*This paper has proposed a simplified procedure for the rapid assessment of the suitability of small-scale articles made from various raw mixtures (hereafter referred to as mixtures) for semi-dry pressing (SP) at molding presses, which could employ fillers composed of slag, ash, dust, and other industrial waste, whose properties are heterogeneous. The procedure is based on an assessment of the degree of negative impact on the quality indicators of articles due to the error of their density* $\Delta\rho\geq\pm2.5$ *%, associated with the imperfection of bulk dosing devices that the SP molding presses are equipped with. It has been established that the mixtures can be graded on the basis of the steepness of a compression curve (CC) – the dependence* $q_i=f(\rho_i)$*, where* $q_i$ *and* $(\rho_i)$ *are the current values of pressure (in MPa) and density of the mixture array (in g/cm*$^3$*). A criterion applied to define the mixture's suitability to SP is a multiplier b (in cm*$^3$*/g) included in the dependence. It is shown that the mixture of type I (at* $b\leq8$*) is suitable for SP at the multi-cavity molding presses. The mixture of type III (at* $b>12$*) is problematic; its composition must be adjusted to re-determine b. The mixture of type II (at b=8...12) requires additional research, proposed to be carried out in two stages. The first stage implies a low-cost determination of the dependence of the strength of SP samples on pressure* $\sigma=f(q)$ *and testing the minimum strength* $\sigma_{min}$*, as well as for the criteria of steepness K and permissible pressure* $q_y$*. The ranges of K and* $q_y$ *have been determined, in which a more laborious second stage is needed to check for the absence of an «overpressing» defect. If all stages of the tests are successful, the mixture belongs to type I; if not – to type III. Techniques to improve the suitability of the mixtures to SP have been considered. A promising technique has proven to be the treatment of the mixture in a high-speed roller-type activator, which simultaneously reduces both the CC steepness of the activated mixture and the required pressure of pressing. The study results could expand the application scope of anthropogenic products by utilizing them in the mixtures for SP*

*Keywords: semi-dry pressing, pressure, pressing curve, dosing error, raw mixtures, suitability check*

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# IMPROVING A PROCEDURE FOR ESTIMATING THE SUITABILITY OF RAW MATERIAL MIXTURES FOR MOLDING ARTICLES BY A SEMI-DRY PRESSING METHOD BASED ON THE ANALYSIS OF COMPRESSION CURVES

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## 1. Introduction

When addressing the issue of resource preservation, the task to reuse anthropogenic products (metallurgical slag, solid fuel combustion ash, crushing dropouts, dust cleaning products, as well as other industrial waste) is becoming more urgent as they are accumulated at an increasing rate, thereby causing increasingly tangible harm to the environment. There are two ways of using anthropogenic products: returning them to production (for example, in the form of briquettes made from the dust from steel mills) and using them as fillers for concrete, in particular, during the production of small building articles (bricks, blocks, tiles, hereafter referred to as SBA) [1]. In line with resource preservation is also a tendency to replace high-quality and expensive fillers for SBA with local cheap ones. One of the main features of anthropogenic products and cheap local natural raw materials, already accumulated in dumps, in comparison with the mineral raw materials extracted in quarries, is a much more pronounced instability of properties – humidity, granulometric, mineralogic, and chemical composition.

The implementation of both above directions is possible using the process of molding the articles by compacting, within a confined space, pre-prepared and moisturized powdered or fine-grain mixtures (hereafter referred to as mixtures) by converging punches. Typical ones are, for example, the mixtures of a binder (cement or lime) and a filler. The process of such molding, commonly termed a semi-dry pressing (hereafter referred to as SP), is carried out at mechanical or hydraulic presses [2]. SP includes operations such as dosing a mixture within a confined space – a cavity («nest») of the mold; compacting to the predefined density using converging punches, which is often referred to as pressing; pushing a freshly molded and typically fragile raw article from the mold; taking the article and laying for transporting for the subsequent hardening.

