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Selection of Molding Sands for Thin-Walled Cast Iron Castings Based on Their Selected Properties

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Abstract

The production process of thin-walled iron castings with complex shapes, characterized by high quality while maintaining the required properties, involves many steps. One of them is the appropriate selection of the technology for molding and core sands, taking into account strict environmental requirements. The need to meet high environmental standards is currently the dominant factor in the development of molding sands technologies. It is even being done at the expense of reducing the technological properties of the materials. As part of the development of molding compounds for thin-walled castings, two compounds with organic binders and two compounds with inorganic binders were tested. Tests were carried out on the tensile and bending strength, density, permeability, and friability of the compounds. Their thermophysical behavior was tested via the hot distortion parameter. The tests carried out on the molding sands showed that all the proposed mixtures have the appropriate properties for the production of thin-walled castings.

Keywords:

thin-walled castings, environmental protection, molding sand, resin, inorganic binder

1. MOLDING MATERIALS VS. GREEN DEAL POLICY

Molding materials are all the raw materials, materials, and products used to make sand molds. Molding sand is a mixture of various molding materials, processed in a specific way and selected in appropriate proportions. Among the numerous classifications of molding sands [1–3], the classification proposed by P. Jelínek [4] stands out for its simplicity and substantive justification.

This classification divides compounds into four generations depending on the type of binding material:

- Generation I – molding sands in which clays are used as binding materials,
- Generation II – molding sands in which the binding material is a binder,
- Generation III – molding sands without binding materials, also known as physically bound sands,
- Generation IV – molding sands bound by biotechnological factors.

Generation II molding compounds, i.e., compounds bound with binders, are most commonly used in casting processes. This is due to their high technological properties, but also to their versatility. They can be used for the production of both molds and cores. Due to their advanced technological properties, they are appropriate for the production of thin-walled castings.

The binders used in these technologies are mainly organic binders (based on synthetic resins) and inorganic binders, such as hydrated / solid [5, 6] sodium silicate and aluminosilicates.

The essence of the problem, however, is that technologically perfect synthetic resin-based binders have a harmful impact on the environment. On the other hand, ecological inorganic binders are characterized by poor knock-out properties and low mechanical regeneration capacity.

Two important events initiated pro-environmental activities in the EU: in 1972, the first United Nations Conference on the Human Environment was held in Stockholm, which approved the principles of sound environmental management, including the Stockholm Declaration; in 1992, the Earth Summit was held in Rio de Janeiro. Many important declarations were adopted at the summit, including Agenda 21 and the Rio Declaration. The international efforts described above led to the adoption of numerous European treaties. Ultimately, in 2007, under the Treaty of Lisbon, climate change and sustainable development became priorities within the European Union [7].

The need to comply with high environmental protection requirements is currently a dominant factor in the development of molding and core technologies. Compliance with these requirements is achieved even at the expense of reducing the technological properties of the compounds used in the production of molds and cores.

These trends have meant that molding technologies and materials that have been used successfully in foundry production processes for decades must be replaced with more environmentally friendly solutions [8–17].

This paper shows the comparison of selected properties of molding sands with both organic (characterized by high hazardous substance emission) and inorganic (ecologically friendly but technologically challenging) binders [18].

2. RESEARCH METHODOLOGY

Within the research, selected properties of molding sands, such as tensile and bending strength, permeability, friability, bench life, and hot distortion parameter, were tested.

2.1. Tests of tensile and bending strength, permeability and friability

Standard dog bone specimens were prepared for tensile tests, and standard longitudinal specimens of length 172 mm and with a square cross-section of 22.4 mm sides were made for bending strength tests. All the tests were done using an LRu-2e/w Multiserw-Morek Universal Strength Tester. Molding sands were compacted by vibration (LUZ-1 device). Strength tests were conducted after 1, 3, and 24 hours of curing. The results presented for all the different tests are the mean of 3 samples tested.

Permeability was measured using the rapid method (with nozzles) on an LPiR1 electric device. The parameter was tested after 1, 3, and 24 hours of self-curing at the ambient temperature of the tested molding sands.

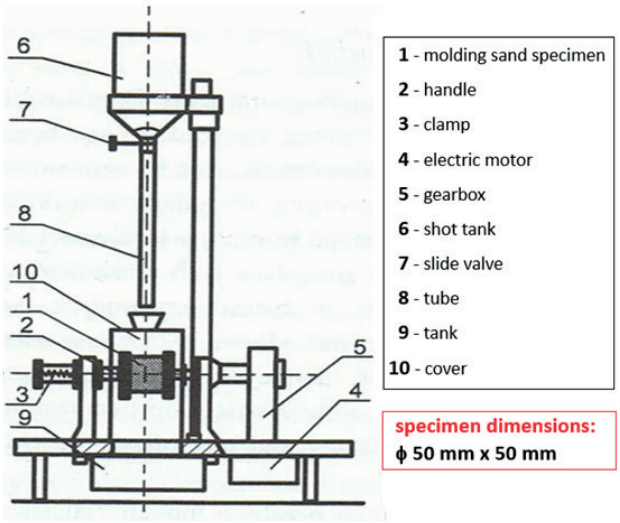

Fig. 1. Scheme of an apparatus for friability testing designed in Poland by the HSW S.A. company [18, 19]

