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Mulling and its Effect on the Properties of Sand-Water-Bentonite Moulding Mixture

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Abstract

Today, foundries are facing increasing demands for greener and more economical production while maintaining or improving the quality of the castings produced. The importance and use of green sand mixtures using bentonite as a binder are thus coming to the fore once again. They have the advantage of both eliminating the chemicalization of production and also allowing the immediate use of the already used mixture, including the binder, after adjustment of the composition and mulling. In order to maintain the quality of the resulting castings, it is necessary to monitor the properties of the moulding mixture through a series of laboratory tests. It is also essential to look at the processing quality of these mixtures, i.e. the combination of good mulling quality and efficient mulling time, which is often neglected. It is the quality of mulling and the effective mulling time that help to develop the bonding properties of the bentonite, improve the properties of the mixture, determine the efficiency of the muller and possibly reduce the time and energy required for mulling. The aim of this work is to present the effect of mulling on the properties of sand-water-bentonite mixtures. The properties studied are mainly the compactability, strength characteristics, moisture content of the mixture and the order of addition of raw materials.

Keywords: Bentonite, Green sand mixture, Mulling time, Green compressive strength, Cumulative mulling

1. Introduction

The quality of this mixture depends not only on the quality of the raw materials used, but also significantly reflects the quality of the preparation and processing of the mixture [1].

One way to influence the quality of the green sand mixture can be the order in which the ingredients are added. According to the literature, for soda-activated bentonites, the order of addition of raw materials plays an important role in determining the effective mixing time. The available information shows that, unlike Ca^{2+} bentonite, Na^{+} bentonite has different properties at the same mixing time and moisture content depending on whether the sand was first rewetted and then the specified bentonite content was added after sand placement or vice versa [2].

Another way to improve the quality of the green sand mixture is to increase the mixing efficiency and find the optimum mixing parameters and mulling time. In general, the aim of mixing is to homogenise the mixture as much as possible so that the mixture has the same composition and thus the same properties throughout the volume. Imperfect mixing leads to clumping of the individual components in the mixture, which can result in various types of foundry defects [3]. The mixing process occurs due to compressive forces with subsequent shear [2]. The action of energy and time, i.e. mulling, results in the incorporation of water or organic oils into the mixture, without which the bentonite cannot develop its binding properties. This is called activation of the bentonite, i.e. the formation of a solid mass of a paste-like consistency [3].

The time for one cycle of mixing the moulding compound is most often in the range of 1 to 3 minutes. The short mixing time does not guarantee the quality of the bentonite dough formation and the uniform coverage of the sand grains, but after several mixing cycles these mixtures already exhibit sufficient strength properties [4, 5]. Cumulative mulling for 15 to 20 minutes may be equivalent to this multiple movement of the mixture through the system [6, 7]. In a study [4] it was verified that it is possible to increase the strength of a bentonite mixture by inducing moisture loss due to prolonged mixing and natural evaporation. Thus, prolonged or multiple mixing of the mixture was necessary for this increase in strength.

Furthermore, in order to control the correct moisture degree, simple series of tests are still carried out which allow the moisture content, and the resulting properties of the mixture, to be determined very quickly and accurately. Besides the actual measured values, correlations between them are also used [8, 9]. The actual bonding capacity of the mixture can be defined by means of a green split tensile strength test. The compactability test is a very sensitive indicator of the bentonite-water ratio in the mixture and is the most commonly recommended procedure for evaluating mixing efficiency [2, 8, 9]. As the mixing time increases, the compactability increases, since it depends on the development of the clay binding capacity and the quality of the sand grains' coating by the clay dough, in addition to the uniform distribution of water [1].

At present, systems of controlled prediction of mixture properties by artificial intelligence or a software network are being considered, which would be able to predict the quality of the mixture and subsequently control or modify the quality of the mixture in real time. Nevertheless, the considered programming of these systems is still based on the observation and measurement of the actual change in mixture properties throughout the mixing process, where the influence of moisture and mixing time are some of the most significant influences and cannot be replaced in any other way for the time being [10]. For this reason, the cumulative mulling process is still an actual topic, even though it has been observed and described countless times in the past.

