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# THE IMPACT OF COMPOSITION AND THE DENSIFICATION LEVEL OF FURAN MOLDING COMPOUNDS ON THE STRENGTH OF LARGE-SIZE CASTING MOLDS

The paper presents the test results of molding compounds, sand casting molds and their analysis. The subject of testing was compound containing furan resins prepared according to the following recipe: matrix – regenerate 90% + fresh sand – 10%, furan resin – 1.10% by weight, hardener – 0.40% by weight. The impact of adhesive type and its quantity ($Q_{uan}$ = 0.90, 1.1 and 1.5%) on the strength indexes of molding compound subject to densification was analyzed. The publication presents the test results: tensile strength $R_m$, compressive strength $R_c$ and flexural strength $R_g$, as well as compound permeability as function of its density. The analysis also covers the impact of density level on mold strength and the distribution of density level along the mold height.

Based on the test results, it was found that the best method to obtain high strength molds made from compounds with chemical adhesives was to densify it by vibrating the system: match plate – molding flask – compound filling the mold. The effectiveness of this densification method depends on the amplitude and frequency of vibrations.

*Keywords:* molding sand, adhesive, densification, properties molding sand

## 1. Introduction

Cast iron is the most commonly used casting alloy. According the latest data published in Modern Casting in December 2019, the weight of global cast production in 2018 was 112 million metric tons [1]. Gray iron products made up 44%, while ductile iron products covered 25% of the total. In 2018, Poland produced 1.036 million metric tons of casts, 44% of which corresponded to gray iron, and 15.4% to ductile iron. Despite such a big production of those alloys, there are many problems to be resolved by research to improve cast quality and to reduce the number of casting defects. The cast quality depends on the metallurgical quality and the quality of casting mold [2]. Manufacturing ductile iron casts without shrinkage porosity in thermal nodes requires using high-rigid molds, both when metal is in liquid state and during its solidification. One of the prerequisites to provide high rigidity is to obtain high strength properties of molds and the high density of compounds. The mold is also responsible for dissipating heat from a cast. Of great importance here is its proper structure that takes into account the existent thermal nodes, components used to accelerate heat dissipation (chills) or components used to facilitate filling (exothermic jackets, riser heads). Of importance are also the molding materials used (sand, resin, adhesive, curing method) whose types, divisions and properties have been described in many literature items [3-5]. Newer generations of currently used: alkyd resin, resol type phenolic resin (process α – set) and furan resin (furan process) are being implemented. Tests are conducted to optimize the composition of molding compound in terms of their properties (strength, permeability, densificability, friction resistance) and the characteristics of binding compounds as a function of time and temperature are specified [6-8]. An important line of conducted experiments was the use of ultrasound tests to determine mold strength properties [9-12]. These are non-destructive tests, allowing to specify e.g. the level of densification and strength of large molds without the need for destruction.

By contrast, the metallurgical quality is affected by: batch materials, type of melting furnace, temperature of superheating and keeping cast iron in a melting furnace, the time of melting and keeping liquid alloy in liquid state, time from the process of spheroidizing to filling the mold. Batch materials used to produce cast iron include: pig iron, steel scrap and circulating cast iron scrap, alloy additives, spheroidizers and modifiers. For many

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foundries, the main criterion for creating batch compositions is the price of materials. It means that the amount of pig iron in the batch is limited by replacing it with steel or circulating scrap. The results of conducted tests show, that is impossible to provide good quality of cast iron (even ductile iron) during melting process without pig iron in the batch [13-15]. Certainly, there will be limitations during melting ductile iron with ferritic matrix, where a low concentration of Mn, S and pearlitogenic elements is required. Limitations will also apply to the selection of melting furnace. In Poland, the majority of cast iron is melted in cupolas showing various innovation levels. The specific feature of melting in those furnaces is a significant sulfur concentration in the cast iron, resulting from using coke as fuel. There is an increasing number of foundries fitted with medium-frequency electric furnaces that provide shorter melting time and reduce the time needed to achieve the required (high) alloy temperature. The undoubted advantage of induction furnaces is their lower environmental emission, more flexible operation mode (they can be used to melt various grades / types of cast iron), lower level of harmful alloy components (S, P). An important parameter of melting cast iron is the temperature and time of keeping it in liquid state. Higher temperature and longer times reduce the quality of liquid alloy. Many of the properties described above can be improved by using a larger amount of a properly selected pre-modifier and modifier. However, it results in higher costs. Therefore, the correct physical and chemical properties of liquid alloy should be provided as early as at the initial melting stage.