The resistance of the mold surface to abrasion was measured with a friability test. The research was conducted with the usage of an apparatus designed in Poland by the HSW S.A. company. Standard Ø50 mm × 50 mm cylindrical specimens were used after 24 hours of self-curing. The mass of the specimen was first measured, then it was rotated along the horizontal axis (1 rev/s) and 1750 g of steel shots of 1-mm diameter were dropped onto it from a height of 307 mm. After all the steel shots had impacted, the mass of the specimen was measured again. The % change in mass gives a value for the friability. The lower the friability, the more wear-resistant the molding sand. Three specimens were tested for each molding sand, and the results are presented as the arithmetic means. Figure 1 shows the scheme of an apparatus for friability testing designed in Poland by the HSW S.A. company [18, 19].

2.2. Bench life

The bench life was determined by measuring the change in strength over time after the uncompacted molding sand was set aside. In each case, 2 kg of molding sand was prepared. The setting time of the molding sand was measured from the point at which the last component was added. After preparing the molding sands, dog bone specimens were quickly made by compacting a portion of the molding sand in a metal mold, using a standard rammer by striking the weight three times. After the last strike, the time of making the specimen was recorded. The portion of the molding sand was selected so that the height of the compacted sand corresponded to a predefined position on the rammer scale. The specimens were prepared until the molding sand became loose. After 24 hours of self-curing, the strength of the hardened specimens was determined. A graph of the tensile strength versus the setting time of the uncompacted molding sand was prepared based on the results determined.

In the case of linear changes in strength, the bench life was determined as the time after which there was a 30% decrease in strength relative to the maximum possible strength. The maximum achievable strength was determined by adding a trend line to the obtained measurement points. This is a theoretical value obtained for a setting time of 0 h, read at the point of intersection of the trend line with the strength axis [18].

In the case of molding sand with aluminosilicate, the bench life was determined as the time after which there was a sharp decrease in strength – a break in the curve of strength changes [18].

2.3. Hot distortion

The hot distortion (thermal deformation) parameter was investigated using a dynamic mechanical analyzer (DMA) apparatus by Multiserw-Morek. One end of the sample was fixed in the jaws of the device, while a tilt sensor rested on the other (free) end of the specimen with dimensions presented in Figure 2. A temperature sensor was also provided for more accurate temperature reading. The sample was then heated in the middle from below by two halogen lamps with a total power of 500 W. The heating temperature rangeed from room temperature to 900°C. For temperature measurement, the sensor was mounted next to the specimen, at the same height, which means that the temperature was not the temperature in the specimen, but the temperature obtained on the sensor. This means that, depending

on the type and amount of binder used, the specimen may have reached different heating temperatures. However, assuming low thermal conductivity of the grain matrix (more than 96% of the composition of the tested molding sands), these differences are within the measurement error range. The apparatus provides deformation readings as a function of both time and temperature. The maximum deformation reading was set at 6 mm. A schematic diagram of the hot distortion test is shown in Figure 2.

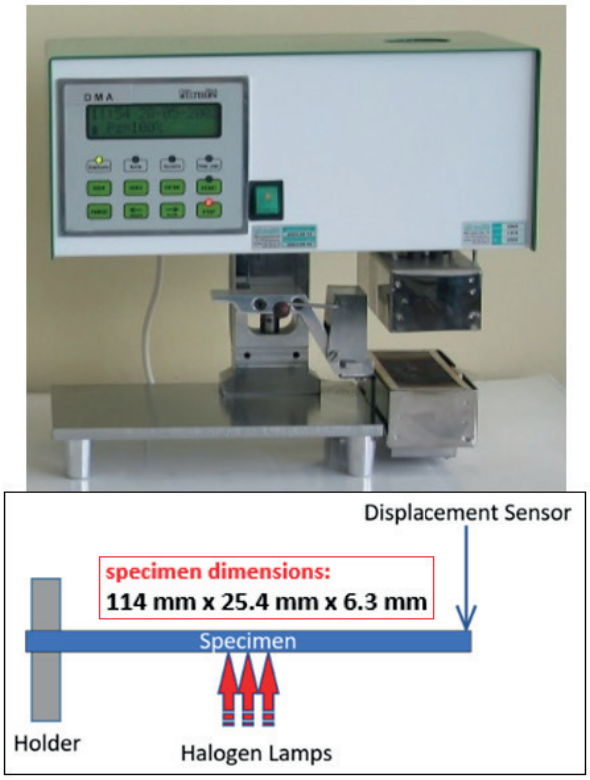

Fig. 2. Prototype device for measuring molding sand deformation at elevated temperatures, DMA-type with a schematic diagram of the Hot Distortion Test, adapted from [5, 18, 20]

3. OWN RESEARCH

The following article focuses on the influence of the binder type and chemical character (organic, inorganic) on the properties of the chosen molding sands dedicated to thin-walled castings. Molding sands' technological properties, such as strength, permeability, friability, and bench life, as well as thermo-physical properties (hot-distortion parameter) were tested.

