Effect of hardening method and structure of linking bridges on strength of water glass moulding sands

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Abstract

The paper presents examination results of the effect of four hardening methods on structure of linking bridges in sandmixes containing hydrated sodium silicate. Test pieces prepared of the moulding sands containing 2.5 % of a binder with molar module between 2.4 and 2.6 were hardened with carbon dioxide, dried traditionally in an oven and hardened with microwaves at 2.54 GHz or using a combination of the CO₂ process and microwave heating. It was revealed that the hardening method influences structure of linking bridges and is correlated with mechanical properties of the hardened moulding sands. It was found that strength of the moulding sands microwave-heated for 240 s is approximate to that measured after traditional drying for 120 min at 110 °C. So, the microwave hardening permits significant reduction of the process time, comparable to the CO₂ hardening, at the same time guaranteeing over 10 times higher mechanical properties. Analysis of SEM photographs of the moulding sands hardened with the mentioned methods allow explaining differences in qualitative parameters of the moulding sands and their relation to structures of the created linking bridges.

Key words: hydrated sodium silicate, moulding sands, microwave heating, CO₂ process

1. Introduction

As previous researches revealed, moulding sands containing water-glass can be successfully hardened using microwave energy [2,3]. In foundry industry, this innovative technology can bring significant profits, among others due to reducing the time required for mould and core preparation. From among many other known hardening methods of this type moulding sands, the following can be mentioned: blowing with CO₂, drying with gases at elevated temperature or hardening with liquid esters.

Common application of 2.45 GHz microwave radiation is first of all known from household microwave ovens. Although microwave heating is commonly used in practice, still not all the mechanisms of microwave interaction with various materials and their combinations are recognised (mixtures, solutions). Possibly strict knowledge of this interaction should result in introducing numerous innovative solutions in various economy sectors, including foundry industry. Results of the research indicate that the hitherto applied energy- and time-consuming technologies of mould and core preparation can be replaced by cheaper and less time-consuming processes using the microwave energy. Comparison of the traditional and the microwave drying processes indicates that energy consumption in the latter solution is 10 to even 100 times smaller and its duration time is 10 to 200 times shorter than at the traditional heating [2].

The here presented work was aimed at explaining, on the grounds of observations of linking bridges created during the hardening process, the effect of bonds between the matrix grains on mechanical and technological properties of water-glass moulding sands hardened with selected methods.

Discussion on the so-far obtained results showed [3] that both quality of the water-glass envelope created on the matrix grains...
and the related structure of the linking bridges in moulding and core sands depend mostly on transition of the orthosilicic acid sol to the silica gel [1], and thus on the selected and applied hardening method (e.g. by dehydration [7]).

In the moulding sands containing binders like hydrated sodium silicate, contact surface area depends first of all on thickness of the binder layer spread by stirring on the matrix grains, i.e. on quantity of the added binder [1]. The contact area is also influenced by the parameters characterising the matrix, like shape and homogeneity of the sand grains.

Figs. 1, 2 and 3 show measured strength parameters \( R_c^U \), \( R_g^U \) and \( R_m^U \) of the moulding sands prepared with use of water-glass grade 145, commonly applied in the foundry practice, see Table 1. The measured parameters were used for further evaluation of the quality index of the created bonds between the matrix grains, as well as for explaining the relationships between the moulding sand strength and structure of the linking bridges in the silica matrix.

Table 1.
Physico-chemical properties of water-glass used in the examinations (acc. to the manufacturer's certificate)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-glass grade</td>
<td>145</td>
</tr>
<tr>
<td>Molar modulus SiO₂/Na₂O</td>
<td>2.4 ÷ 2.6</td>
</tr>
<tr>
<td>(SiO₂+Na₂O) content [%]</td>
<td>39.0</td>
</tr>
<tr>
<td>Density (at 20 °C) [g/cm³]</td>
<td>1.45 ÷ 1.48</td>
</tr>
<tr>
<td>Fe₂O₃ max. [%]</td>
<td>0.01</td>
</tr>
<tr>
<td>CaO max. [%]</td>
<td>0.1</td>
</tr>
<tr>
<td>Dynamic viscosity (P), at least 1</td>
<td></td>
</tr>
</tbody>
</table>

The moulding sands were hardened with the following methods:
- with non-heated CO₂ in the CO₂ process
- by traditional drying in a convection-type oven
- by microwave heating
- by the CO₂ process combined with microwave heating [3].

