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Evaluation of Mixing Efficiency and How it Affects the Properties of the New Green Sand Mixtures

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Abstract

The current trend in the preparation of green sand mixtures emphasizes the acceleration of the mixing process while maintaining the quality of the mixture. This requirement results in the necessity of determining the optimal conditions for mixing the mixture with a given mixer. This work aims to determine the optimal mixing conditions for the newly introduced eddy mixer LM-3e from the company Multiserw-Morek in the sand laboratory at the Department of Metallurgical Technologies, Faculty of Materials and Technology, VŠB - Technical University of Ostrava. The main monitored properties of mixtures will be green compressive strength and moisture of the mixture. The measured properties of the mixture mixed on the eddy mixer will be compared with the properties of the mixture mixed on the existing LM-2e wheel mixer. The result of the experiment confirmed that the eddy mixer is suitable for the preparation of a mixture of the same quality as the wheel mixer but with a significantly reduced mixing time.

Keywords: Green sand mixture, Eddy mixer, Mixing time, Optimization of mixing, Green compressive strength

1. Introduction

Nowadays, more sophisticated materials are being developed and used in the foundry industry for the production of foundry moulds, which make it possible to increase labour productivity and produce higher quality castings than green sand mixtures. As an example, metal moulds are used to produce thin-walled aluminium alloy castings for the automotive industry, but these moulds are not suitable for high-temperature alloy castings [1]. Another example of modern moulding materials are mixtures bonded with organic resins. Despite their many advantages, they impose a significant burden on the environment. Although green sand mixtures are obsolete and have a number of disadvantages, they are and will continue to be a widely used material for mould making, mainly due to their economic availability and low ecological burden on the environment [2].

The basic components of green sand mixtures are abrasive (usually silica sand), bentonite clay and water. However, these ingredients often do not provide the desired properties and therefore other suitable admixtures need to be added to improve the properties of the moulding compound [2]. The properties and associated quality of the moulding mixture are therefore mainly determined by the individual raw materials. The issue of raw materials for foundry moulds has been the subject of a number of studies, for example the assessment of the dilatation of hybrid sand depending on its composition [3] or the search for new possibilities in the field of carbonaceous additives [2]. However, the quality of moulding compounds is also influenced by the process of compound preparation. This primarily means the mixing process, during which the mixture must be perfectly mixed. Added to these requirements is the tendency to streamline production processes, so one of the main requirements for mixing is to achieve the desired mixture properties in the shortest possible time. This leads to the development of new more efficient mixers with shorter mixing times. In order to determine the efficiency of the new mixers and to determine the mixing parameters, an evaluation of the mixing efficiency is carried out. Using the same ingredients and the same mixing time for several different mixers, it is certain that each of the mixed mixtures will have different properties. From this fact, it is quite clear that specific mixing parameters must be determined for each mixer. The first step to correctly determine the efficiency of the mixer is to achieve the maximum properties of the given mixture, from which the efficiency of the mixer is subsequently evaluated and the optimal mixing parameters are determined [4].

The subject of the research was the determination of the optimal mixing parameters of the green sand mixture for the newly introduced eddy mixer LM-3e of the company Multiserw-Morek. In previous research, optimal mixture properties were determined on an existing LM-2e wheel mixer [5]. These two mixers are based on different mixing principles. In the case of the wheel mixer, mixing is carried out by means of impellers. The mixing takes place between the impellers and the bottom surface of the mixer. In the case of an eddy mixer, the mixture is mixed by means of the rotating blades of the mixer and the rotating bowl. The mixture is set into a swirling motion and mixing takes place throughout the entire volume of the mixture. Thus, it can be stated that the mixing of the mixture in the eddy mixer is much more intense. It can be assumed that the properties of the mixture mixed in the LM-3e eddy mixer should at least match those of the mixture mixed in the existing wheel mixer. Ideally, these properties should be better. To obtain an overall picture of the mixtures, moisture content, apparent density, compactability, green compressive strength, green split tensile strength, green shear strength and toughness were measured.

2. Experimental Part

2.1. Used Equipment and Materials

Determination of optimal mixing conditions was performed on a LM-3e eddy mixer from Multiserw-Morek. The parameters of the LM-3e eddy mixer are listed in Table 1 [6].

