reclaimed silica sands, with variations in water and binder contents to assess the effect on mould strength. Selected formulations were further subjected to small-scale casting trials to evaluate mould integrity and surface finish. The results indicate that sodium metasilicate pentahydrate can achieve high mould strength through thermal hardening, providing performance comparable to that of conventional industrial binders. Casting trials also revealed good as-cast surface condition. These findings suggest that this binder represents a promising alternative for inorganic sand moulding in metal casting.

Keywords:

sodium metasilicate pentahydrate, sand moulding, binder optimisation, mould strength, metal casting

1. INTRODUCTION

As manufacturing increasingly adopts sustainable practices, sand casting is likewise shifting towards lower-emission processes. This shift has renewed interest in inorganic sodium silicate binders, which are more environmentally friendly and better for workers' health by reducing harmful volatile organic emissions at elevated temperatures compared to organic binders [1–3]. Other advantages include a reduced need for costly air filtration systems and little to no unpleasant odour, thereby helping foundries maintain cleaner working environments. Moreover, tighter environmental regulations may make compliance increasingly difficult for foundries that use organic binders. For example, EU BAT/BREF frameworks encourage foundries to move from high-emission organic binders towards low-emission alternatives. Inorganic sodium silicate binders currently have particularly strong potential in this context.

Traditionally, liquid sodium silicates have been used in foundry practices. Modified sodium silicate binders are already being used in aluminium casting for critical automotive components [4]. However, solid sodium silicate binders are now attracting interest because their lower weight and longer shelf life make them easier to transport, store and use [5]. Solid binders may also simplify 3D printing of sand moulds. If a mixture of sand and solid binder is spread over the printing bed, only thickened water needs to be jetted [5–7]. As viscous binder is not being jetted through the printhead, maintenance requirements are reduced, and printhead service life increases.

Several solid forms of sodium silicate are available. One example is the hydrous sodium disilicate (SDS) powder that has been studied in numerous past studies. Good mould strength was demonstrated, and the effects of different additives were determined [5, 8, 9]. Casting trials have produced good quality results with aluminium and different cast irons. The powder has been used in 3D sand printing as well with good results [7]. Hydrous forms with a lower molar ratio typically dissolve faster in water [10], making them more suitable for foundry operations. The molar ratio is the ratio of silicon dioxide to that of sodium oxide in the silicate, and for the most used liquid sodium silicates in foundries, this is typically between 2 and 2.9 [3].

The current study investigates another alternative for the same purpose: sodium metasilicate pentahydrate (SMP). It broadens the portfolio for solid binders and may also possess other potential advantages, such as reduced dusting or caking, or improved pH regulation. The production of SMP also demands lower raw material and energy consumption compared to SDS production [11], making its use a more sustainable choice for sand casting. Heat hardening of the SMP binder is investigated in the current study.

Sodium metasilicate pentahydrate

Sodium metasilicates have a molar ratio of one, which means the ratio of silicon dioxide to that of sodium oxide is one. Anhydrous metasilicates are devoid of any water, metasilicate pentahydrates have five moles of crystalline water, while nonahydrates have nine moles of crystalline water in their structure. Although the melting point of SMP is given as 72°C on data sheets, sodium metasilicate pentahydrate dehydrates rather than truly melting at this temperature. It starts losing its water of hydration and forms a viscous liquid mixture of silicate and water. True melting of anhydrous Na_2SiO_3 occurs at a much higher temperature. However, this phenomenon also provides a unique opportunity in the way it is used as a sand mould binder. Apart from utilising the metasilicate in a similar fashion to the previously studied disilicate powder, where additional water was added separately, it was also a point of interest in the current study to determine if SMP binder can be used without additional water, by investigating whether the water released by heating is enough to successfully bond the sand. SMP was also used in the preparation of silicate-coated sand in a recent study [12].