The use of SP is only expedient at the warranted output of articles with the required level of quality indicators. Various regulatory documents state numerous quality indicators (for SBA, the requirements for the physical appearance, shape, size, density, frost resistance, etc.) while the basic regulated quality indicator of both a raw article and any finished product after hardening is the strength at compression σ, MPa. Typically, for a certain number of bricks in a batch [3], an average product strength σ after hardening is rated, as well as the minimum strength in the batch, such as $\sigma_{\min}=80\ \%\cdot\sigma$ [4]. The minimum allowable raw article's strength is dictated by the requirements for its non-defective removing and laying for transporting for the subsequent hardening. Is it possible, and how costly, will it be to provide the above stringent quality requirements for SP articles given the pronounced variability of properties inherent in the anthropogenic or cheap local raw materials? The answer to this question when using traditional procedures and regulations is: very costly. Particularly clear is the economic inefficiency of the costly traditional assessment of the possibility of using (suitability) such raw materials for SP, given their wide range of properties when they are accumulated in dumps of a relatively small volume. Devising a technology for the low-cost rapid assessment of the suitability of raw materials with a pronounced instability of properties for SP would expand the scope of their use, thus contributing to resolving the issue of resource conservation.

The main indicators of SP are the maximum pressure ($q$) of a punch on the mixture at the time of completing the compaction, and the density of a raw article (ρ). Each mixture is characterized by a certain relationship between the two specified quantities, termed a compression curve (compression without the possibility of lateral expansion). For each mixture, there is a rational pair «pressure – density», and the levels of the values of this pair for different mixtures vary widely (pressure $q$ ranges from 10 to 40 MPa). The raw article strength $\sigma_r$ and the product strength σ (under identical hardening conditions) for each mixture are determined by the density ρ and the related pressure $q$.

Most presses in general, and all modern SP molding presses for the production of SBA, in particular, involve the bulk dosing of the mixture into the cavities of molds. Bulk dosing, carried out most often by a carriage (a box without a bottom), is constructively much easier than the weight-based dosing, although it has a large error. At bulk dosing, the mass of a mixture batch, discharged into a mold cavity, is adjusted by the cavity depth – a position of the lower punch during dosing. Thus, the main and only, for the vast majority of SP molding presses, factor of control over an SP process (density, pressure, and strength) is the batch mass $m$. Increasing $m$ increases the density ρ, the pressure $q$, and the strength $\sigma_r$ and σ, which is why it can be effective to a certain level. However, in this case, the SP energy intensity grows, as well as the cost of the press and the cost of its maintenance (due to the accelerated wear of the working surfaces of molds and punches). For many mixtures, especially those containing a significant amount of dust-like anthropogenic products, there is a maximally allowable (threshold) pressure $q_{threshold}$, at which the plastic deformations are completed while the elastic ones begin. Excess $q_{threshold}$ leads to the occurrence of encircling cracks in an article when it is pushed out. This phenomenon (termed as overpressing) is associated with an uneven elastic deformation of a raw article and becomes more likely as mold cladding wears out.

Conventional SP studies aim to build models and procedures that optimize the composition of the mixture (primarily, minimize the consumption of a binder) and the pair ρ–$q$, while providing for the rated σ, $\sigma_{\min}$, and $\sigma_r$, σ, taking into consideration the minimization of the cost of implementing SP. The composition of a mixture is selected from the planned raw materials during special laboratory tests (often termed regulatory ones) according to the conventional procedure given in [1]. This generally does not take into consideration the inevitable deviations of SP factors from the rated values.

However, during actual production, there are errors in the composition and properties of the mixture, as well as errors of volumetric dosing. Errors in the composition and properties are often associated with the segregation of the mixture, whose negative impact can be especially significant when implementing SP on increasingly popular hydraulic multi-cavity molding presses that simultaneously, over a single cycle, mold several articles – from 4 to 40 pieces in the array. The segregation of the mixture is present to varying degrees when the bunkers of all SP molding presses are filled [5–8] – larger particles end up in the peripheral cells of the molds of a multi-cavity press. In this case, the batch mass $m$ and the properties of mixtures in the central and peripheral mold cavities will be different. This may lead to a difference in the entire set of SP parameters (ρ–$q$, $\sigma_r$, σ) because the depth of all cavities in multi-cavity presses is the same, as well as the total run of punches in the process of compaction. The use of multi-cavity presses is possible only if even the worst articles in the array of simultaneously molded ones achieve the rated level of quality indicators.

Equally significant is the effect exerted on the SP process by an error in volumetric dosing, which can lead to two types of articles' defects: «overpressing» with a maximum plus margin of error and an unacceptable reduction in strength at a minus margin of error. The lack of a simplified, low-cost express assessment of the suitability of raw materials to the SP of articles from them, taking into consideration the error of bulk dosing and other factors, inhibits the wider use of anthropogenic raw materials. Research on the creation of such a procedure expands the possibilities of reusing a wide range of local anthropogenic and cheap natural products to manufacture SBA or a variety of briquettes by the SP method, including the application of modern efficient multi-cavity hydraulic presses.