Table 1.
Parameters of an eddy mixer LM-3e [6]

Bowl speed	Rotor speed	Bowl volume	Bowl diameter	Bowl height
rpm	rpm	l	mm	mm
10-72	100-2760	18.4	305	252

Furthermore, a semi-automatic laboratory rammer UA-2e/Z was used to determine compactability and to prepare samples for strength measurement. This was measured on a universal device LRu-2e for measuring the strength of the molding mixture [6].

Silica sand BG27 from the Biała Góra site with the value of the mean grain d_{50} of 0.27 mm was used to prepare the molding mixture [7]. Bentonite Sabenil activated with sodium carbonate from Keramost a.s. was also used [8]. Tap water was used to prepare the green sand mixture so that the experimental conditions were identical to normal operating conditions. For these reasons, the moisture content of the raw materials was also not taken into account.

The mixture for determining the optimal mixing conditions (Table 2) in an eddy mixer was selected based on the results of previous research, in which the influence of the order of individual raw materials and the amount of moisture on the properties of the mixture was investigated.

Table 2.
Mixture parameters

	Sand	Bentonite	Moisture content
Weight part [%]	100	8	2.5
Weight [g]	3000	240	75

2.2. Experimental Procedure

In the previous research [5], a mixture was selected from three mixtures that had the optimal composition and sequence of added raw materials and the associated desired properties of the mixture. These parameters are listed in Table 2. To determine the optimal initial properties of the molding mixture, the mixture was stirred for 1 to 5 minutes. At each minute of mixing, a sample of the mixture was taken for a series of measurements. The properties of the moulding mixture in the interval from the 1st to the 5th minute of mixing are given in Table 3.

Table 3.
Properties of the mixture mixed on a wheel mixer LM-2e [5]

Time [min.]	1	2	3	4	5
Moisture content [%]	2.90	2.89	2.90	2.91	2.84
Apparent density [kg/m^3]	556	529	519	503	500
Compactability [%]	55	55	55	55	55
Compr. strength [kPa]	91.0	88.4	89.4	90.0	94.3
Split tensile strength [kPa]	28.9	32.1	30.1	30.6	32.7
Shear strength [kPa]	19.2	19.5	21.1	21.3	22.1
Toughness [-]	0.32	0.36	0.34	0.34	0.35

The optimum mixture properties were determined to be those at the 5th minute of mixing on the wheel mixer as shown in Table 3. The mixture mixed on the eddy mixer should meet at least the following characteristics. The decisive parameter for these properties is the green compressive strength, which should be around 100 kPa. According to an optimistic forecast, the green compressive strength could reach values around 130 kPa. The compactability reached 55% throughout the mixing process, which is the maximum measurable limit of the device. The actual compactability of the mixture was probably higher.

Determination of the optimal mixing speed

For the LM-3e eddy mixer, a mixing process was established where the mixture was mixed in the order sand–water-bentonite. Silica sand was poured into the mixing bowl and then water was added. The mixing time of sand and water was set to 10 seconds. After this time, bentonite was added to the mixer and the mixture was mixed for a further 90 seconds. Moisture content and green compressive strength of the mixed mixture were determined.

Depending on the compressive strength achieved, the mixing process was further modified. In this case, the speed of rotation of the bowl and rotor was adjusted. From an economical point of view, repeated mixing of the mixture was resorted to. After measuring the moisture and green compressive strength, the mixed mixture was moistened to the required level and was mixed again for further speeds.

These results were averaged over the three measurements and in the case of a deviation greater than 5%, the measurement was considered erroneous and was not included in the result. In this case, the measurement was repeated. This procedure has been applied to all the results presented in this article.

The mixing parameters for mixing silica sand with water were set according to Table 4. This mixing of sand and water was done only when the mixture was first mixed.

Table 4.
Parameters of mixing sand with water for the first cycle

Time [s]	Bowl speed [rpm]	Rotor speed [rpm]
10	31	1330

During the next mixing of the mixture, this step was omitted and the mixture was mixed for only 90 seconds at the given bowl and rotor speed. The mixing parameters are given in Table 5 together with the measured moisture content and compressive strength.