2. Materials and methods

The aim of the experiment was to evaluate the effect of prolonged mixing on the mechanical properties of the green sand mixture. The evolution of the mixture properties in individual minutes of mixing was evaluated, as well as the effect of prolonged, so-called cumulative mulling. As mentioned in Section 1 cumulative mulling simulates in the laboratory the evolution of clay batter and binding properties of bentonite after multiple passes through the system, i.e. mixing, casting, reclaiming, rewetting and re-mixing. To this day, the cumulative mulling methodology is the default procedure for evaluating mixer efficiency.

For the purpose of the experiment, only the new green sand mixture from the new raw materials was used. This mixture was not used for casting or regenerated during the experiment.

2.1. Materials

The following materials were chosen to determine the optimum mixing time:
Basic sand: Biala Góra silica foundry sand BG 27 with d_{50} = 0.27 mm.
Binder: soda-activated Bentonite Sabenil, manufacturer Keramost a.s.

The parameters of the mixture to be used for cumulative mixing are given in Table 1.

Table 1.
Composition of used green sand mixture

	Sand	Binder	Water
Weight ratio [%]	100	8	2.5
Mass [g]	8000	640	200

The experiment was carried out in the laboratory environment with constant temperature of 23 °C and humidity of 20 %.

In this experiment, the water content of the bentonite and sand moisture were not considered, as it is a negligible amount relative to the total amount of mixture that was not relevant for our purposes. The aim was to be close to the actual operating conditions of the foundries, where the control of the initial moisture content of the mixture does not include the moisture content of the bentonite. Furthermore, in contrast to the common laboratory procedure and literature [2], distilled water was not used, but water from the standard water supply. The possible influence of minerals contained in the water will not be assessed here.

Cumulative mulling was performed on a laboratory wheel muller LM-2e with 160 rpm. Detailed mixing time and conditions are described in Section 2.3. In addition, a universal strength testing machine LRu-2e was used to measure the strength properties of the green sand mixture and an automatic laboratory rammer LUA-2e/Z was used to prepare cylindrical test samples with dimensions Ø 50 x 50 mm and determine the compactability. The equipment was supplied by Multiserw-Morek, Poland.

2.2. Monitored mixture parameters

Components order - The experiment studied the effect of the order of water addition, compared to the order of other components, on the properties of the green sand mixture. Sand and bentonite were added to the first mixture type and after mixing the dry components, water was added (water 3rd in order). For the second mixture type, sand and water were mixed first and bentonite was added after the sand was wetted (water 2nd in order). For each observed order of addition of raw materials, 3 new mixtures were prepared and tested.

Mulling effect - The effect of cyclic, so-called cumulative mulling, which simulates the cyclic circulation, rewetting and mixing of the mixture in the foundry plant. 5 cycles of cumulative mulling for the one individual mixture were evaluated. The description of the entire mulling cycle is given in Section 2.3.

The evolution of the mixture properties - in individual minutes of mixing was monitored for the newly made mixtures. The minute mixing intervals were 1-15 minutes for the mixture type with water 3rd in order and 1-5 minutes for the mixture type with water 2nd in the order. Time 1-5 minutes was chosen due to real conditions in foundries where mixing is no longer than 5 minutes due to the high heating of the mixture, time and energy savings. Mixtures and testing parameters are presented in Table 2. For each mixture type (different order of addition of raw materials), 3 new mixtures were prepared and tested.

Mixture properties - The properties monitored were changes in moisture content, compactability, green compressive strength on test cylindrical specimens ø 50 x 50 mm (also for green split tensile strength) and evolution of mixture toughness. The green sand mixture toughness is given by the ratio of the green split tensile strength to the green compressive strength. The compactability and strength tests were carried out for 5 test samples each time. The mentioned properties represent the initial and most important mixture properties for the evaluation of the mixing effect. According to Troy, other properties, such as permeability or water condensation zone strength, are not relevant for the purpose of evaluating the prolonged mixing effect and were therefore not evaluated.