The research was carried out in the laboratory of the Department of Moulding Materials, Mould Technology and Cast Non-Ferrous Metals at the Faculty of Foundry Engineering AGH University. Both organic and inorganic binders were chosen for the study.

Four representative self-curing molding mixtures with commercial binding materials that are widely used in the foundry industry were chosen for the research. The composition of the compounds is presented in Table 1. From among the compounds containing organic binders, a compound with furfuryl resin of typical composition and a compound with phenolic resin were selected for the tests. The furfuryl resin used in the tests contained 90% furfuryl alcohol, which classifies it as toxic, but ensures the highest technological properties of the molding sands. In the case of the phenolic resin, which is less harmful to the environment, an atypical composition was chosen for the tests, but one that ensures high reactivity of the binding system. The idea was to adjust the system for application in the production of thin-walled castings, ensuring the ability to remove patterns from the mold without damage after a short curing time. From among the compounds containing inorganic binders, a compound with hydrated sodium silicate of typical composition and a compound with aluminosilicate with a reduced amount of the binding material were selected for testing. Such a composition of molding sand with aluminosilicate results in better molding sand knock-out properties, while the binding system's reactivity is similar to the sodium silicate system's reactivity.

The following molding sands were used:

- organic self-curing molding sand with **furfuryl resin**, with the presence of free formaldehyde in the range of ≤ 0.1%, an amount of furfuryl alcohol of 90%, and a viscosity (20°C) of 5–20 mPa·s;
- organic self-curing molding sand with **phenolic resin**, with the presence of free formaldehyde in the range of < 0.1% and free phenol of < 0.5%, an amount of potassium hydroxide of 10–15%, and a viscosity (20°C) of 200–300 mPa·s;
- inorganic self-curing molding sand with **aluminosilicate**, with a SiO_2/Na_2O module (1.6–2.6, pH (25°C)) of 11–13 [21] and a tested viscosity (25°C) of around 160 mPa·s [22];
- inorganic self-curing molding sand with R145 hydrated **sodium silicate** [23], with a SiO_2/Na_2O module (2.4–2.6, pH (25°C)) of 11–13 and a tested viscosity (25°C) of around 150 mPa·s [22].

Quartz sand from Sibelco Poland (Bukowno) was used in all the conducted tests as the matrix. According to the Polish standard PN-85 / H-11001, its main fraction of 0.2/0.32/0.16 and average grain size of 0.27 mm classify the sand as medium. The main fraction amounts to 81.58% of, which determines the sand as homogeneous. The sintering temperature of the sand is 1525°C and its humidity was 0.02%. The obtained results are illustrated in Figures 3–15.

Table 1
Composition of tested molding sands

Binder type	Matrix [p.p.w.]	Amount of binder [p.p.w.]	Amount of hardener [p.p.w.]
furfuryl resin	100	1.00	0.50
phenolic resin		2.00	0.50
aluminosilicate		2.00	0.20
sodium silicate		3.00	0.30

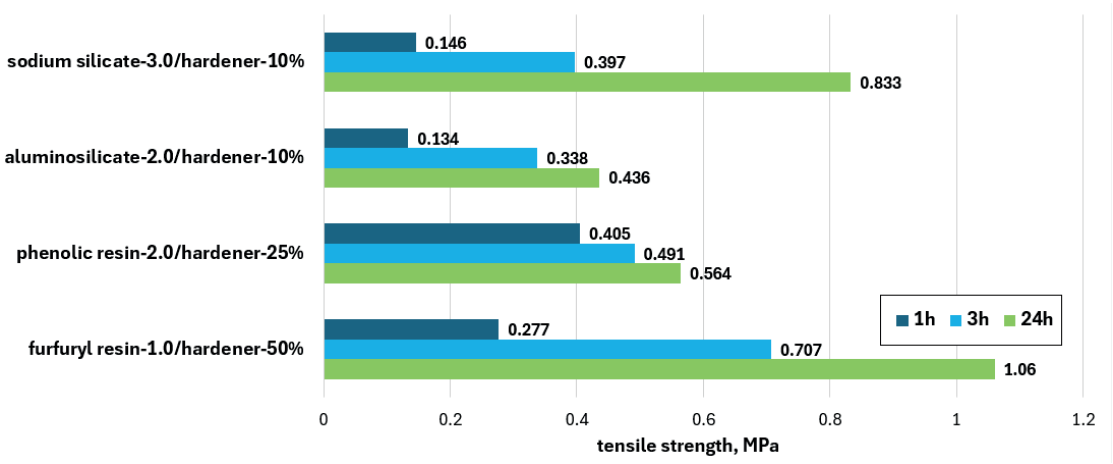

Fig. 3. Influence of binding material on tested molding sands' tensile strength after 1, 3, and 24 hours of self-curing at ambient temperature [18]