## 2. Literature review and problem statement

Underlying the analysis of a mixture SP process is the dependence characterizing the ability of the mixture to compact, termed compression – the capability to reduce the volume, determined experimentally in the process of so-called compression tests (compression of the mixture without possible lateral expansion). The result of compression tests is a compression curve (CC) – a graphic representation of the relationship between the deformation of a compacted array and the strength forcing on it. Many procedures for deriving CC are proposed in various industrial areas, from tablets of medicines, powder metallurgy, the production of various ceramics to the study of soils in construction. In the construction industry, compression tests involving soil are standardly required [9] – the results of such tests are used in practice in the construction of foundations to assess the properties of the ground. There are unified instruments (a compression device, or odometer) and the devised procedure for building a CC diagram in the coordinates «compression force $P$ – porosity factor $e$» – $e=f(P)$. Based on a CC diagram, in the predefined interval of pressures, the ground compression ratio $m_0$ is determined, which is the proportionality factor between a change in porosity $de$ and a change in stress or pressure: $de=-m_0 d\sigma$. The $m_0$ factor, which characterizes the CC steepness, is compared with the specified intervals of soil compression – from low compressible ($m_0 \leq 0.1$ MPa$^{-1}$) to strongly compressed ($m_0 > 1.0$ MPa$^{-1}$). Based on the comparison results, a decision is made on the type of foundation base. The use of the described equipment and procedure to analyze the properties of mixtures and suitability for SP is impossible for a number of reasons (an order of magnitude lower pressures, the inconvenience of using porosity as an indicator of deformation, etc.). However, it seems appropriate to apply the same maximally verified logic: the availability of unified instruments and a procedure for building a CC, as well as an indicator of its steepness in the chosen region of pressure; determining the intervals of the steepness values characteristic of the mixtures – suitable, transitional, and problematic (not suitable without additional measures) for SP.

As regards the production of SBA, the SP molding presses commonly apply the CC varieties such as the so-called pressing curves investigated in works [10, 11], as well as by numerous researchers. Such curves, which link the pressure or force to a compacted array and its deformation, are convenient for calculating the molding presses but their use to analyze the properties of the mixture is difficult. More universal are CCs in the coordinates of the «density $\rho_0$ of the compacted array of the mixture – pressure $q$», applied in study [12] for the case of powder metallurgy.

As regards the mathematical notation of CC, which underlies any SP model and links the pressure and deformation in the process of material compaction by converging punches, the most complete models are used in construction mechanics when studying the stressed state of a bulk material layer during the compacting process. Their application implies the resource-intensive identification of a series of material characteristics and corrective coefficients to take into consideration the differences between the actual process and its idealized scheme. There are many simpler descriptions of the dependence of the average volumetric density $\rho_x$ of material on stress $\sigma_x$ at the surface of the punch. A description in the form of an exponent $\rho_x = \alpha \sigma_x^{\beta}$, where $\alpha$, $\beta$ are the coefficients determined from the results of compression tests, seems to be the simplest and most appropriate to the nature of an SP process. Based on this notation, paper [12] suggested a dependence of the stress at the punch surface on the properties of the mixture and the parameters of the compacting device:

$$\sigma_n = \sigma_0 \cdot \left[ 1 + \frac{\beta \cdot k \cdot f \dfrac{\Pi}{F} l_0 \cdot \rho_0}{\alpha \cdot \sigma_0^{\beta}} \right]^{\frac{1}{\beta}}, \qquad (1)$$

where $\sigma_0$ is the stress at the rear wall of the working volume; $l_0$, $\rho_0$ are the initial height and density of the batch of a compacted material; the physical and mechanical properties of the material (a lateral pressure factor – $k$, an internal friction factor – $f$); the shape and size of the working volume of the compacting device (perimeter $\Pi$ and the cross-sectional area $F$). However, the disadvantages of this, as well as a large number of other notations, are the high resource-intensiveness in determining numerous indicators, as well as the lack of unified equipment and a procedure for determining them.

The factors that influence the pressure in mechanical double-cavity presses are the dosage errors and errors in mixing the components of a mixture; the effect of the structural elements of the molding press and, most importantly, errors in the volumetric dosing of the mixture into the mold cavities. Work [13] shows that these factors, when operating molding presses that produce silicate bricks, lead to that the pressing pressure varies by more than three times, to that the variation in the strength of a raw article reaches 40 %, and to that the brick strength variation is up to 20 %.