## 2. Molding compound

As already mentioned, proper rigidity and mold strength should be provided for large-size ductile iron casts. Here this is mainly about compressive strength that can be increased by:

– changing the type of adhesive replacing "older" generation adhesives with "new generation" adhesives,
– increasing the amount of adhesive introduced to the compound,
– increasing the level of matrix grains compaction (densification level).

Introducing "stronger" adhesives usually takes place every few or every dozen years or so, as they are launched onto the market. They result in the change of properties by only a few percent points.

The tests covered a recipe consisting of a circulating compound acquired from a foundry (subject to mechanical regeneration process). The first step was to evaluate the regenerate in terms of ignition losses (annealing at 1000°C for about 3 hours) and the evaluation of granularity characteristics (sieve analysis). As a result of conducted tests, it was found that the average value of ignition losses for the material under analysis was 2.7%. The main fraction level was 82.35%, which shows that the compound is uniform and it covered sieves with numbers 0.40, 0.315, 0.20, which allowed to classify regenerate as coarse-grained. The average grain size of the regenerate was $d_L$ = 0.35 mm.

Another step of tests was to specify the impact of adhesive types on the strength of the molding compound prepared. The tensile strength tests as a function of compound density (Fig. 1) were performed. Two compounds with furan Resin1 and Resin2 using regenerate (90%) and fresh sand (10%) for the amount of adhesive of $Q_{uan}$ = 1.1% by weight and hardener – 0.40% by weight, respectively, were used in the tests. Tests were conducted at the ambient temperature of about 20°C.

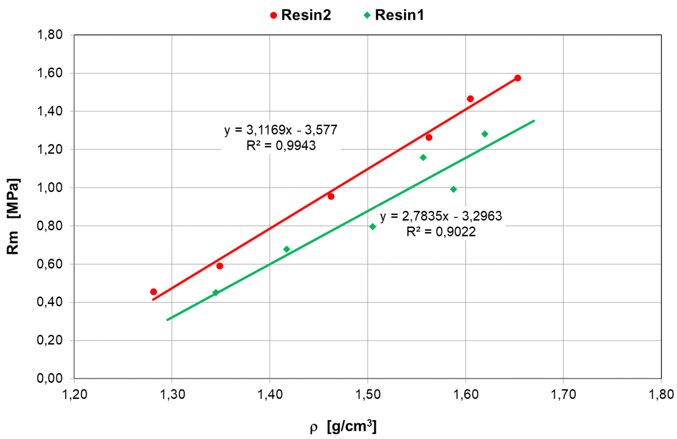


Fig. 1. The impact of furan compound with Resin1 and Resin2 on $R_m$ tensile strength

The compound can show a densification level ranging from about 1.3 to 1.65 g/cm$^3$. At this growth, the compound increases its $R_m$ strength, ranging from about 0.4 to 1.6 MPa, i.e. almost 4 times. This correlation is linear in nature. Resin1 and Resin2 differ a bit in terms of providing tensile strength. Higher strength is achieved by the compound with Resin2, while the differences reach the value of approx. 0.2 MPa. High tensile strength of molding compounds is necessary to remove the model from the mold to prevent tearing away its protruding parts, called "humps". Therefore, we should seek to increase the strength by densifying the compound in molds and core boxes.

Compressive strength is a very important feature to make ductile iron casts free from any internal defects in the form of porosity. For two types of adhesives under test, in addition to $R_m$ strength test, a $R_c$ compressive strength test was also performed. The results of those tests are presented in Figure 2. They have confirmed that proper densification of the compound can increase its compressive strength.