The first step in the industrial manufacture of sodium metasilicate pentahydrate is to produce a sodium metasilicate solution, either by dissolving sodium silicate glass or by reacting amorphous silica with sodium hydroxide [13]. The solution composition is adjusted with NaOH to obtain a SiO_2:Na_2O ratio of about 1.0, forming a metasilicate feed liquor [13]. This liquor is then concentrated in an evaporator and cooled in a crystalliser, where controlled supersaturation leads to the preferential crystallisation of sodium metasilicate pentahydrate ($Na_2SiO_3 \cdot 5H_2O$). The crystals are sized and screened, with the fine ones recycled, yielding a free-flowing pentahydrate product [13].

2. MATERIAL AND METHODS

Micrographs of both binders used in the study are shown in Figure 1, at the same magnification. Sodium disilicate (SDS) was used as a control because it had been investigated in previous studies, providing extensive data for comparison [8, 9, 14, 15]. The SDS powder has a molar ratio of 2.0, mean particle size of 70 µm, and water content of 16–20%. By contrast, the sodium metasilicate pentahydrate (SMP) used in this study had a much larger granule size than the SDS, a molar ratio of 1.0, and purity of at least 95%. The tests were conducted with reclaimed silica sand that had been thermally reclaimed from a system using a phenolic binder. The mean particle size of the sand was approximately 330 µm, and the AFS grain fineness number (GFN) was 45.3.

2.1. Sand and binder mixture preparation

Two different mechanisms are investigated in this study. The first tests the addition of extra water (Mechanism 1), and the second adds no extra water, so tests the solid binder alone (Mechanism 2).

Mechanism 1: During mixture preparation, the binder was first mixed with the sand; water was then added and the mixing continued until a uniform mixture was obtained. A laboratory stand mixer with three speed settings was used for this purpose. First, the sand and solid binder were mixed at the lowest speed for 30 seconds (136 RPM). Water was then added, and the mixing continued at a faster speed (281 RPM) for another 30 seconds. Finally, it was mixed at the highest available speed (580 RPM) for one more minute to ensure a uniform mixture. The initial SMP formulation contained 0.83% binder and 1.17% water. However, this composition did not dissolve the metasilicate adequately, as large granules of the binder remained undissolved; therefore, more water was added to the SMP binder.

Mechanism 2: No additional water was used. The sand was first heated to 160°C and then mixed with the binder at speed level 2 (281 RPM) for 30 seconds, followed by one minute at the highest speed setting (580 RPM). This raised the temperature of the binder above its apparent melting point of 72°C, releasing some of the crystallised water and converting the binder into a viscous phase. This mixing distributed it over the sand as a thin film. The binder dosage, 3% of the sand mass, was significantly higher than that used in Mecha-