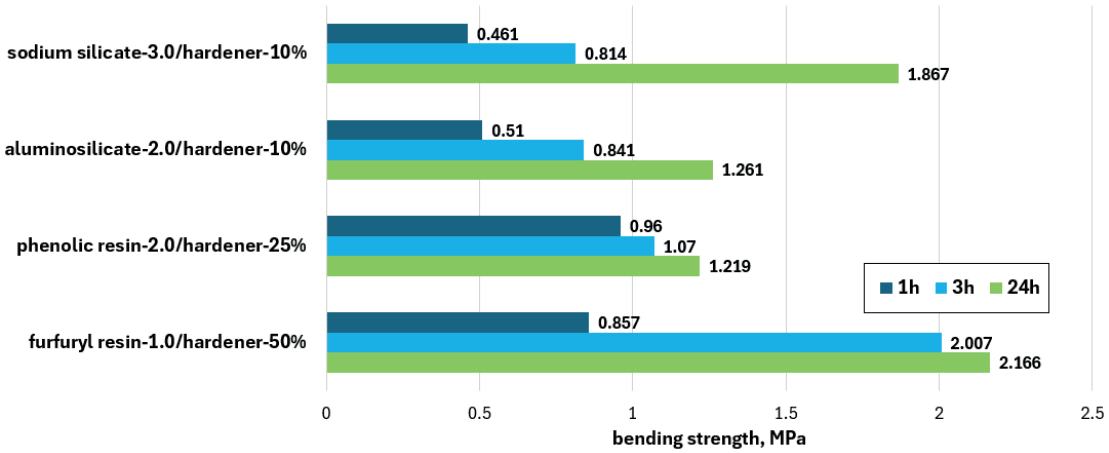

Fig. 4. Influence of binding material on tested molding sands' bending strength after 1, 3, and 24 hours of self-curing at ambient temperature [18]

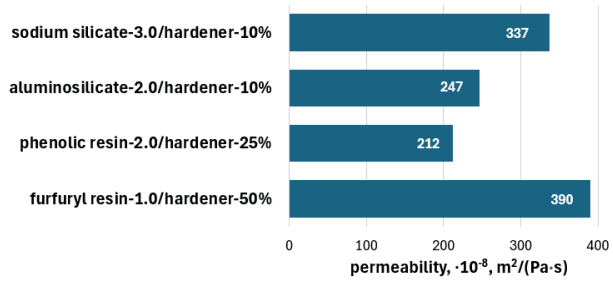

Fig. 5. Influence of binding material on tested molding sands' permeability; tested after 24 h of self-curing [18]

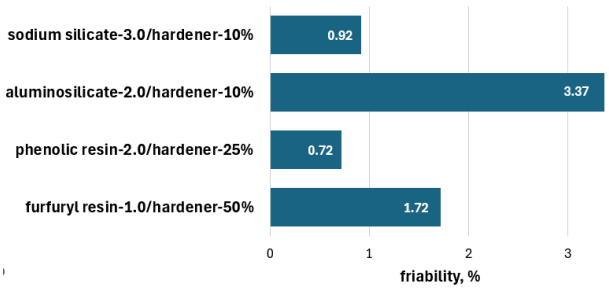

Fig. 6. Influence of binding material on tested molding sands' friability; tested after 24 h of self-curing [18]

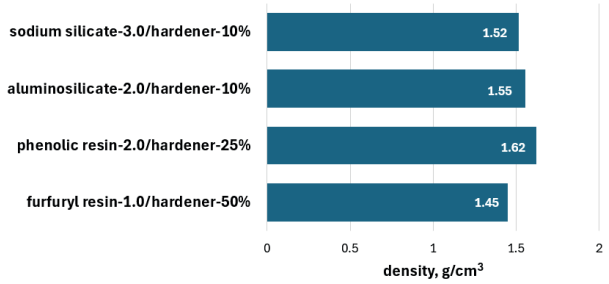

Fig. 7. Influence of binding material on tested molding sands' density; tested after 24 h of self-curing