Table 5.
Mixing parameters of the mixture with bentonite; properties of mixed mixtures for the first cycle

Mixing	1.	2.	3.	4.	5.
Time [s]			90		
Bowl speed [rpm]	31	36	41	45	50
Rotor speed [rpm]	1330	1370	1410	1500	1600
Moisture content [%]	2.57	2.47	2.47	2.35	2.40
Compr. strength [kPa]	68.5	70.4	73.3	77.8	82.0

Table 5 shows that after the first mixing of the mixture at medium speeds of the mixing bowl and rotor, the mixture was nowhere near the desired strength. For this reason it was decided to increase the mixing speed. With increasing speed, the strength of the mixture increased up to a green compressive strength of 82 kPa at 50 rpm bowl speed and 1600 rpm rotor speed as shown in Table 5.

A new mixture was mixed to prevent a cumulative increase in strength. Based on experience from previous mixing the parameters for mixing silica sand with water were adjusted. These adjusted parameters are shown in Table 6. After mixing the sand with water, bentonite was added to the mixer and the mixture was mixed in the same manner as the first mixing cycle. The bowl and rotor speeds used, together with the measured values of moisture content and green compressive strength, are given in Table 7.

Table 6.
Parameters of mixing sand with water for the second cycle

Time [s]	Bowl speed [rpm]	Rotor speed [rpm]
10	40	1400

As can be seen from Table 7, for this cycle the bowl rotation speed was set at 60 rpm. No further increase in bowl speed was made because the maximum speed limit (71 rpm) was approached, which could lead to excessive loading of the mixer.

Table 7.
Mixing parameters of the mixture with bentonite; properties of mixed mixtures for the second cycle

Mixing	1.	2.	3.	4.	5.	**Cont.**
Time [s]			90			
Bowl speed [rpm]			60			
Rotor speed [rpm]	1800	2000	2200	2400	2600	2600
Moisture content [%]	2.72	2.70	2.50	2.46	2.40	2.80
Compr. Strength [kPa]	75.7	81.7	80.7	97.5	106.7	81.8

On the fifth mixing, a pressure of 106.7 kPa was reached. This value exceeds the required limit and a new control mixture was mixed to confirm this green compressive strength at the given mixing speeds. The mixing parameters and properties of this control mixture are again shown in Table 7. For better orientation in the measured data, a graphical dependence of green compressive strength on rotor speed was constructed and can be seen in Figure 1.

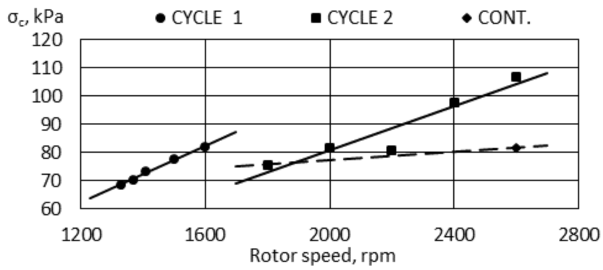

Fig. 1. Development of green compressive strength depending on the rotor speed

Figure 1 shows the first mixing cycle where the mixture was mixed at rotor speeds from 1330 to 1600 rpm. Next, the second mixing cycle is shown, at the end of which a strength of 106.7 kPa was achieved at a rotor speed of 2600 rpm. The last line shows the mixing control point at a rotor speed of 2600 rpm. . If we compare the strength measured for the second mixing cycle at 2600 rpm with the strength measured for the newly mixed mixture at this speed, we find that the difference in strength is approximately 25 kPa. The intersection of the strength of the first mixing of the mixture in the second cycle and the newly mixed mixture gives the theoretical development of the green compressive strength of this mixture without the increase in strength due to cyclic mixing. This theoretical green compressive strength is indicated by the red dashed line in the graph in Figure 1.

Unfortunately, the newly mixed control mixture did not confirm the previously measured green compressive strength of 106.7 kPa. The strength measured during the control measurement was only 81.8 kPa and therefore did not reach the required limit.

The results of these measurements showed that optimum mixing speeds were not found at which the compressive strength would reach values around 100 kPa within 90 seconds of the start of mixing. For this reason, mixing speeds corresponding to the maximum mixing speeds tested in Table 7 were set for further measurements.