Table 2.
Green sand mixtures and testing parameters

	Order of water addition	Tested mixtures	Cumulative cycles	Minutes
Mixture 1	3rd in order	3	5	1-15
Mixture 2	2nd in order	3	5	1-5

2.3. Cumulative mulling methodology

For the evaluation of the mulling effect the cumulative mulling according to E. C. Troy was chosen. This procedure indicates that for each bentonite content in the mixture there is a constant of binding which is related to the actual moisture content of the mixture [2]. This binding constant is denoted A and its calculation is as follows:

$$A = \sigma_{Pt} W \sqrt{W} \qquad (1)$$

where σ_{Pt} represents green compressive strength [kPa] and W moisture content of the mixture [%].

The procedure for cumulative mulling, sampling and measurement were as follows:

- Accurate weighing of the specified quantity of raw materials. Addition of dry silica sand to the wheel mixer.
- Moisten the sand with the addition of the specified amount of water or add bentonite according to the selected order of materials and mix for 1 minute with the lid closed.
- Addition of the last component of the mixture, bentonite or water, and mixing with the lid closed for 1 minute.
- Moisture control. If the moisture content did not meet the required initial value to start cumulative mulling, the mixture had to be rewetted. This was followed by mixing for 4 minutes.
- After 4 minutes, the lid of the mixer was opened to allow natural evaporation of moisture and mixing was continued until the mixture appeared visually dry, approximately another 10 minutes.
- After mixing, a portion of the mixture was removed for immediate determination of moisture content, compactability and strength properties on cylindrical test specimens. Determination of A-value from the results. The rest of the mixture was kept in a closed container to prevent further moisture loss.
- All used bentonite mixture from the test samples was returned, as far as possible without residue, to the mixer.
- The whole process mentioned above represents one mulling cycle, the properties of which were further evaluated.
- Based on the actual measured moisture content, the necessary water addition to achieve the required moisture content of 2.5 % was calculated and the required amount of water was added into the mixer.
- The whole mixing and measuring process was repeated until the calculated A-value was stable at a certain value and did not change further.
- Once A was constant, the mixture was again rewetted to the required moisture content of 2.5 %. The mixture was again mixed and continuously, without switching off the mixer, removed into sealable containers after each of the 1st and 3rd minutes of mixing.
- The exact moisture content, the compactability and the strength tests were determined in the shortest possible time for both times of mixing (1st and 3rd minute).

3. Results and discussion

3.1. Cumulative mulling

Cumulative mulling was performed on 3 mixtures for each mixture type (different order of component additions) and 5 cycles of cumulative mulling were observed for each mixture. In Figures 1-4 it is possible to observe graphically the changes in the evolution of the individual properties of the green sand mixture during the individual cycles of cumulative mulling. The values represent the average values from all measurements. The individual cycles of cumulative mixing are plotted with lines. Subsequent individual points in the graphs, in cycles 7 and 8, show the measured values of samples taken after the 1st and 3rd minute of mixing after the cumulative mulling has reached a constant value of A.