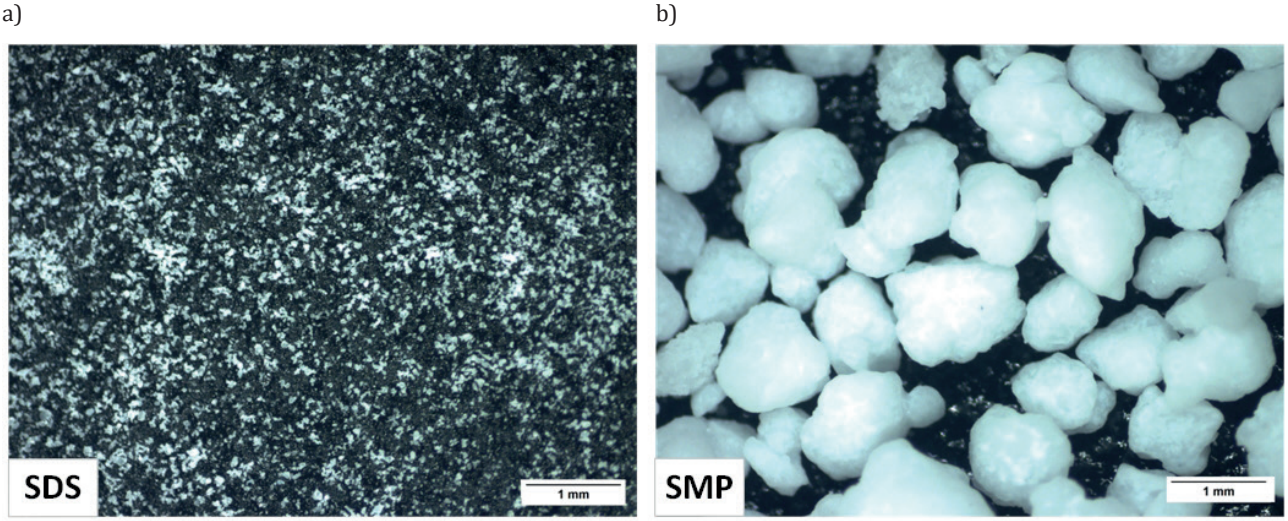


Fig. 1. Micrograph of the solid binders used in the study: a) SDS; b) SMP

nism 1. This dosage was selected to align with a recent study that utilised SMP to produce silicate-coated sand [12].

2.2. Bending strength tests

Each sand mixture was placed into a metal core box to produce bending-strength test bars and heated at 160°C for one hour. The test bars measured 172 mm in length and had a cross section of 22.4 mm × 22.4 mm. After removal from the oven, they were allowed to cool for 30 minutes before the bending strength test was carried out using an LRu-2e/w Multiserw Morek Universal Strength Tester. Three samples were tested, and the mean is reported.

2.3. Moulding and casting trial

Sand moulds were produced with reclaimed sand and a heat-resistant pattern, as shown in Figure 2. The heat-resistant pattern was fabricated using an SLA printer and a resin that the manufacturer states are heat resistant up to 230°C. The pattern's heat resistance allowed the pattern to remain inside the drying oven with the mould, which was heated at 160°C for one hour.

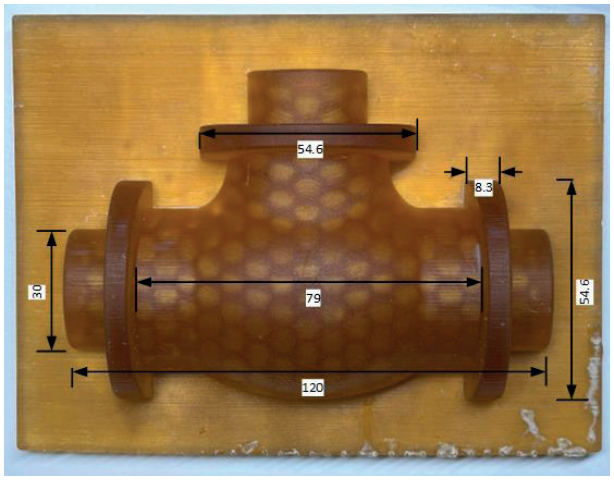


Fig. 2. SLA printed heat-resistant pattern, dimensions in millimetres

Four different surfaces were investigated with four different moulds, by casting two complete metal valves. The first mould was made with SDS, sodium disilicate binder (0.83%) and 1.17% water and designated SDS. This served as the reference. The second mould was produced with 1% sodium metasilicate pentahydrate and 2% water by the sand mass and designated SMP. This binder content was chosen as it produced the highest strength through Mechanism 1. Two more surfaces were investigated, with two different water-based coatings applied. These are designated SMPC1 (coating 1) and SMPC2 (coating 2). Coating 1 is a water-based coating containing a ceramic of aluminosilicates, corundum and graphite. Coating 2 is a water-based coating with an aluminosilicate matrix and added graphite. Both coatings are produced by the same manufacturer for iron castings. The coatings were mixed and gently brushed onto the surface of the mould, followed by air drying at room temperature. The cores were not coated. The casting alloy used was grey cast iron GJL-250. The surface was examined both visually and using a 3D optical profilometer after casting. 2 mm by 2 mm areas were investigated with the profilometer, micrographs were taken, and the profilometer software (Vision 64) was used to calculate an overall surface roughness, R_a of the surface. Compensating measures were used to convert curved surfaces to planar before surface roughness calculation using the profilometer software.