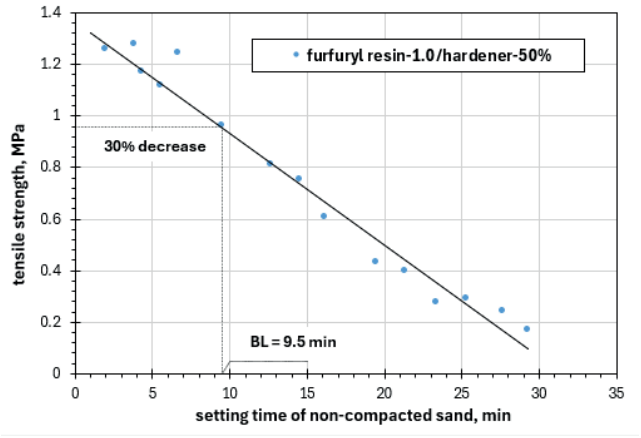

Fig. 8. Bench life of self-hardened molding sand with furfuryl resin [18]

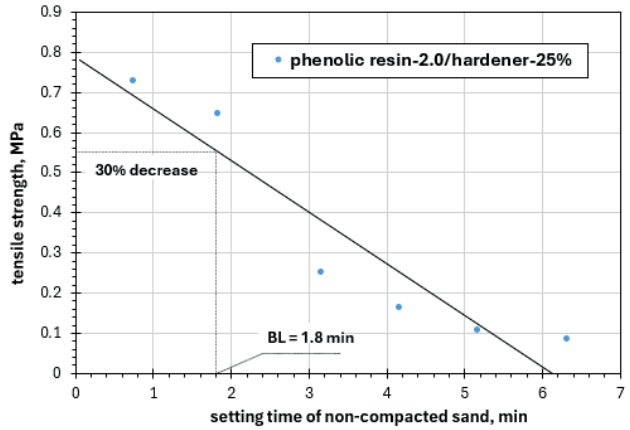

Fig. 9. Bench life of self-hardened molding sand with phenolic resin [18]

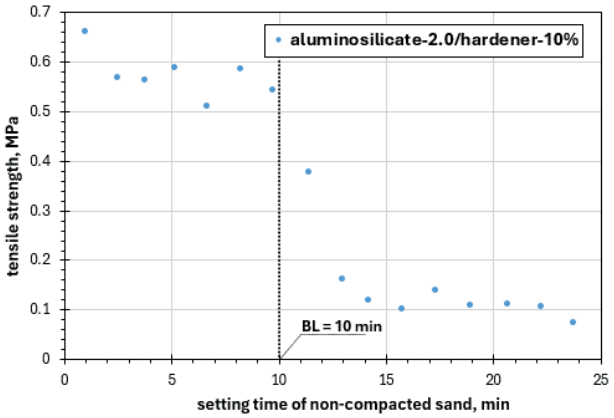

Fig. 10. Bench life of self-hardened molding sand with aluminosilicate [18]

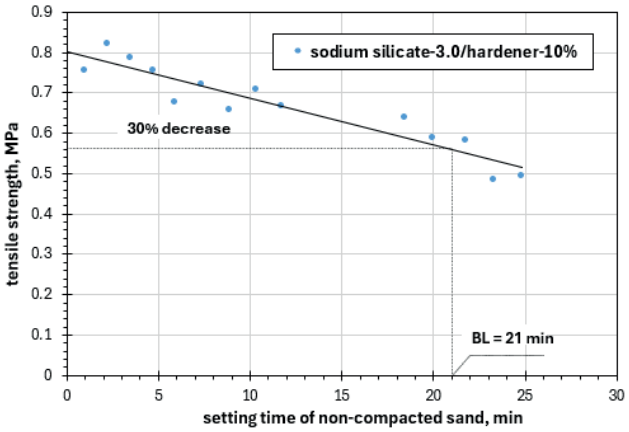

Fig. 11. Bench life of self-hardened molding sand with sodium silicate [18]

The tests conducted on selected technological properties of the molding sands showed that, among the compounds with organic binders, the compound with furfuryl resin has better strength properties. Its tensile strength is 1.06 MPa after 24 hours of curing and 0.277 MPa after 1 hour of curing. The bending strength of this compound is 2.166 MPa after 24 hours of curing and 0.857 MPa after 1 hour of curing (Fig. 3). The second molding sand with an organic binder – a compound with phenolic resin – is characterized by significantly lower strength after 24 hours of curing – tensile strength of 0.564 MPa and bending strength of 1.219 MPa. However, this compound is more reactive than the compound with furfuryl resin and achieves higher strength after 1 hour of curing – tensile strength of 0.405 MPa and bending strength of 0.96 MPa. The bench life of the compound with furfuryl resin is 9.5 min (Fig. 8), and the bench life of the compound with phenolic resin is 1.8 min (Fig. 9). It is worth noting that in the case of self-curing molding compounds, more reactive binding systems are more sensitive to conditions in the foundry, particularly the ambient temperature. They are also more sensitive to the temperature of the sand, which can vary depending on the ambient temperature. The properties obtained after 1 hour of curing for the molding sand with the proposed phenolic resin-based binding system may be best from the point of view of the production of thin-walled castings.