Determination of the optimal mixing time

Based on the mentioned results, two mixing times of 10 and 20 seconds were determined for mixing the sand with water. For these two mixing times of silica sand with water, four mixing intervals of the mixture with bentonite were determined, which corresponded to 60, 90, 120 and 150 seconds of mixing for a comprehensive picture of the green compressive strength development.

The mixing procedure was similar to that used to determine the optimum mixing speeds. Measurements were then taken on the mixed mixture to determine the moisture content and green compressive strength of the mixture. These measured values are given in Table 8.

Table 8.
Mixture properties for given mixing times cycle

	Time [s]	60	90	120	150
10 s	Moisture content [%]	2.72	2.80	2.72	2.43
	Compr. strength [kPa]	75.3	81.8	85.7	100.9
20 s	Moisture content [%]	2.55	2.51	2.45	2.45
	Compr. strength [kPa]	90.1	92.4	98.7	102.6

On the basis of these measured properties, a graphical dependence of green compressive strength on mixing time was created for better clarity, which can be seen in Figure 2.

Two lines are drawn on the graph. The first line shows the dependence of the green compressive strength on the mixing time at which the sand and water were mixed for 10 seconds. The second line shows the mixture mixed for 20 seconds.

Figure 2 shows a large difference between the strengths of the mixtures at 60 seconds, where longer mixing of sand and water results in a strength increase of 15 kPa due to better water dispersion. As the mixing time increases, the strengths of the mixtures level off and exceed 100 kPa at a mixing time of 150 seconds. In terms of mixing efficiency based on green compressive strength monitoring, a mixture in which the sand has been mixed with water for 20 seconds is much preferable because it has a much faster strength increase than a mixture with a mixing time of 10 seconds. For this reason, a mixture with an extended mixing time of silica sand and water was chosen for further measurements.

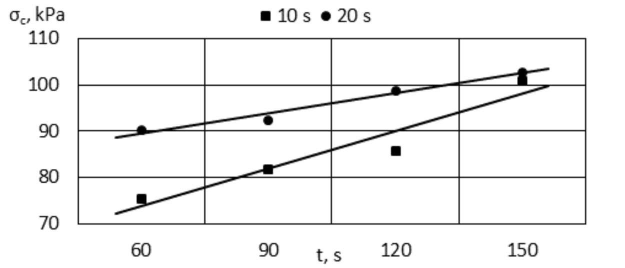

Fig. 2. Development of green compressive strength depending on mixing time

In order to obtain an overall picture of the development of the individual properties of the mixture and to determine the correct parameters for optimal mixing, control measurements of the mixture with an extended mixing time of sand and water were carried out. These mixing runs were performed for mixtures with mixing times of 90, 120 and 150 seconds.

For these mixtures, moisture content and green compressive strength were again measured, but apparent density, compactability, green split tensile and green shear strength were also determined. From these measured values, the toughness of the mixture was further calculated.

Table 9.
Properties of mixtures with extended mixing time of sand with water

Time [min.]	90	120	150
Moisture content [%]	2.60	2.49	2.48
Apparent density [kg/m^3]	633	632	610
Compactability [%]	55	55	55
Compr. strength [kPa]	91.6	101.4	104.5
Split tensile strength [kPa]	32.2	33.4	30.8
Shear strength [kPa]	21.1	22.2	22.5
Toughness [-]	0.35	0.33	0.30

3. Analysis of the Results

From the data measured during the previous research (Table 3) and from the data of this experiment presented in Table 9, graphical dependencies of the individual properties of the moulding mixture on the mixing time were constructed. These graphs compare the mixtures mixed on the LM-2e wheel mixer and the LM-3e eddy mixer to compare the two mixers and determine the optimum mixing parameters for the LM-3e eddy mixer. The graphical dependencies are shown in Figures 3-10.

The moisture content graph in Figure 3 shows the difference between the moisture content of the mixtures mixed on the wheel mixer and the eddy mixer, with the mixture mixed on the wheel mixer having a much higher moisture content than the mixture mixed on the eddy mixer. The highest difference is approximately 0.4%. This difference may be due to different water distribution in the mixers or different evaporation conditions.