The measured values \( R_c^U \), \( R_g^U \) and \( R_m^U \) obtained for traditional drying and microwave heating are similar (see Figs. 1 to 3) and much higher than the values for the CO₂ process alone or combined with microwave heating. However, especially with respect to the \( R_g^U \) parameter (Fig. 2), the innovative microwave heating method is more profitable than traditional drying.

Improvement of the \( R_g^U \) values in the CO₂ process combined with microwave heating and lack of improvement in the CO₂ process alone can be related to larger volume of standard cylindrical samples than that of octal or longitudinal samples. In the cylindrical samples, parts of compacted moulding sand in the internal and external regions could be hardened by the penetrating gas to various degrees. So, influence of the innovative method of additional intense heating with microwaves in the entire volume was especially visible in the case of the cylindrical samples.

Therefore, it can be expected that application of the innovative method of hardening water-glass moulding sands with microwave energy should be profitable for quality of the created bonds between matrix grains, with maintained short hardening time, comparable to that in the CO₂ process.

![Fig. 1. Effect of water-glass hardening method on compression strength of moulding sand [3]](image1)

![Fig. 2. Effect of water-glass hardening method on bending strength of moulding sand [3]](image2)

![Fig. 3. Effect of water-glass hardening method on tensile strength of moulding sand [3]](image3)
2. Examined materials, preparation of moulding sands and test specimens

Moulding sands were prepared of high-silica sand 1K from the mine Nowogród Bobrzyński with main fraction 0.32/0.20/0.16 and hydrated sodium silicate 145 made by Chemical Plant „Rudniki” S.A. with properties (acc. to certificate) given in Table 1. The selected water-glass is the most popular binder used for preparing casting moulds and cores.

Components were mixed in a laboratory muller mixer [5,6]. Individual components were dosed according to the literature data: high-silica sand 100 %, water 0.5 %, water-glass 2.5 %. Proper sequence of adding was observed during mixing. At the beginning, high-silica sand was stirred with water for 60 s to reduce dusting and to improve wettability of grain surfaces, next the binder was added and stirred for another 180 s. Thus, the preparation way was identical for both the above samples and the moulding sand subject to mechanical testing.

The so prepared moulding sands were compacted on a standard rammer and preparations for SEM observations were taken from the obtained samples. The obtained apparent density ranged from 1.56 to 1.64 g/cm³.

The samples were next hardened in two ways: by traditional drying and by microwave heating. Material portions for further examinations were taken from the hardened samples only after cooling down to the ambient temperature. Specimens for SEM observations were taken in a way eliminating additional stresses which could cause cracking of the water-glass film created during hardening.

The specimens for SEM observations were sprayed with graphite.

3. Methods of moulding sands hardening

Strength of bonds between matrix grains is influenced by both cohesion forces of linking bridges and adhesion forces present in the system created by hydrated sodium silicate and surfaces of the matrix grains. The examination results of adhesion and cohesion forces published in [8,9] indicate that strength of a moulding sand is decidedly affected by quality of cohesive bonds of the hardened binder. Under action of external forces at ambient temperature, the moulding sand is destroyed by breaking continuity of the linking bridges. The moulding sands composed of high-silica matrix and water-glass binder, hardened in the CO₂ process using liquid or loose hardeners and dried in the traditional way, are included to the group of moulding sands showing typical cohesive destruction.

When considering possibility of controlled increasing or decreasing strength of a hardened binder, shape of the created linking bridges as well as nature and places of discontinuities in their structure should be taken into account. In the process of creating the bridges, an important role is also played by wettability of the silica matrix and precision of spreading water-glass on its surface [6,11].

According to literature data [1], microporosities 1 to 2 μm deep are observed on the silica grains. Depending on kind of binder, capillary pressure in these microcavities ranges from 2 to 10 MPa and exceeds adhesion value of binding substances, measured between smooth silica plates. Thus, microporosities on the surface of the matrix grains and related to them capillary pressure is an important factor contributing to supremacy of adhesion forces over cohesion forces as observed in examinations of moulding sand quality after traditional hardening processes.

According to literature data [5], temperature rise is accompanied by change of water-glass viscosity that can reduce wettability of the grain surface, which could make a problem in the case of traditional drying and microwave heating.

When examining the bridges linking the matrix grains, one should consider both the hardening method and the related to it changes of physicochemical properties of the binder, including density, during the process of creating the silica gel.