In the case of molding sands with organic binders, the friability test results are noteworthy (Fig. 6). This parameter was tested after 24 hours of curing; however, the resistance of the compounds to mechanical damage is the opposite of their strength tested after 24 hours of curing. Although the friability of both compounds remains low (below 2%), the friability of the molding sand with furfuryl resin is approx. 140% higher than the friability of the molding sand with phenolic resin. In addition, tests of the density of the specimens showed that the compound with furfuryl resin has a lower density (Fig. 7). For the tests carried out, the density of the specimens is influenced only by their composition and the kinetics of curing. All the specimens were compacted by vibration with the same parameters. However, since the tested molding sands are self-curing, it will be crucial in this case to determine their curing kinetics, which will be the subject of further research. In the case of sands with furfuryl resin, a tendency to adhere to the equipment is observed, which may also cause damage to the surface of the specimens. In this case, no reduction in bending or tensile strength or metallostatic pressure transfer capacity will be observed. However, the abrasion resistance (reduced resistance to mechanical factors) of the mold or core surfaces may be increased. This may be important in the production of thin-walled castings, where thinner mold elements may have reduced strength. In this case, a reduced degree of mold or core compaction may also result in lower strength of the mold elements. Due to the reduced degree of compaction of the specimens, better permeability was obtained for the furfuryl resin compounds (Fig. 5).

In the case of molding sands with inorganic binders, it was observed that the compound with sodium silicate has better strength properties than the compound with aluminosilicate. Its tensile strength is 0.833 MPa after 24 hours of curing and 0.146 MPa after 1 hour of curing, and its bending strength is 1.867 MPa after 24 hours of curing and 0.461 MPa after 1 hour of curing. In the case of the aluminosilicate compound, the tensile strength is 0.436 MPa after 24 hours of curing and 0.134 MPa after 1 hour of curing, and the bending strength of this compound is 1.261 MPa after 24 hours of curing and 0.51 MPa after 1 hour of curing. The tests have therefore shown that the properties of these compounds tested after 1 hour (and after 3 hours) of curing are similar and are sufficient for the production of small and medium-sized castings and may also be sufficient for the production of thin-walled castings. After 24 hours of curing, both the compounds have satisfactory strength from the point of view of foundry practice. However, it should be emphasized that current trends are focused on the production of castings in self-curing compounds immediately after they reach the minimum required strength [24]. That is why the results of the research conducted after 1 and 3 hours of curing are so important. It should also be noted that the aluminosilicate sand contains approximately 33% less binder than the sodium silicate sand. In this compound, the amount of binder was deliberately reduced in order to demonstrate satisfactory molding sand properties. At the same time, reducing the amount of

inorganic binder in the mixture will improve its knock-out properties, which is a technical problem for this mixture. Despite the reduction of the aluminosilicate binder content in the mixture, the system is reactive enough to ensure properties similar to those of the sodium silicate system in the first hours of curing. The bench life of the molding sand with an aluminosilicate binder is 10 minutes (Fig. 10), and the bench life of the molding sand with sodium silicate is 21 minutes (Fig. 11). The long bench life of the sand with sodium silicate may be advantageous in the production of large-size castings. In the case of production with castings with complex shapes and thin-walled castings, it may be preferable to use systems with higher reactivity (which have a shorter bench life). In the case of mixtures with inorganic binders, the differences in the strength results tested after 24 hours are consistent with the friability results. The permeability of the compounds with inorganic binders is slightly lower than that of the compounds with organic binders and corresponds to a higher degree of compaction of the specimens.

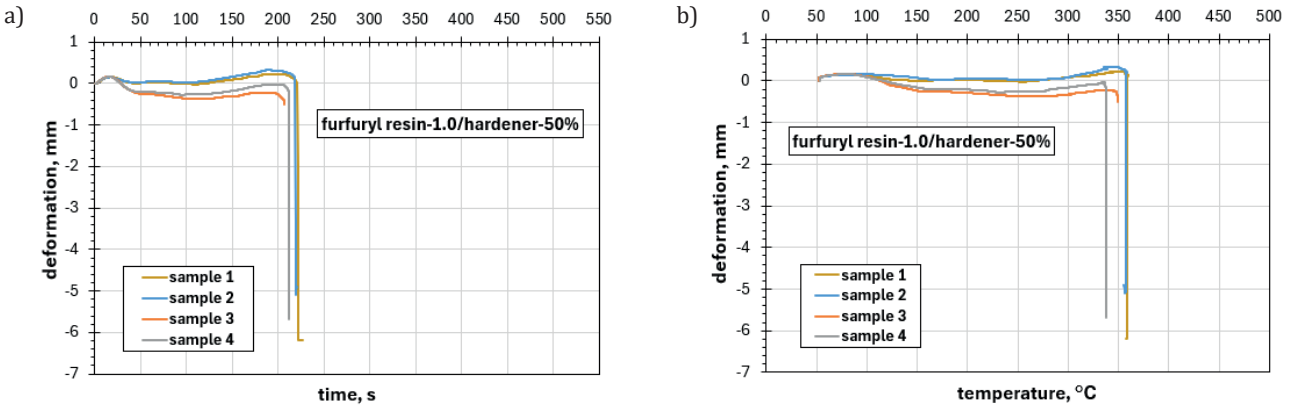

Fig. 12. Thermal deformation (hot-distortion) of molding sand with furfuryl resin as a function of: a) time; b) temperature [18]