$R_g$ flexural strength was also measured for both compounds. Just as previously, raising compound density increases its flexural strength (Fig. 3).

Casting molds made from compounds with adhesives should feature good permeability. The permeability of compounds under test is relatively high, but is reduced as their density grows. The fact should be taken into account when designing highly densified molds using a larger number of venting channels. The test results have shown that the type and amount of adhesive do not have a significant impact on the permeability of compound with adhesives, if the densification level is the same. Therefore, for adhesive compounds with general good

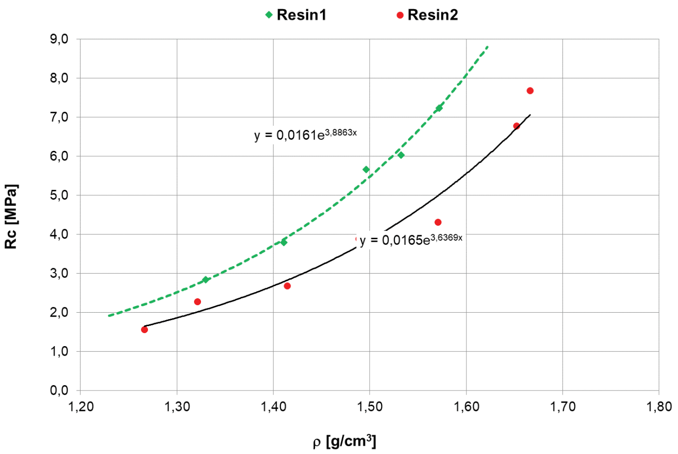


Fig. 2. The impact of furan compound densification with Resin1 and Resin2 on $R_m$ tensile strength

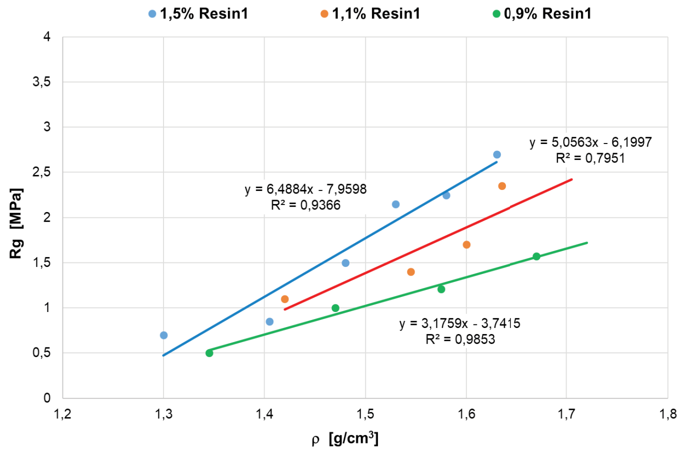


Fig. 4. $R_g$ flexural strength of compound with Resin1 at its concentrations of $Q_{uan}$ = 0.90; 1.1 and 1.5%