3. RESULTS

3.1. Mould strength and mould preparation

SMP binder with reclaimed silica sand demonstrated good mould strength. Figure 3 shows the bending strength achieved with SDS, and SMP with varying water and binder contents; error bars correspond to ±1 standard deviation.

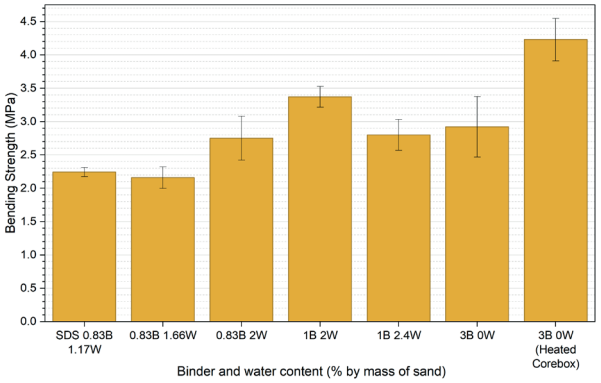


Fig. 3. Bending strength with different binder and water compositions

The sample nomenclature is expressed as xB yW, where x denotes the binder content (wt.%) and y denotes the water content (wt.%), both calculated with respect to the sand mass. For example, 0.83B 2W represents a mixture containing 0.83 wt.% binder and 2 wt.% water, while 1B 2W represents 1 wt.% binder and 2 wt.% water. When Mechanism 1 was used, the bending strength achieved with SDS (0.83B 1W) was approximately 2.20 MPa. When the same amount of water and binder was used with the SMP, most of the granules remained undissolved after mixing. Hence, it was decided to increase the water content in the subsequent tests. With the same amount of binder (0.83%) and an increased water content of 1.67%, the bending strength attained with SMP was almost as high as SDS, at about 2.10 MPa. Small undissolved white granules of the SMP could still be seen at this water level. Hence, another test was carried out with even more water, which achieved a slightly higher strength of about 2.75 MPa. The maximum strength attained with this binder in this mode of usage was when 1% SMP was used with 2% water, which reached a bending strength level of 3.40 MPa. This combination was chosen to be used for the casting trials. When 2.4% water was added to 1% binder, the strength dropped to about 2.80 MPa. The last two columns in Figure 3 show

the bending strength achieved with Mechanism 2 with 3% binder and no additional water. The bending strength reached was about 2.90 MPa when the sand mixture was put into a core box at room temperature before heating in the oven. However, when the test bars were produced in an already heated core box, the strength reached was well over 4.00 MPa, as shown in the last column of Figure 3. Figure 4 shows the SMP mould, with 1% sodium metasilicate pentahydrate and 2% water, produced with reclaimed silica sand, while Figure 5 shows the very small white undissolved granules of SMP visible before heating in the oven. The image was processed and some colours were adjusted to make the white granules more visible to the reader. Figure 6 shows the different moulds chosen for the casting trial prior to assembly and pouring. Figure 7 shows a mould produced with Mechanism 2, SMP 3% binder and no water. It is evident from the image that uniform density was not achieved, and that there are breakages in the areas where there was contact with both the pattern and the flask. Although the mould held the general shape, Mechanism 2 needs to be optimised before it could be used for moulding. For example, the pattern could be preheated, or the sand could be heated to a much higher temperature to prevent the mixture from rapidly losing its workability.

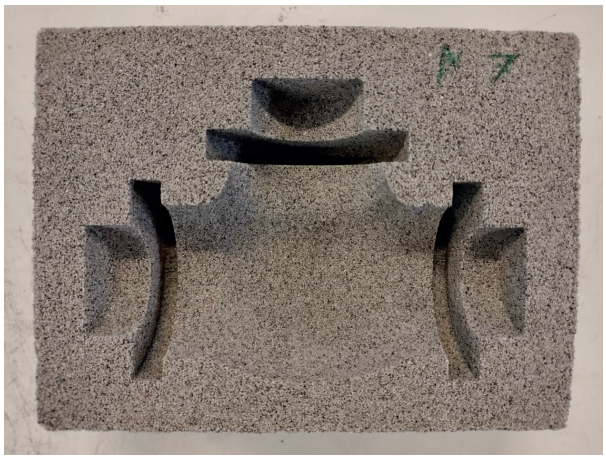


Fig. 4. SMP mould showing good mould surface (1% binder, 2% water)