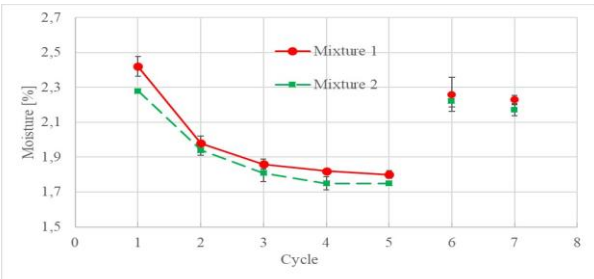

Fig. 1. Development of moisture content during cumulative mulling

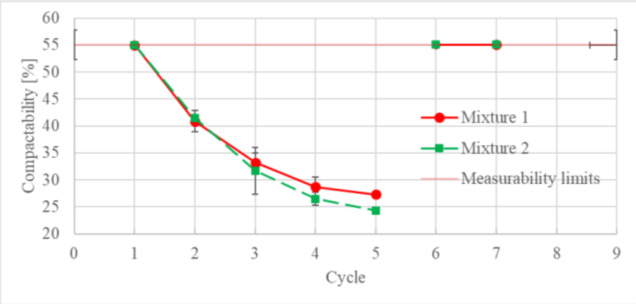

Fig. 2. Development of compactability during cumulative mulling

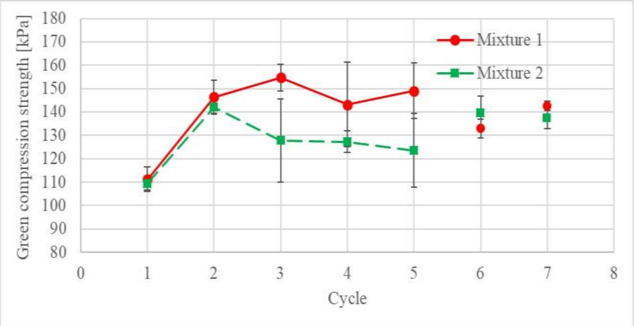

Fig. 3. Development of green compression strength during cumulative mulling

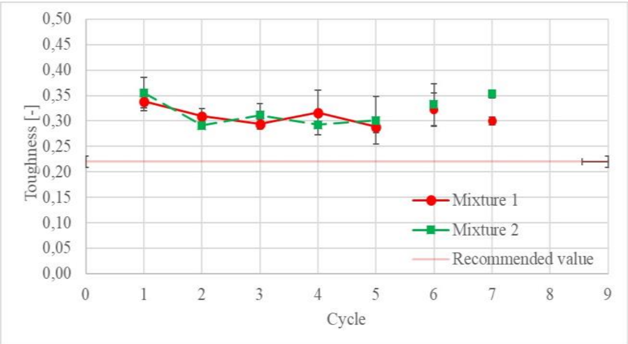

Fig. 4 Development of toughness during cumulative mulling

When comparing the moisture content curves of the mixture with the addition of 2.5 wt.% water, it can be seen that in the case of the mixture where water was added after the addition of bentonite as 3rd in order (Mixture 1), the moisture content drop is lower than in the case of the Mixture 2 where sand was wetted first and then bentonite was added (water 2nd in order). Nevertheless, this difference is in the order of hundredths of % and can be considered negligible. The gradual decrease in measured moisture content for both mixture curves is a way of gradually changing the evaporation conditions during mixing due to the heating of the mixture by mulling and natural evaporation. This is a decrease of approximately 0.2-0.3 % moisture between the 1st and 3rd minute of mixing.

The compactability values of both mixtures showed a continuously decreasing character, which followed the decreasing moisture contents of the mixtures. During the 1st to 3rd cycle of cumulative mulling, both mixtures achieved almost identical compactability, while in the 4th and 5th mixing cycles Mixture 1 maintained a higher compactability value than Mixture 2, by up to 12%, respectively. After cumulative mulling and sampling after the 1st and 3rd minute of mixing, both mixtures exceeded 55 % compactability, which was the upper limit of the measurability.

The green compressive strengths of both mixtures showed a sharp increase in strength between the 1st and 2nd mixing cycles, by 30 %. While Mixture 2 reached its maximum compressive strength for cumulative mulling at this point of 142.1 kPa, Mixture 1 reached its maximum of 154.7 kPa in the 3rd mixing cycle. Both mixtures experienced a steady decrease in strengths after reaching their strength maximum, up to 7.4% for Mixture 1 and 13% for Mixture 2, and these strengths were maintained by both mixtures for the remainder of the cumulative mulling cycles. In contrast, after cumulative mulling and sampling after the 1st minute of mixing, Mixture 2 reached much higher compressive strengths close to its maximum and maintained these strengths even in the case of the 3rd minute of mixing. Conversely, Mixture 1 did not approach its maximum strengths and exhibited compressive strengths at the same level as Mixture 2, 142.6 kPa, at minute 3.