In the first of the applied hardening methods, the moulding sands samples were blown through with non-heated CO₂ at 0.02 MPa for 30 s. According to literature data [1], in the case of such blowing through, the hardening reaction runs acc. to the formula:

\[ \text{Na}_2\text{O} \cdot n\text{SiO}_2 \cdot x\text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{Na}_2\text{CO}_3 + n\text{SiO}_2 + x\text{H}_2\text{O} + Q \]  

The second of the used methods consisted in drying the samples in a traditional laboratory drier at 110 °C for 120 min. Then, the dehydration reaction runs acc. to the formula [1]:

\[ \text{Na}_2\text{O} \cdot n\text{SiO}_2 \cdot x\text{H}_2\text{O} + Q \rightarrow \text{Na}_2\text{O} \cdot n\text{SiO}_2 \]  

where: n, x = stoichiometric coefficients.

The third method was aimed at examining influence of microwave heating on creation of linking bridges between the matrix grains. The compacted moulding sand was hardened in a microwave chamber for 240 s. On the grounds of the previous examination results [4], the power output of microwaves was set as 700 W. Microwave heating was performed using the microprocessor-controlled device, described in literature [3]. It is expected that the reaction in this case can proceed acc. to the formula (2) describing the water-glass dehydration process.

The fourth hardening method consisted in combining the CO₂ process with microwave heating. After compacting, a moulding sand sample was blown through with non-heated CO₂ for 30 s and next subject to dielectric drying in a microwave chamber for 240 s. The power output of microwaves in this method was also 700 W.

4. Examination results

The so prepared samples were subject to SEM observations. The envelope covering the grains and the linking bridge, created in the CO₂ process, are shown in Figs. 4, 5 and 6.

As can be seen in Figures 4, 5 and 6, the bridges linking the matrix grains are characterised by numerous cracks and exfoliated parts of the hardened binder. Their appearance is related to the hardening method and first of all to the hardening rate. During blowing through with CO₂ acc. to the reaction (1), created is silica gel in form of spherical particles with various diameter s [8,9].
The particles are concentrated in clusters blocking unbounded water and by-products of the hardening process. Changes of rheological properties during transition of the binder from viscoelastic condition to brittle solid are accompanied by shrinkage resulting from volume changes. As the examinations indicate, an additional factor contributing to discontinuities in the linking bridges is hampering the shrinkage of the binder by changes of its viscosity during cooling. When the moulding sand, overcooled as a result of hardening with non-heated CO₂, turns back to the ambient temperature, this is accompanied by further reduction of water content that is decisive for the moulding sand strength. The resulting defoliation of the hardened binder envelope explains reduced strength of the linking bridges. This phenomenon is confirmed by the observed cracks, not only superficial, but also penetrating, see Fig. 6.

The cracks are also visible in the places where water-glass is concentrated in irregularities and cavities on the silica grain surfaces, see Fig. 6.

Therefore, adding more binder to the sand is necessary to obtain higher strength. Mechanical properties can be also improved by using an installation for heating the gaseous hardener to intensify the process of removing water unbounded in the binder. Preheating of the gas hardener permits using smaller quantities of the binder (2.5 to 5 %) than in the traditional CO₂ process (5 to 7 %).

Subsequent photographs in Figs. 7 and 8 show linking bridges created in the traditional drying process. A layer of water-glass spread in the moulding sand preparation process and hardened during heating-up that creates links between the silica matrix grains, is more regular than after the CO₂ process. However, occasionally observed are distinct cracks or binder flakes peeling-off (Fig. 7).

Due to slow heating-up the binder its fluidity increases, which after further heating and dehydration is demonstrated by smooth and gentle transitions of the binder envelope in the linking bridges, see Fig. 8. The observed changes in form of discontinuities on the film surface (places indicated by arrows in Fig. 7) can result in slightly lower strength parameters \( R_{1u} \) and \( R_{1m} \) in comparison with the microwave hardening method. Figs. 9 and 10 show links between the matrix grains after microwave hardening of the water-glass moulding sands.

In the SEM photographs of links between the matrix grains (Fig. 9), visible is a positive effect of quick hardening with microwaves on creating durable and strong linking bridges. Like traditional drying, microwave heating is not unfavourable for viscosity of the applied binder and thus for wettability of silica grains at temperatures over 100 °C. No surface defects are observed, caused by rapid contraction of the binder as a result of very quick hardening.
Fig. 8. Linking bridge with gentle bends characteristic for traditional drying

Fig. 9. Complex of bridges linking matrix grains and structure of water-glass envelope (microwave heating)

Fig. 10. Envelope creating bridges between silica matrix grains (microwave heating)

Fig. 11. Linking bridge with visible cracks that can weaken the created link (CO₂ process with microwave heating)

Fig. 12. Linking bridge with visible cracks that can weaken the created link (CO₂ process with microwave heating)

Figs. 11 and 12 demonstrate the effect of combining the CO₂ process with additional microwave drying. After preliminary hardening with CO₂, the binder was subject to dielectric drying with microwaves penetrating the moulding sand.