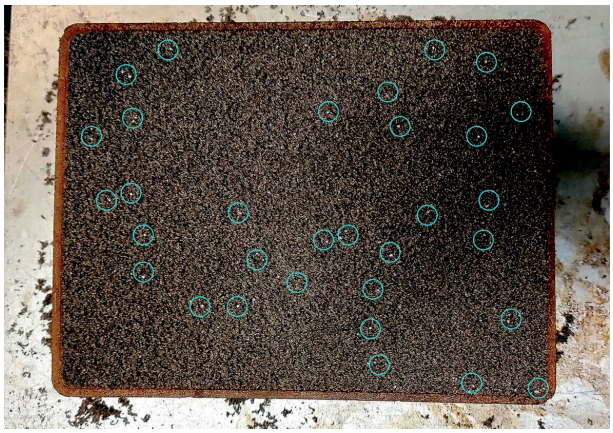


Fig. 5. Small undissolved granules (some are circled in cyan) of SMP before heating the mould in the oven (1% binder, 2% water). Image was processed to enhance the appearance of white SMP granules

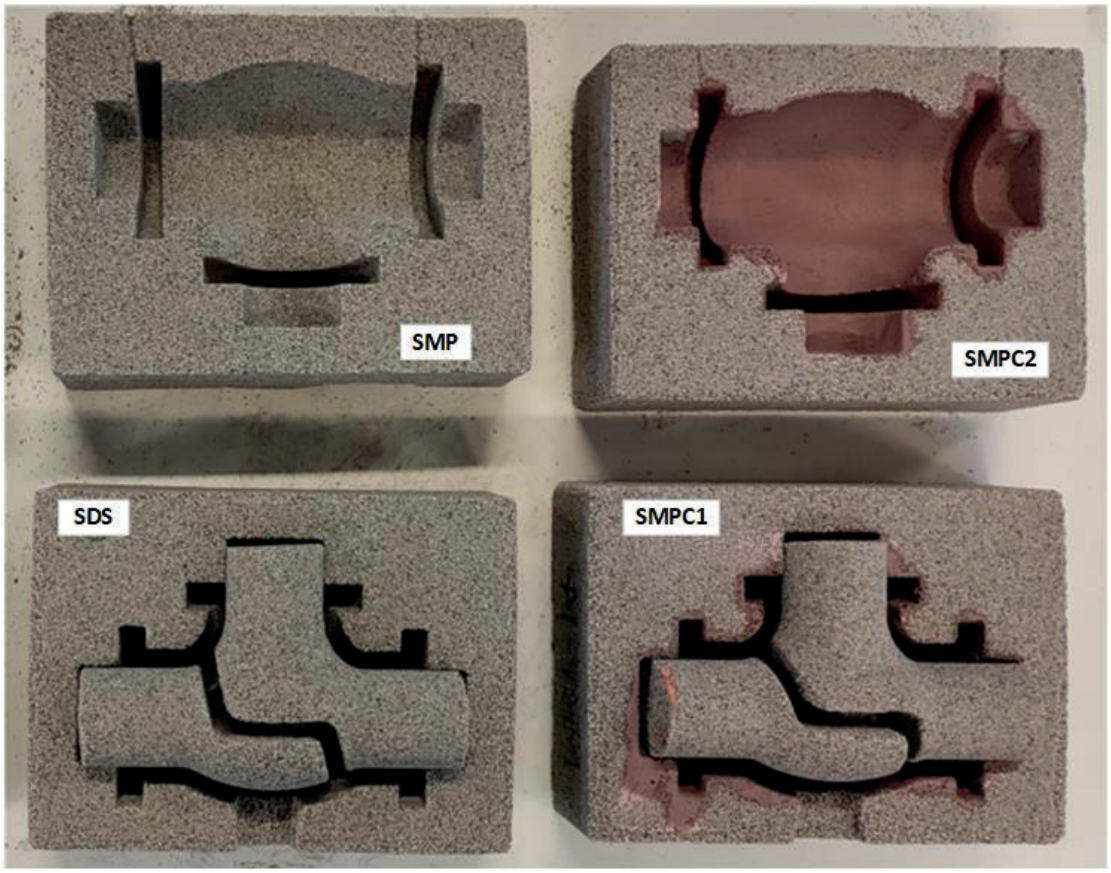


Fig. 6. Moulds and cores, prior to assembling the mould for casting

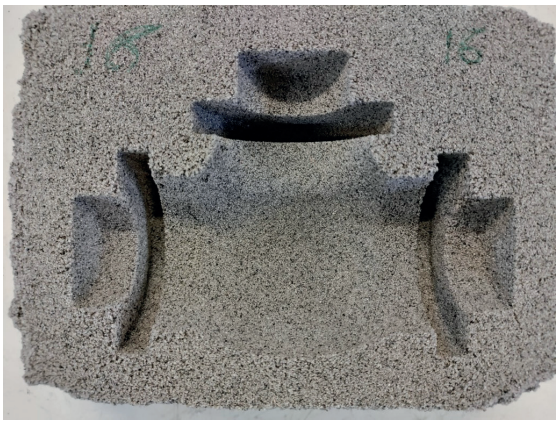


Fig. 7. A mould produced using Mechanism 2, 3% binder and no additional water

3.2. Casting trial

Good cast results were obtained with SMP. A better surface was obtained in comparison to the control (SDS). Figure 8 illustrates the surfaces obtained with the control SDS, presented in the blue section of the image (top), while the SMP is presented in the orange section (bottom). The surface roughness value (R_a) is marked in different parts of the casting. Across different sections, the roughness was less with SMP compared to SDS. In general, the flange areas had a better surface finish than the middle section. Castings produced with the two coatings are shown in Figure 9. Both coatings improved the surface slightly; however, some reddish residue was seen on the surface with coating 2.