The margin of error in dosing a moist mixture increases due to the formation of conglomerates that are inevitable when making mixtures in conventional mixers. Applying the quantitative tests by Kolmogorov-Smirnov, Lilliefors, Shapiro-Wilk [14], underlying the software «STATISTICA» [15], reveals that the density of filling and, therefore, a deviation in density from the average value, is subject to the law of normal distribution.

Article [16] describes the positive results from testing the mathematical model of an SP process, which makes it possible to take into consideration the effect of variability of the above factors on pressure. The degree of factors' influence on pressure is suggested to account for using a pressure instability factor $K_{instabil} = \Delta q / \bar{q}$, where $\Delta q$ is the range of possible pressure values; $\bar{q}$ is the average pressure (mathematical expectation). This mathematical model can be used to assess the suitability of mixtures based on anthropogenic products for SP; however, its implementation requires a very cost-intensive determination of many coefficients and indicators, that is, the considered model is not suitable for an express assessment of the suitability of mixtures for SP, which is also the case for other procedures analyzed above.

Thus, there is a need for research aimed at devising a simplified procedure for the rapid evaluation of the suitability of mixtures for molding articles from them using an SP method, which could expand the raw material base through the reuse of local anthropogenic products. Given the above, there are tasks to design the hardware, the procedure for determining the mixtures' CCs, as well as to determine the steepness indicator of the CC working part for using it as a criterion for the specified express assessment of the suitability of various mixtures for SP.

## 3. The aim and objectives of the study

The aim of this study is to devise and test a procedure for the simplified low-cost preliminary express assessment of the suitability of raw mixtures, including those made from anthropogenic products, to molding articles from them by a semi-dry pressing method, taking into consideration the error of volumetric dosing and other factors. Conventional high-cost regulatory tests of the mixture involving mathematical models are supposed to be conducted only after positive results from rapid evaluation.

To accomplish the aim, the following tasks have been set:

– to analyze the factors affecting the shape and location of a CC; by using the CC, investigate the effect of the error in the volumetric dosing of the mixture into a cavity of the molding press on the pressure error in the process of SP of articles from a variety of raw materials, including based on a filler made from anthropogenic waste, and assess the quantitative error in pressure;

– to assess the effect of an error in the bulk dosing of the mixture into a cavity of the molding press, as well as the errors in dosing the components of the mixture, on the strength of products and the probability of the occurrence of an overpressing defect;

– to analyze methods for improving the suitability of mixtures for SP, including at multi-cavity presses.

## 4. Materials and methods

### 4. 1. Materials used in the study

Our research examined the following mixtures:

a) cement-sand with different cement content (from 10 % to 30 %) and humidity of 8 % and 10 %, as well as cement-dolomite with different cement content (9 % and 17 %); the Portland cement M500;

b) cement-sand with the addition of varying amounts of limestone screening (a limestone fraction less than 2.5 mm in the amount of 10 % and 20 %; a limestone fraction less than 0.63 mm in the amount of 10 %, 30 %, and 60 %);

c) silicate (sand and slaked lime) with a 7.5 % activity with varying humidity (5 %, 7 %, and 9 %);

d) cement-sand with the addition of different amounts of chalk (a fraction of chalk less than 5 mm in the amount of 10 %, 20 %, and 30 %);

e) cement-sand and silicate mixtures activated in a drum-roll activator;

d) the mixtures based on scale (metal production waste) without cement and with different content of cement.

### 4. 2. Study methods

#### 4. 2. 1. A procedure for the compression study of mixtures

The effect of volumetric dosing error on pressure was studied during compression studies of raw mixtures. The capacity of the studied mixtures to compact was determined by constructing compression curves (CC) – the diagrams that characterize the relationship between deformation and stress or pressure of a particular material compressed by the oncoming movement of punches in a mold cavity without the possibility of lateral expansion of the compacted array. In order to solve the above tasks of our study, it was more expedient to build a CC in the «density-pressure» coordinates – the dependence diagrams in the form $q_i=f(\rho_i)$, where: $q_i$ and $\rho_i$ are the current pressure values (MPa) and the mixture density (g/cm$^3$) in the process of SP. The process of CC acquisition implied measuring the height $h_i$ of the compacted array under the influence of the punch forced into the array from the top, at pressure $q_i$.