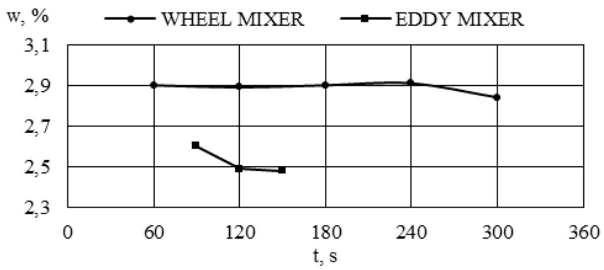

Fig. 3. Development of moisture content

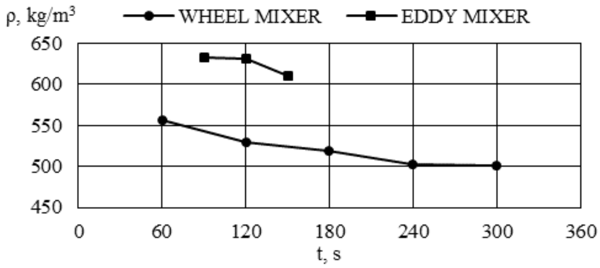

Fig. 4. Development of apparent density

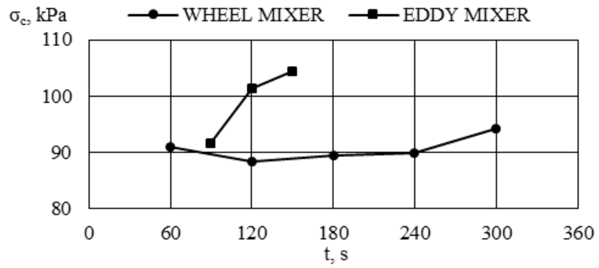

Fig. 5. Development of green compressive strength

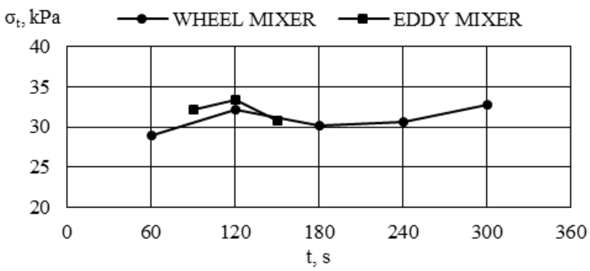

Fig. 6. Development of green split tensile strength

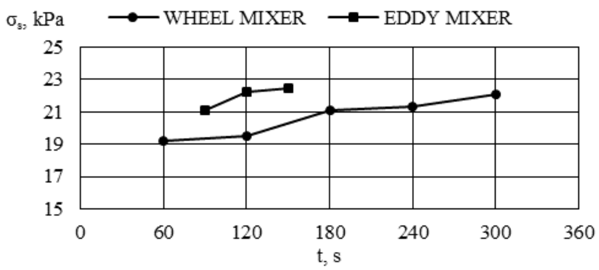

Fig. 7. Development of green Shear strength

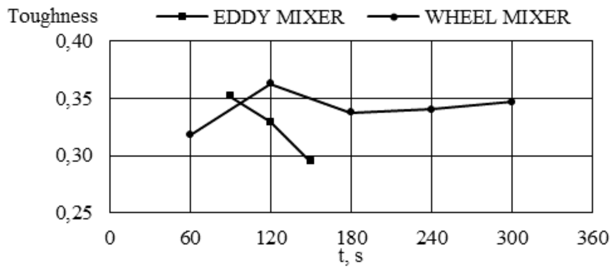

Fig. 8. Development of toughness

The development of apparent density is dependent on the moisture content of the mixture, because for every moisture content in the mixture there is an apparent density. As the moisture content of the mixture increases, the apparent density decreases. This can be seen by comparing Figures 3 and 4, where the apparent density of the mixture mixed on the vortex mixer is much higher due to the lower moisture content of the mixture.