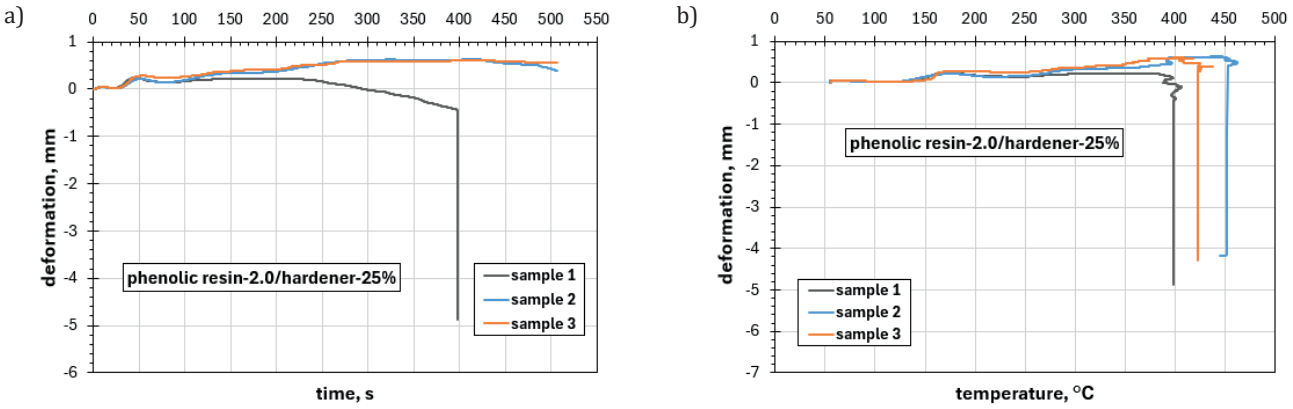

Fig. 13. Thermal deformation (hot-distortion) of molding sand with phenolic resin as a function of: a) time; b) temperature [18]

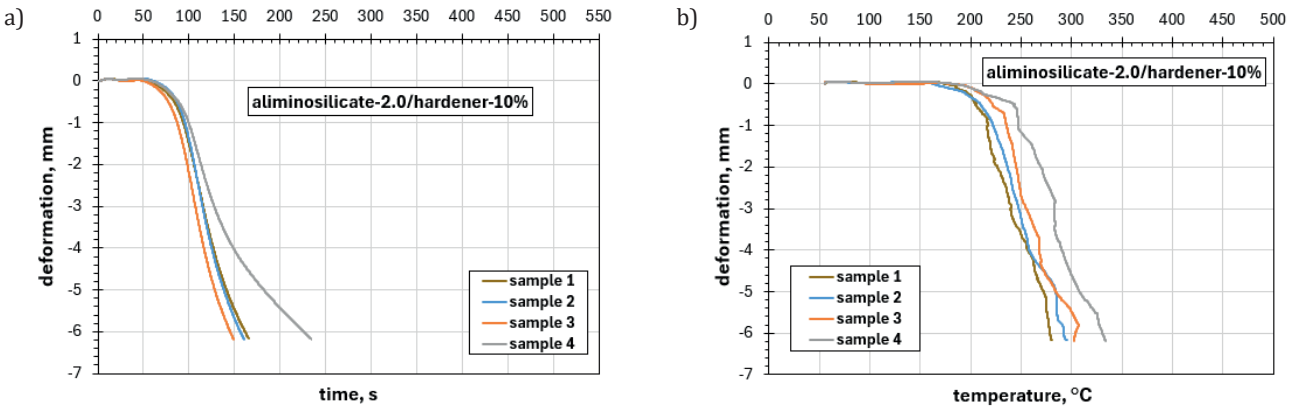

Fig. 14. Thermal deformation (hot-distortion) of molding sand with aluminosilicate as a function of: a) time; b) temperature [18]