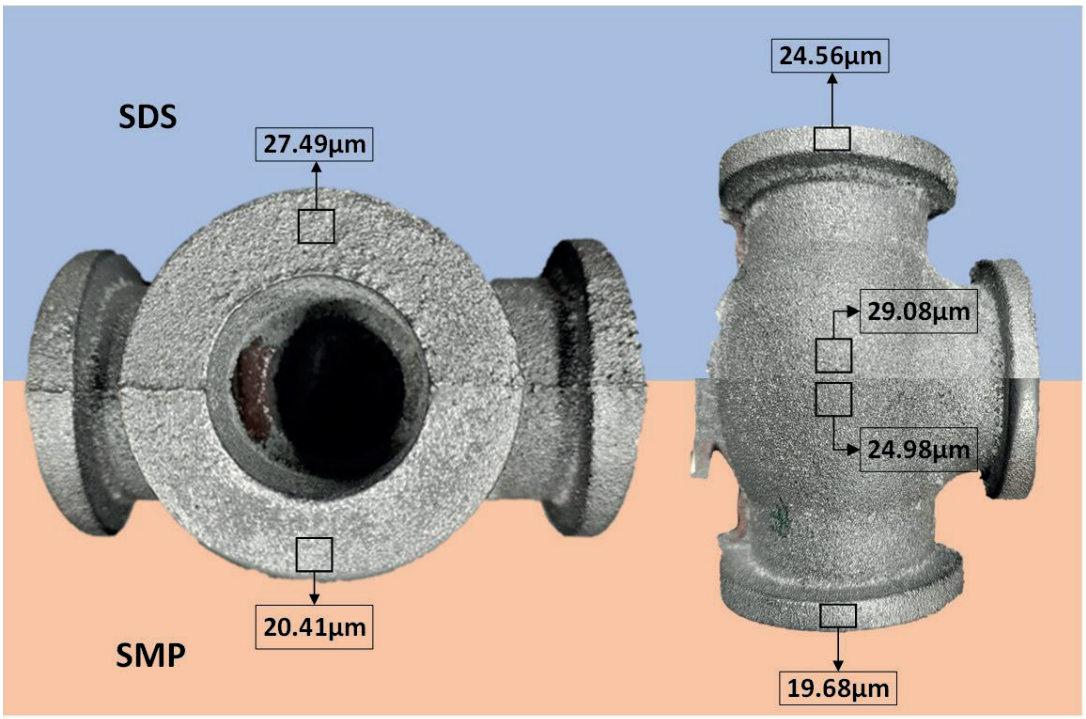


Fig. 8. Casts produced with SDS (top section) and with SMP (bottom section)

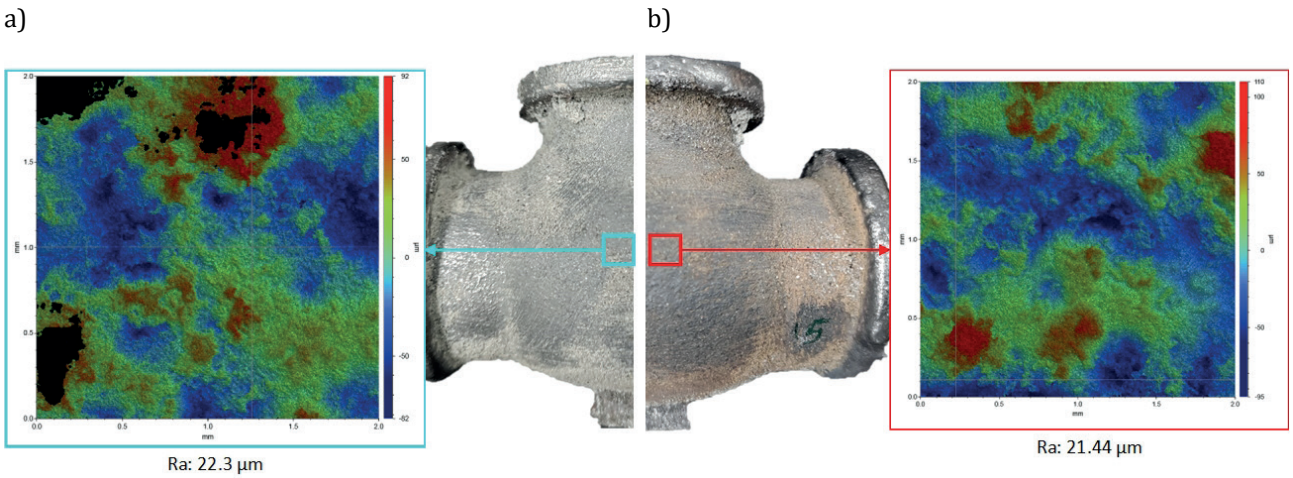


Fig. 9. Castings produced with the coatings: a) SMPC1; b) SMPC2 (insets show optical micrographs of the surfaces)

4. DISCUSSION

The tested sodium metasilicate pentahydrate binder performs effectively well as a foundry sand binder, with successful moulding and casting demonstrations. However, some optimisation needs to be considered to improve the process. The highest strength demonstrated was with 1% binder and 2% water. However, as was demonstrated, traces of undissolved binder could be seen in the sand + binder + water mixture. Potential solutions to this could be to improve the mechanical mixing or to decrease the grain size of the SMP used. Smaller granules increase the solubility and decrease the dissolving time, although it must be pointed out that too small a grain size will also increase the dusting tendency. When the highest amount of water was used in this study (2.4%) against a binder addition of 1%, the undissolved granules were reduced but not eliminated. However, a reduction in strength was noticed at this water addition rate. This is likely due to the presence of too much water, and complete dehydration was not achieved within the heating time used in the experiment. The binder content was not increased beyond 1% with Mechanism 1, as adequate strength was already achieved.