The impact of a scale factor was preliminarily investigated by acquiring a CC in three molds with the cavity sizes in the plan of 50×50, 70×70, and 120×125 mm [17]. The mass of the mixture batch for each mold was selected so that a pressure of 40 MPa produced the height of the array $h_{article}$ to ensure the same generally accepted criterion of similarity SP for all three molds – $K_{simil}=2$. This similarity criterion $K_{simil}=(\Pi\cdot h_{article}/F_{mold}=h_{article}/R_{hydr}=2$ is typical, for example, for a SP of the standard thickened brick, the size of 250×120×88 mm ($\Pi$, $F_{mold}$ and $R_{hydr}$ – the perimeter, area, and hydraulic radius of a mold cavity; $h_{article}$ is the height of the compacted array at a pressure of 40 MP). To significantly reduce labor-intensity, it is decided to acquire a CC from a small mold with the cavity size in the plan of 50×50 mm – this is the mold used in most laboratories when conducting regulatory tests of raw materials. The mass of the mixture batch, poured into the mold cavity, is taken equal to 130 grams – the results from a special series of measurements confirmed the absence of influence exerted by the mass of filling in the range of 100–150 g on CC.

The CCs were acquired by measuring the current value $l_i$ (Fig. 1) when the pressure $q_i$ was changed, based on the indications of the hydraulic laboratory press gauge.

Fig. 2 shows an example of CCs for the cement-sand mixtures with a humidity of $W=10$ % with the addition of different amounts of chalk to increase the strength of a raw article and improve its physical appearance. The SP working pressure zone ($q=10$–40 MPa) is within an area where small variations in density lead to significant changes in pressure, which are the greater the larger the level of pressure.

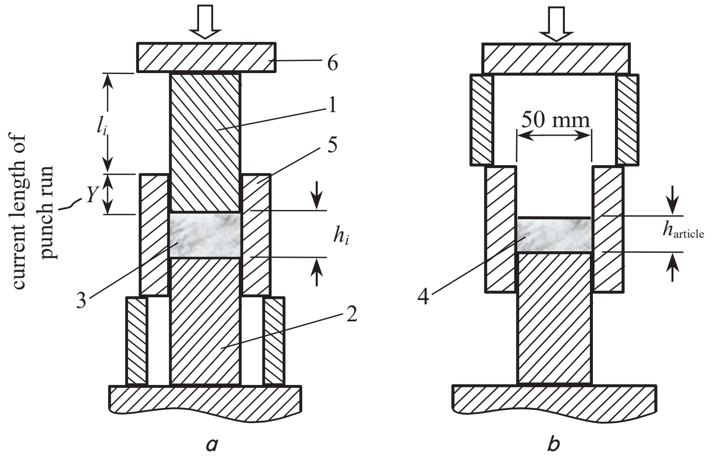


Fig. 1. The scheme of a mold for acquiring a CC:
*a* – the process of compacting the array; *b* – the process of pushing the molded raw article out of the mold cavity; 1 – upper punch; 2 – lower punch; 3 – mixture; 4 – a molded raw article prototype; 5 – mold; 6 – the upper plate of a hydraulic laboratory press; $l_i$ – the current distance from the plate to the top edge of the mold; $h_i$ – the current height of the array in the process of its compaction; $h_{article}$ – the height of a raw article prototype

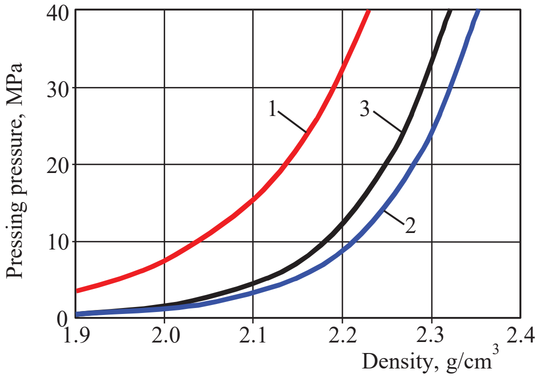


Fig. 2. Compression curves for the cement-sand mixtures with a humidity of $W=10$ % with the addition of different amounts of chalk (a fraction of chalk less than 5 mm; base pressure $q_0=10$ MPa): 1 – $b=7.3$; $\rho_0=2.04$; 10 % chalk; 2 – $b=9.9$; $\rho_0=2.21$; 20 % chalk; 3 – $b=9.9$; $\rho_0=2.18$; 30 % chalk