After the first cycle of cumulative mulling, Mixture 2 showed higher toughness (0.36) compared to Mixture 1 (0.34). Both mixtures showed a decrease in toughness during the 2nd cycle, by 8.8 % for Mixture 1 and 19.4 % for Mixture 2, however, from this point onwards the toughness values for both mixtures were equalised and both mixtures maintained the same average toughness of 0.30 until the end of the cumulative mulling. At the 1st minute of sampling, both mixtures showed the same increase in toughness to a value of 0.32. The difference occurred at the 3rd minute of mixing, when Mixture 1 showed a significant decrease in toughness of 6.3 %, but Mixture 2 showed an increase of 6.0 %, when it almost reached its maximum toughness. However, it should be noted that both mixes were above the recommended toughness value of 0.22, which guarantees the suitability of the mix for hand moulding and easier removal of the patterns from the moulds due to its improved plasticity.

From the results of cumulative mulling it is clear that wetting the sand before the addition of bentonite (Mixture 2) helps the mixture to reach its strength maximum faster, after fewer mixing cycles, but on the contrary it does not reach the same compressive strengths as the mixture with the addition of water (Mixture 1). In contrast, the mixture with the addition of water as 2nd in order shows much better mixing strength and is therefore much more suitable for hand moulding. The effect of the order was therefore confirmed.

3.2. Properties at different mulling time

Mixing was performed on 3 newly prepared mixtures for each mixture type (different order of component additions). In Figures 5-8 it is possible to observe the evolution of the properties of the newly mixed green sand mixtures during the mixing process. The mixing parameters for each mixture can be seen in Table 2. The values represent the average values from all measurements.