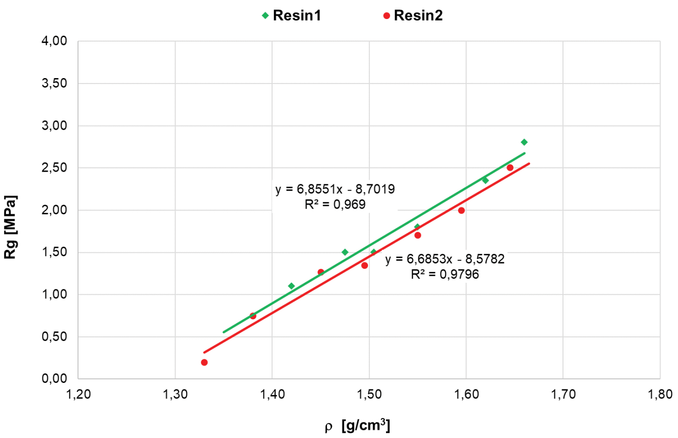


Fig. 3. The impact of compact densification on $R_g$ flexural strength

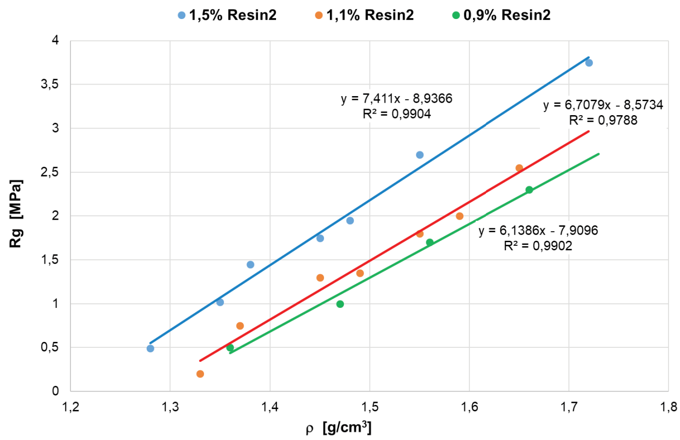


Fig. 5. $R_g$ flexural strength of compound with Resin2 at its concentrations of $Q_{uan}$ = 0.90; 1.1 and 1.5%

permeability, it is densification that affects its level. Another factor could be the size of grain, but when using regenerate, the size of grain is stabilized in the specific foundry workflow and is not subject to changes.

Another step of tests was to specify the impact of adhesive amount on the strength of the molding compound prepared. Two compounds with furan Resin1 and Resin2 using regenerate (90%) and fresh sand (10%) for the amount of adhesive $Q_{uan}$ = 0.90, 1.1 and 1.5 %, respectively, were used for tests. Test results are presented in Fig. 4 and 5.

Another extremely significant parameter specifying mold quality is its permeability – the capacity of mold to let gas flow through it. Test results are presented in Fig. 6.

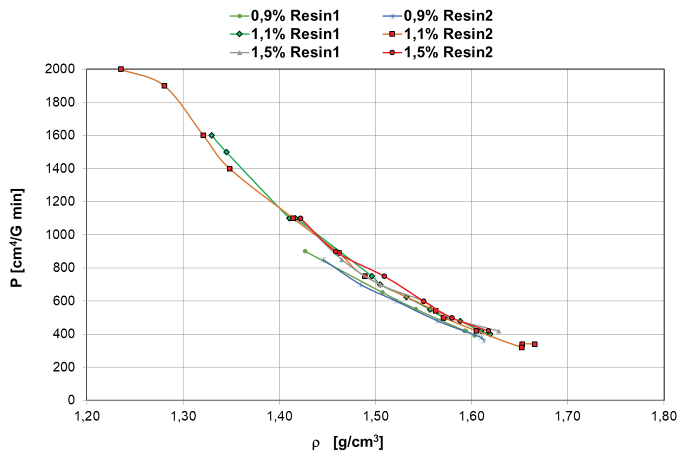


Fig. 6. The impact of compound densification, with two types of adhesives, at different adhesive concentrations, on its permeability

## 3. Ultrasound testing

Many studies developed at the Faculty of Foundry Engineering, AGH University of Science and Technology, over recent decade show that ultrasound technology can be a tool to inspect compounds with adhesives, including inspecting binding processes, kinetics of those processes, but it can also be used to check the densification level or to evaluate the strength of compounds in molds once the binding process is completed [7-12]. The ultrasound tests are non-destructive tests and for that reason alone are very “attractive” and operator-friendly for testing large-size molds. The speed of wave increases as compounds with chemical adhesives become denser. However, this quantitative correlation is typical for a specific compound. Therefore, tests were performed to obtain standard correlations to be used as basis for tests in ready to use molds and cores. In the conducted tests, low-frequency heads (50 or 100 kHz) were used to generate hard to suppress waves, the ones needed to propagate waves in porous media, e.g. in sand molds. Tests were conducted using ultrasound material testers sized ϕ50×50 mm, placed during measurement between ultrasound heads. Correlation between wave speed, its $R_m$ and $R_c$ strength is presented in Fig. 7-10.