The green compressive strength (Figure 5) of the mixture after 1.5 minutes is approximately the same for both mixers, around 90 kPa, but its development over time is different. The mixture mixed on the wheel mixer is rather stagnant and its strength does not change significantly. After 5 minutes of mixing, the mixture reaches a strength of 94.3 kPa. The green compressive strength of the mixture mixed on the eddy mixer increases with time and reaches 104.5 kPa at a mixing time of 150 seconds. In terms of green split tensile strength, the measured values for both mixers are almost identical and there is no significant difference between them, as can be seen in Figure 6. The green shear strength evolution graph (Figure 7) shows a slight difference in the strength of the mixture mixed on the wheel mixer and the eddy mixer, with the mixture from the eddy mixer reaching a higher strength with the highest difference of 2.7 kPa.

Green split tensile strength and green compressive strength determine the toughness of the mixture, which is their ratio. From Figure 8 graphical dependence of toughness on mixing time, it can be seen that the mixture that was mixed on the eddy mixer has a decreasing tendency. However, these values are comparable to the toughness of a mixture mixed on a wheel mixer.

When visually comparing the mixture mixed in a wheel mixer and an eddy mixer, the mixture from the eddy mixer is much more aerated and fluffier. On the other hand, lumps of undecomposed bentonite occasionally occur in the mixture. The mixture mixed in the wheel mixer is much denser and does not show lumps of bentonite.

Based on the results obtained in this work, the optimum mixing parameters for the LM-3e eddy mixer were selected. One of the main requirements for the mixture mixed in this mixer was a 100 kPa green compressive strength limit, which was achieved. The selected optimum mixing parameters are shown in Table 10. The optimal mixing parameters were chosen to be prolonged mixing times of silica sand with water by 20 seconds at a bowl speed of 40 rpm and a rotor speed of 1400 rpm. Mixing of the mixture with bentonite was set to 120 seconds at a bowl speed of 60 rpm and a rotor speed of 2600 rpm. The mixing time of 120 seconds was determined based on the green compressive strength at which time 101.4 kPa was reached. With longer mixing times, the strength of the mixture increased only gradually. Due to the ineffectiveness of mixing the mixture after 120 seconds, this time was determined as the optimal mixing time.

Table 10.
Optimal mixing parameters for the eddy mixer

	Time [s]	Bowl speed [rpm]	Rotor speed [rpm]
S + W	20	40	1400
S and W + B	90	60	2600

4. Conclusions

The bentonite mixture, whose composition and raw material addition order was determined in previous research, was subjected to a series of mixing on an LM-3e eddy mixer under different conditions to determine the optimal mixing parameters. The optimum bowl and rotor speeds in standardized time were first evaluated based on the measured data of the individual mixtures. Subsequently, these optimum mixing speeds were applied for different mixing time intervals, namely 2 time intervals for mixing silica sand with water and 4 time intervals for mixing the mixture with bentonite. From the result of this series of mixing, the most suitable mixture was evaluated as the one for which the mixing time of sand and water was extended. For this extended period, 3 time intervals for mixing the mixture with bentonite were determined. For these mixtures mixed at three intervals, in addition to moisture content and green compressive strength, the apparent density, compactability, green split tensile strength, green shear strength and toughness of the mixture were also measured.

Graphical relationships were developed for these mixture properties, comparing these mixture properties with the measured properties of the mixture mixed on the LM-2e wheel mixer. These mixtures mixed on different mixers were compared and the optimum mixing parameters were selected based on the analysis of these properties. Optimum mixture properties were achieved by mixing sand and water for 20 seconds at a bowl speed of 40 rpm and a rotor speed of 1400 rpm. After addition of bentonite, the mixture was mixed for 120 seconds at a bowl speed of 60 rpm and rotor speed of 2600 rpm. The mixture thus mixed reached a green compressive strength of 101.4 kPa. When mixing the mixture on a wheel mixer, the green compressive strength after 5 minutes of mixing was only 94.3 kPa. When mixing the mixture on the eddy mixer, a higher green compressive strength was achieved in a shorter mixing time than with the wheel mixer.

Although optimistic strength assumptions of 130 kPa were not met, the mixture still meets the minimum green compressive strength requirement (100 kPa) and retains a relatively high toughness and is therefore still suitable for use as a filler and model mixture.

In the future, it would certainly be beneficial to apply this experiment in industrial operation and verify whether the measured values in laboratory conditions correspond to the properties of mixtures in real operation, which are mixed in much larger volumes.

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