The bridges visible in Figs. 11 and 12 show characteristic cracks on their surfaces (indicated with arrows). However, they are of different nature than those observed at hardening with non-heated CO₂ only. After preliminary gelation process by means of a gaseous hardener, unbound water contained in the binder volumes distant from the hardened surface intensely evaporated under action of microwaves. Dehydration of the binder by additional evaporation of water molecules did not result in higher strength of the linking bridges. This fact is confirmed by strength measurements shown in Figs. 2 and 3.

Results of compressive strength measurements (Fig. 1) of the moulding sand hardened by the combined CO₂ and microwave method revealed one of disadvantages of the CO₂ blowing process. Namely, this is the effect of non-uniform hardening of the moulding sand by volatile hardener due to its various penetration degree. The hardening process was completed only after using the innovative method that guaranteed uniform hardening of the moulding sand in its entire volume.

Fig. 10 shows a typical single linking bridge with its structure similar to that observed at traditional drying, see Fig. 10. However, the surface is more even, with no irregularities. In the case of microwave drying, less discontinuity areas of the hardened binder are observed on the bridge surfaces, than at traditional drying.
The subsequent planned stages of the research will be focused on observations of linking bridges in moulding sands prepared using other water-glass grades used in foundry industry. The examinations will be enlarged by observations of mechanical destruction of the bridges after mechanical testing. Moreover, chemical analyses will be made, as well as structures of the binder envelopes and bridges will be examined after various water-glass hardening processes. The results will make an important database helpful for determining influence of various hardening methods on creation of durable links between the matrix grains.

5. Conclusions

- The hardening method significantly affects structure and quality of linking bridges in the moulding sand with 2.5 % of water-glass grade 145.
- A characteristic, typical cohesive destruction of linking bridges is observed after hardening with non-heated CO₂ combined with microwave heating.
- Nature of destruction of the linking bridges was not explicitly determined by SEM observations after traditional drying and microwave heating.
- Structure of water-glass envelopes obtained in the traditional and the microwave drying processes indicates similar nature of the dehydration process of the used binder.
- A correlation exists between basic mechanical properties of the examined moulding sand, determined in the previous research, with structure of the linking bridges, as confirmed by SEM photographs.
- The water-glass moulding sands hardened with microwaves, in which the linking bridges and binder envelopes are more defect-free than at various hardening methods, are characterised by the highest strength.
- The water-glass moulding sands hardened with non-heated CO₂ are characterised by the lowest strength.
- Higher effectiveness of the microwave heating process and intensive evaporation of water during the binder hardening do not result in lower mechanical properties of moulding sands and in mechanical destruction of the linking bridges, e.g. due to a rapid volume change.

- In comparison with the traditional drying that gives similar final results, the innovative microwave heating is more effective and economical.

References


Wpływ na wytrzymałość mas ze szkłem wodnym sposobu utwardzania
i budowy mostków wiążących

Streszczenie

W pracy zaprezentowano rezultaty badań wpływu czterech metod utwardzania na budowę mostków wiążących w masach z uwodnionym krzemianem sodu. Próby do badań, sporządzone z masy z dodatkiem 2.5% spoiwa o module molowym 2.4 - 2.6, utwardzano dwutlenkiem węgla, suszono klasycznie w piecu, utwardzano mikrofalam o częstotliwości 2.45 GHz lub utwardzano metodą łączącą proces CO₂ i nagrzewanie mikrofalowe. Wykazano, że metoda utwardzania ma wpływ na budowę mostków wiążących korelując z właściwościami wytrwałościowymi utwardzonych wymienionych metodami mas. Stwierdzono, że wytrzymałość nagrzewanych mikrofalomowo przez 240 sekund mas jest bardzo zbliżona do zmierzonej po procesie klasycznego ich suszenia w temperaturze 110 °C przez 120 min. Zastosowanie utwardzania za pomocą nagrzewania mikrofalowego zapewnia zatem istotne skrócenie procesu, porównywalne do czasu utwardzania dwutlenkiem węgla, gwarantując równocześnie, w porównaniu z tą ostatnią metodą, ponad 10-krotny wzrost właściwości wytrzymałościowych. Analiza zdjęć z mikroskopu skaningowego mas formierskich, utwardzanych wymienionymi metodami, umożliwiła wyjaśnienie różnic w parametrach jakościowych mas i ich powiązanie z budową utworzonych mostków wiązących.