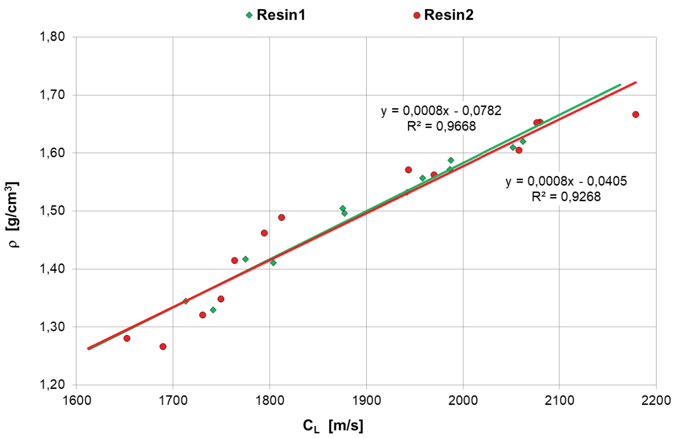


Fig. 7. Correlation between ultrasound wave speed in a compound sample and its density

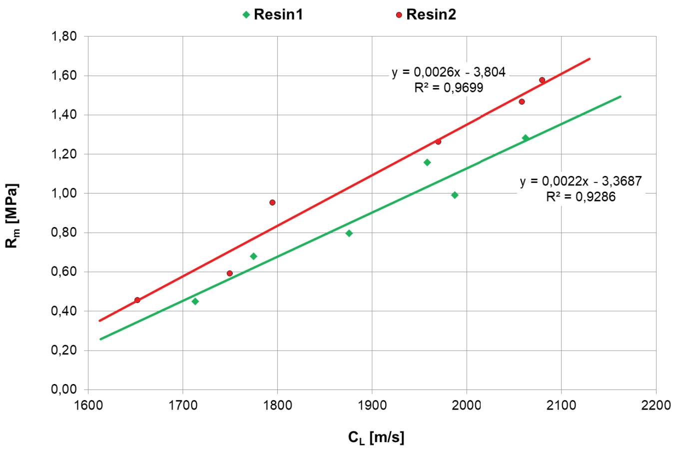


Fig. 8. Correlation between ultrasound wave speed in a sample and its $R_m$ strength

## 4. Densifying the compound by using mold vibrations

One of the most effective and low-cost strength enhancement methods is to increase its compound density level. Densification is obtained by using a vibration technique that is more effective for higher molds, considering the process mechanism. However, problems with vibration tables that can be loaded with a weight of a few metric tons make that the technique is still not commonly used.

As part of the study, laboratory tests were conducted to determine compound densification level using the regenerate matrix to be obtained by using vibrations as densification technique. Densification was performed at variable vibration table parameters, i.e. at various frequencies and vibration amplitude values. The ultrasound method was used to determine the level of densification. In tests, a compound with the following recipe was used: regenerate – 90%, fresh quartz sand – 10%, resin: – 1.1%, hardener – 0.4%

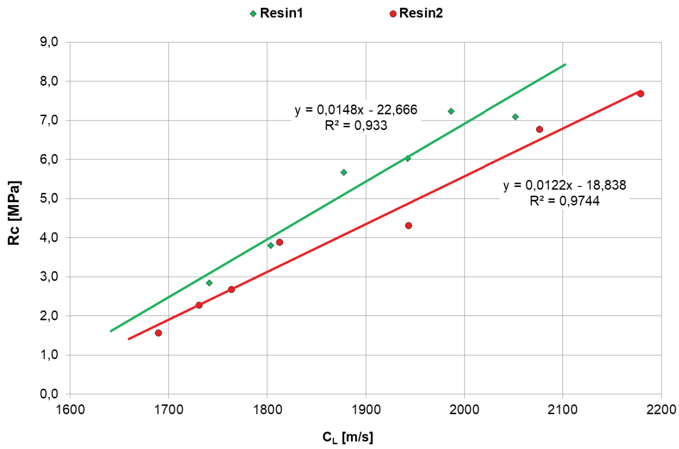


Fig. 9. Correlation between ultrasound wave speed in a compound sample and its $R_c$ strength