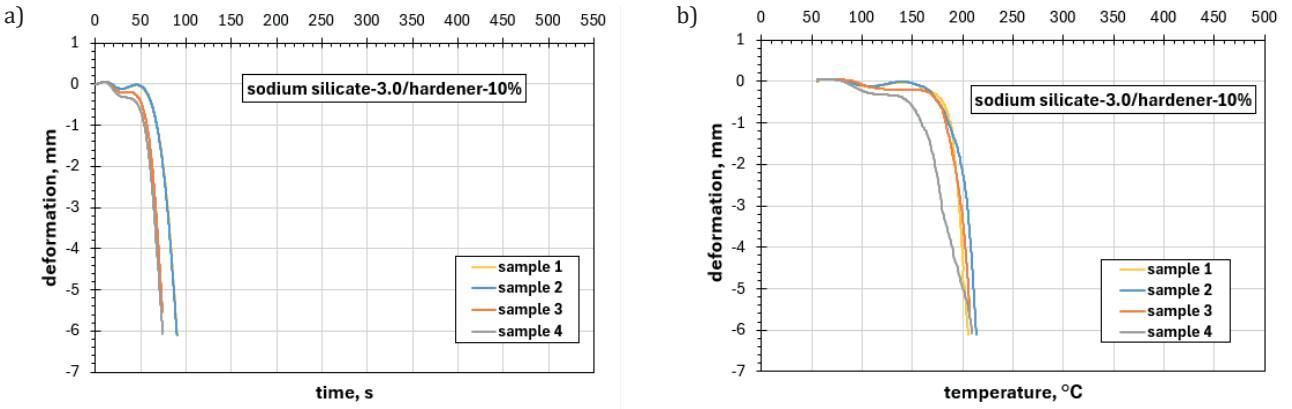

Fig. 15. Thermal deformation (hot-distortion) of molding sand with sodium silicate as a function of: a) time; b) temperature [18]

Studies of the thermophysical properties of molding sands, based on the measurement of the hot distortion parameter, show that compounds with organic binders have better thermal stability compared to compounds with inorganic binders. According to literature data [25–27], their bonding bridges are more flexible and resistant to deformation at ambient temperature. During heating, the deformation curve obtained for the sand with furfuryl resin is typical. In the initial phase of heating, a slight positive deformation (thermal expansion) is observed, followed by a short plastic phase (deformation becomes negative) and thermal hardening – inhibition of deformation and even positive deformation. After approx. 210 seconds and at a temperature of approx. 350°C, a sudden breakage of the specimens is observed, associated with the destruction of the binder. The phenolic resin sand is characterized by better thermal stability. In the initial heating phase, slight positive deformation associated with thermal expansion is observed, followed by a sudden breakage caused by the destruction of the binder after approx. 400 seconds of measurement and at a temperature of approx. 430°C (Fig. 13).

The binding bridges in the compounds with inorganic binders are more brittle at ambient temperature and have lower thermal stability during heating [25–27]. However, there is no thermal degradation of the binder in inorganic sands. Instead, their plasticization is observed. In the case of both tested compounds, the transition time to the plastic state of the specimens does not exceed approx. 70 seconds for the sand with aluminosilicate at a temperature of approx. 200°C (Fig. 14), and approx. 50 seconds for the sand with sodium silicate at a temperature of approx. 170°C (Fig. 15). In the case of the compound with sodium silicate, during heating from 0 to 50 seconds, greater positive deformation associated with thermal expansion is observed than in the case of the compound with aluminosilicate. A significant increase in plasticity is observed with both tested sands. The deformation increases, causing the specimens to drop abruptly. The high plasticity of the compounds is proved by the fact that the specimens do not break when the deformation exceeds 6 mm.

4. CONCLUSIONS

The original research presented in the paper showed that:

- From a practical point of view, all molding sands selected for testing are characterized by sufficient strength, good permeability, and adequate resistance to mechanical damage (friability).
- The bench life of molding sands depends on the binder type. The longest bench life was observed for molding sand with sodium silicate (21 min) and the shortest was for molding sand with phenolic resin (1.8 min). It should be noted, however, that all the compounds used in the tests are self-curing. Their bench life can therefore be adjusted by modifying their composition, thereby tailoring the system to the specific industrial needs. In the production of thin-walled castings, it is essential that the mold material achieves high strength after only a short curing time. It is therefore advisable to choose more reactive curing systems.
- Thermal stability tested by the hot distortion parameter showed that molding sands with an organic binder are more thermally stable. The best results were achieved for molding sand with phenolic resin. The inorganic binder molding sands with aluminosilicate were characterized by better thermal stability. The processes occurring during the initial stage of casting can cause thermal deformation of the core, leading to casting defects that are difficult to remove or even irreversible. This issue requires particular attention in the case of thin-walled castings. Analyzing the thermal deformation parameters and selecting the appropriate molding sand can help to prevent these phenomena [27].
- The presented article shows only a fragment of broader research on the selection of molding sands for the production of thin-walled castings. The research is ongoing. In the next stage of the research, the molding sands will be evaluated in terms of their gas emissions. To confirm the results obtained from the laboratory tests, thin-walled castings are planned to be produced and tested in terms of the influence of the molding sand type on their properties.

ACKNOWLEDGMENTS

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