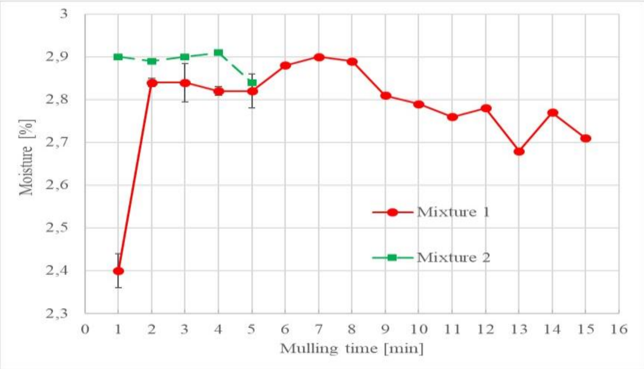

Fig. 5 Development of moisture content in minutes of mixing

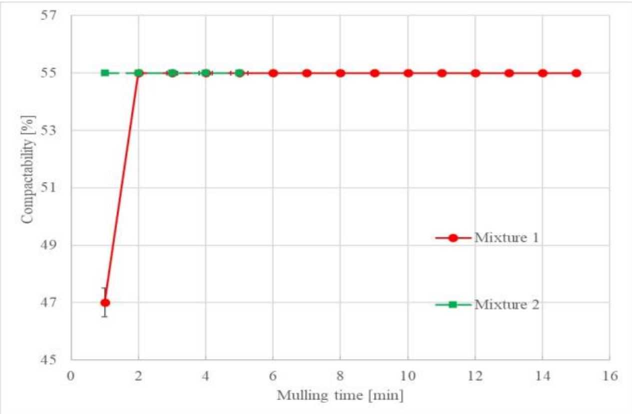

Fig. 6 Development of compactability in minutes of mixing

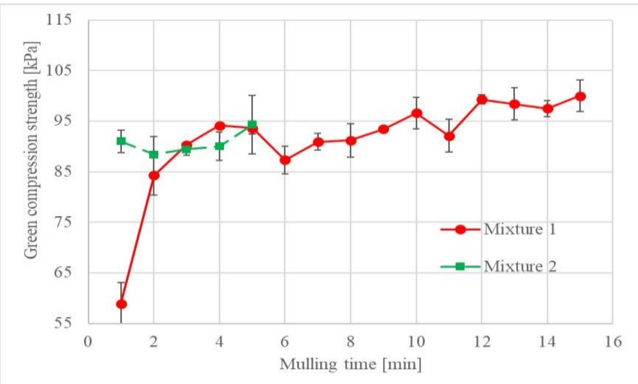

Fig. 7 Development of green compression strength in minutes of mixing

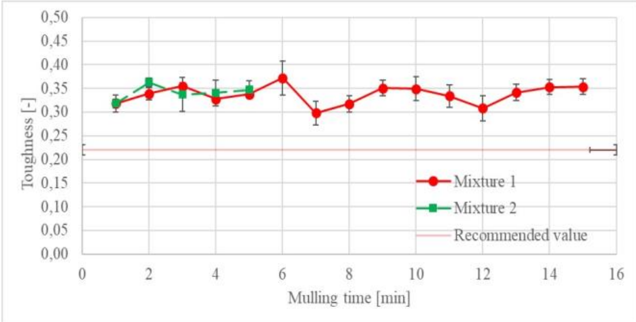

Fig. 8 Development of mixture toughness in minutes of mixing

As can be observed for both new green sand mixtures, the actual moisture content of the mixture at each minute of mixing exceeds the 2.5% moisture content that was maintained and controlled in the case of cumulative mixing. This is due to the addition of water, converted to weight % of sand, and also to the presence of a certain percentage of moisture in the individual raw materials (sand and bentonite). As can be seen, for Mixture 1 there was a sharp increase in moisture content between the 1st and 2nd minute of mixing. This is due to the gradual distribution of moisture and the incorporation of water into the mixture. Up to 15 minutes of mixing, the moisture content decreased slightly. The total moisture drop from the 2nd minute of mixing in the case of Mixture 1 was 4.6 %. This can be considered as a slight moisture drop due to natural evaporation. In the case of Mixture 2, where the sand was already wetted and premixed, a faster incorporation of water into the bentonite was achieved during the first minute of mixing. It can also be seen that the mixture maintained a constant moisture content throughout the 4 minutes of mixing.

In both cases, the compactability exceeded 55% and was therefore above the measurability limit. It can therefore be concluded that during the first 15 minutes of mixing, despite the slightly decreasing moisture content of the mixture, the compactability does not change significantly.

In the case of green compressive strength, a significant difference in the initial strength development can be observed based on the different order of addition of the raw materials of the two mixtures. While Mixture 1 reaches a compressive strength of 90.3 kPa in the 3rd minute of mixing and the strength continues to increase, Mixture 2 reaches a strength of 91 kPa in the 1st minute of mixing. The increase in compressive strength up to the 5th minute is then gradual, i.e. only 3.6 %.

The mixture toughness is then almost identical for the first 5 minutes for both mixtures, namely 0.34. For both mixtures the toughness is well above the recommended limit of 0.22.

Again, the advantage of initially wetting the sand before adding the bentonite to the mixture is confirmed, as the mixture gains higher strengths more quickly. In the case of the reverse order of addition of raw materials, i.e. water 3rd in order, the mixture does exhibit much higher strengths, as demonstrated by cumulative mulling, but at the cost of much longer mixing times, as can be seen from Fig.7.

4. Conclusions

In this experiment, two different green sand mixtures were tested to verify the effect of the order of addition of each raw material and to observe the effect of mixing time on the properties of these mixtures. For this purpose, cumulative mixing and evaluation of the effect of mixing on a minute-by-minute basis were carried out. The results can be summarized as:

- A significant effect of the order of addition of raw materials on the properties of mixtures containing Na^+ bentonites was confirmed. It appears to be more advantageous to improve the moisture distribution in the mixture by initially wetting the sand before the addition of bentonite.
- The mixture with water addition as the 2nd in the order can achieve higher strengths and better toughness than the mixture with the opposite order of raw materials after several cycles of mulling.
- The mixture with the addition of water as 2nd in order shows a faster increase in strength in the first minutes of mixing. To achieve 90 kPa compressive strength, the mix can be mixed for a shorter time while maintaining the same toughness.
- The mixture with the addition of water as 3rd in order achieves higher strengths but at the expense of longer mixing times than the previous mixture.

By selecting the appropriate time and method of mixing, as well as the appropriate order of addition of raw materials, it is possible to significantly influence the properties of the mixture and to adjust or shorten the mixing time. These steps will then have an effect on the final quality of the mixture and the castings and can help to make production more economical.

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