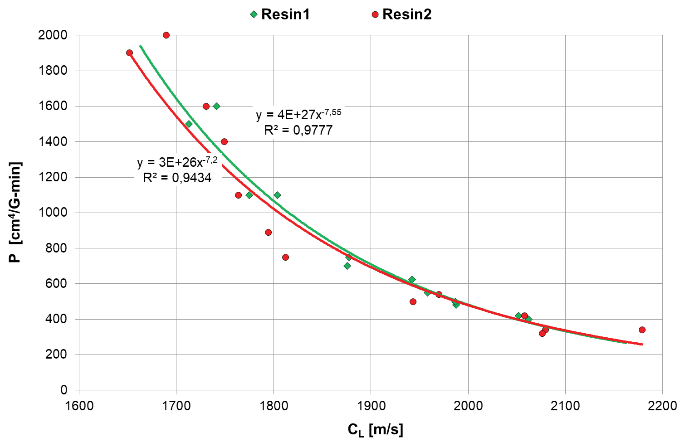


Fig. 10. Correlation between ultrasound wave speed in a compound sample and its $P$ permeability

The idea of vibration densification process was performed at the test stand presented in Fig. 11.

The test mold had the following dimensions: 60×300 ×400 mm. The rectangular shape of the mold was forced by measuring densification level using ultrasound technique, while this technique requires keeping parallel the walls, through which the ultrasound wave is transferred and received.

Testing compound densification along the mold height was performed once the compound was fully cured, i.e. after 24 hours. A method using two heads was used for measurement, i.e. the permeability method (not the echo method). Molding compounds are media that intensely suppress vibrations (ultrasound waves), which, in a way, forces the use of a method of permeability and the use of heads generating low frequencies, most frequently 0.1 MHz or 0.05 MHz (100 or 50 kHz).

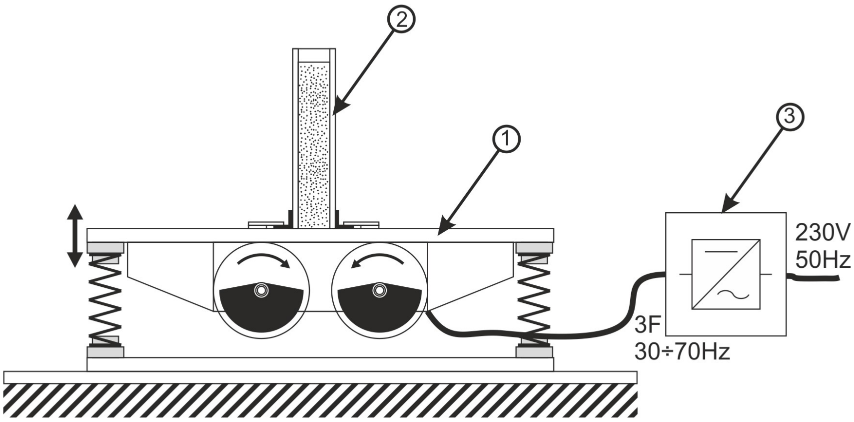


Fig. 11. Schematic diagram of laboratory stand for testing the effectiveness of vibration densification: 1 – vibration table 650×650 mm, 2 – mold for compound densification, 3 – inverter used to control table operation (frequency and amplitude), 4 – frequency sensor

Testing the density using the ultrasound technique is indirect in its nature, based on characteristics previously determined for specific compounds and correlations shown in section 3. As it can be seen in Fig. 7, compounds used in testing have practically linear function characteristics $\rho_o = f(C_L)$. After measuring the wave speed in a hardened compound, the value of density was read in a specific location – measurement point. Ultrasound tests were performed along the whole mold surface to specify both the densification level and its uniformity.

Fig. 12 presents the data from wave distribution measurement along the mold height. It shows how effective it is to use the vibration table as densification method. The wave speed related with compound density in a densified core is on average by 700÷800 m/s higher, which indicates significant changes in density. After calculating ultrasound test results, the results of compound density in particular core locations are obtained. The results are shown in Fig. 13. In Fig. 13, we can see that during manual compacting of the compound in the core box, very low compaction may take place, even below 1.2 g/cm$^3$, especially near the side walls. Vibration not only results in a significant increase in density exceeding the limit of 1.7 g/cm$^3$, but also allows to align density along the mold height. This is a very important issue for producing high ductile iron casts.