The use of SMP without additional water is promising, as it eliminates the step of adding water. Directly transferring the mixed sand–binder to the oven was not tested as this approach was not expected to evenly distribute the binder across the sand particle surface. Instead, the sand was first heated to 160°C before 3% binder by sand mass was added. The heat of the sand turns the binder into a viscous liquid, which is then mixed into the sand particles, forming a coating over the sand. It must be stated at this point that the mixture behaves more like a viscous paste, and the uniform flow characteristic required of moulding sand is not achieved. Also, as the mixture continues to quickly lose heat, it becomes difficult to shape into the desired form. However, during the bending strength test, it was possible to shape it into the test bar core box quickly, which was then heated again in the oven at 160°C. Some discontinuity could be seen across the test bars, which may have contributed to some loss in strength. Despite this, a bending strength of 2.90 MPa was achieved. When a cold core box was used, the sand mixture lost heat very quickly, making it difficult to work with. A second attempt was made where the test bar core box was heated to 160°C before the sand and binder mixture was added. This improved the bending strength to about 4.20 MPa. It should, however, be noted that a much higher binder addition rate was used for Mechanism 2 compared to Mechanism 1. Moulding with Mechanism 2 was tried as well. Although it was possible to produce the general mould shape, as with Mechanism 1, since the sand was losing heat very quickly, the mouldability was lost very quickly, and it was difficult to achieve uniform compaction and density across the entire mould. However, it should be noted that the process could work adequately for core production in a heated core shooter.

Moulds made with sodium silicate-based binders are prone to penetration damage when cast with grey cast iron. However, good surfaces were achieved with the SMP, even slightly better than the control. The rationale behind the use of grey cast iron was that if good results could be achieved without mould penetration, it would be more likely to produce good results with other types of cast iron as well. It must also be emphasised that large grain sand particles of 330 μm were used in this study and there is a limit to how smooth a surface can be realistically obtained with sand particles of this size.

The use of coatings to protect mould surfaces from extremely high-temperature molten metal is an established foundry practice. Also, when sodium silicate binders are used, they may react with silica sand at very high temperatures to form a glass-like layer that is very hard to remove.

The industry focus is currently to change from alcohol-based to water-based coatings out of concern for environmental protection. Thus, two different water-based coatings were used in this study to test their effects. While both coatings improved the surface slightly, a reddish appearance was noted in the case of SMPC2. The coatings were air-dried by keeping them exposed to open air for some time before casting. For aluminium castings, the temperature is much lower, and coatings are typically not required.

Sodium metasilicate nonahydrate ($Na_2SiO_3 \cdot 9H_2O$) is another potential candidate for research into foundry use. However, it must be noted that nonahydrates have more water molecules, which may prove useful in the case of Mechanism 2, although the presence of large amounts of water reduces the share of sodium silicate. Therefore, more binder by mass may be necessary with the use of nonahydrates.

5. FUTURE WORKS

The current work can be extended in several directions, which are outlined below:

- Further research into the use of sodium metasilicate pentahydrate, especially in Mechanism 2, without additional water.
- Use of other hardening methods like CO_2 or esters.
- Use of other variants of sodium silicates, e.g. metasilicate nonahydrate, sodium trisilicates etc.
- Use of different silicate powders and solutions in the production of silicate-coated sand.

6. CONCLUSION

Sodium metasilicate pentahydrate has been tested in this study for its suitability as a foundry sand binder for sand casting. Two different mechanisms were tested for mould strength: one with additional water and one without. For Mechanism 1 with added water, more water was necessary compared to sodium disilicate powder for effective solubility with sodium metasilicate pentahydrate. Highest mould strength was achieved with 1% binder and 2% water, with respect to sand using Mechanism 1. Good mould strength and mould surface quality was demonstrated with reclaimed silica sand (reclaimed from a system utilising a phenolic binder). Casting surface produced was smoother than the control SDS. Water-based coatings also worked well with this binder and improved the surfaces slightly.

Good strength was also demonstrated using Mechanism 2; however, there are challenges to be overcome if it is used for moulding. All in all, sodium metasilicate pentahydrate has strong potential for use as a solid foundry binder.

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