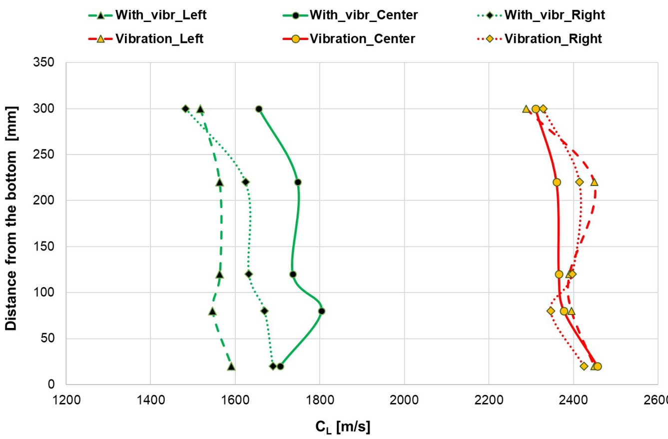


Fig. 12. Results of ultrasound tests covering cores (molds) without using table vibrations and using table vibrations at a frequency of 50 kHz

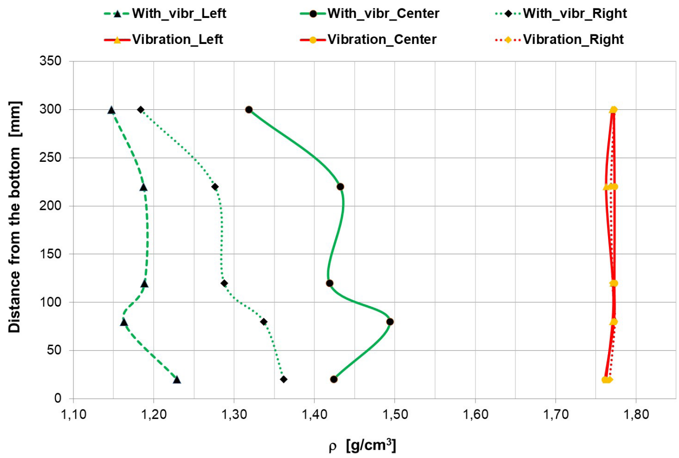


Fig. 13. The distribution of compound in cores (molds) made by using vibrations and without using vibrations

As part of tests, the correlations between compound properties and the capacity to propagate a longitudinal ultrasound wave were developed, for use as calibration standards (calibration data) applied under industrial conditions to provide non-destructive mold testing. Based on them, the compound densification level, its strength and permeability were monitored in completed industrial molds, made of tested compounds with furan resins.

## 5. Summary and conclusions

The above presented results have shown that one of the most effective methods for improving mold strength is to increase the molding compound density level with adhesives. It can be achieved by manual compound densification (which is hard to repeat and most frequently used near the model) or by using vibrations.

The tests conducted in the laboratory allowed to present the following conclusions:

1. Densification of molding compound with organic (furan) adhesive during table and mold vibrations makes it possible to achieve the apparent density exceeding 1.65 g/cm$^3$,

2. The densification process using vibrations allows to obtain high uniformity of densification along the height of molding flask.
3. The experiments performed has shown that the effect of strong compound densification is obtained only when the vibration frequency is not lower than 40 kHz, while vibration amplitude hovers around 1.0 mm.
4. The molding compound is well densified around the model, under chills and in the space more distant from the model.
5. The level of compound densification with matrix-regenerate (~1.55 g/cm$^3$) obtained by vibrations makes it possible to meet the requirement of high mold density.
6. Raising compound density can be used to reduce the amount of adhesive in the compound, because the higher the densification, the higher are all compound strength indexes.
7. The laboratory test results made a basis to design a vibration-induced mold densification stand to be used under industrial conditions.

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