### 4. 2. 2. A procedure for studying the assessment of the effect of pressure spread on the strength of SP articles

The spread of pressure, even exceeding 100 %, is, in itself, not catastrophic because the quality of SP articles is determined by density; it changes slightly. It is obvious that a significant increase in pressure, compared to the rated one, would lead to the negative increased energy intensity and wear. However, two other possible negative effects of a large spread in pressure are crucial: the unacceptable decline in quality indicators (primarily strength) below the rated level due to reduced density, as well as the increased likelihood of defects and damage due to the above-described «overpressing». The latter is associated with excess pressure, at which the plastic deformations are completed while the elastic ones begin – a defect in the form of circling crack when pushing out a raw article can emerge after reaching the pressure $q_{threshold}$ characteristic of each mixture. Therefore, the assessment of mixture suitability for SP, especially with a high steepness of the CC, can be objective only in the joint analysis of the CC and the dependence of the «pressure-strength» type, as well as in the experimental confirmation of the absence of an «overpressing» defect.

The series of measurements aimed to devise a procedure for the experimental rapid assessment of the effect of pressure $q$ (MPa) on the strength $\sigma$ (MPa) of SP articles for the examined mixtures. We determined the dependence $\sigma=f(q)$ by the parallel molding of SP samples in the small and large molds (Fig. 3) from mixtures of the same composition. In this case, the mass was chosen to possess the similarity criterion $K_{simil}=h_{article}/R_{hydr}=2$ while the pressure levels were set the same. It was established that when studying the dependence $\sigma=f(q)$ of most mixtures, it would suffice to determine the strength at three pressure levels: 10, 20, and 30 MPa.

The samples, after joint hardening under regulated conditions and drying, were crushed; one from a small mold and two (one on the other, as required by the standard for bricks [18] – from a large one. The comparative analysis of the series results, first, allowed us to determine the factor for converting the strength of small samples into the strength of large ones: $K_{converting}=0.7$. Second, it confirmed the sufficient informativeness of the dependences $\sigma=f(q)$ derived from a low-cost molding in a small mold; their reliability was enough to conduct a preliminary rapid assessment of the mixture's suitability for SP, at much less labor cost.

Fig. 3. Photograph of the bench for measuring the threshold pressure $q_{threshold}$ of the start of the overpressing and the sample strength after pushing it out

### 4. 2. 3. A procedure for the analytical study of compression curves

The gradation of numerous mixtures, studied above, for molding small-scale articles by an SP method with CC requires a criterion whose numerical value would characterize the steepness of the working zones of CC (10–40 MPa). Such a criterion can be obtained on the basis of an analytical description of the CC. From numerous descriptions, in order to assess the spread of pressure due to dosage error, the analysis allowed us to choose the following dependence that describes the CC in the zone of pressures of the work area with sufficient accuracy [17, 19, 20]:

$$q = q_0 \cdot \exp\big(b\cdot(\rho-\rho_0)\big) \text{ or } q_i = q_0 \cdot e^{b(\rho_i-\rho_0)}. \qquad (2)$$

Here, $q_0$ is the so-called «basic pressure» (for example, such a minimum pressure, at which it is expected to produce a sufficiently durable raw article and a finished product); $\rho_0$ is the density of the mixture when pressure $q_0$ is reached ($\rho_0$ is the «basic density»); $q_i$, $\rho_i$ are the current values of pressure and density; $b$ – a coefficient that characterizes the mixture's capacity to compact. As shown by dependence (2), this coefficient has a dimensionality inverse to the density dimensionality. Thus, if we use the dimensionality of g/cm$^3$ for density ($\rho_0$ and $\rho_i$), we shall use the dimensionality of cm$^3$/g for the coefficient $b$.

The '$b$' coefficient is determined on the basis of experimental data from a formula given in [17, 19]:

$$b = \frac{\ln\left(\frac{q_{\max}}{q_0}\right)}{\rho_{\max}-\rho_0}. \qquad (3)$$

Here, $q_{\max}<q_{threshold}$ is the maximum pressure at which the above-described overpressing does not occur; $\rho_{\max}$ is the mixture density at pressure $q_{\max}$. Of the three indicators that are included in this expression, two (the base pressure $q_0$ and density $\rho_0$) are real physical quantities that are determined experimentally. The range of real possible values: $q_0$=8...15 MPa, $q_{\max}$=20...40 (up to 70) MPa, $\rho_{\max}$=1.6...4.4 g/cm$^3$, $b$=6...16 cm$^3$/g.

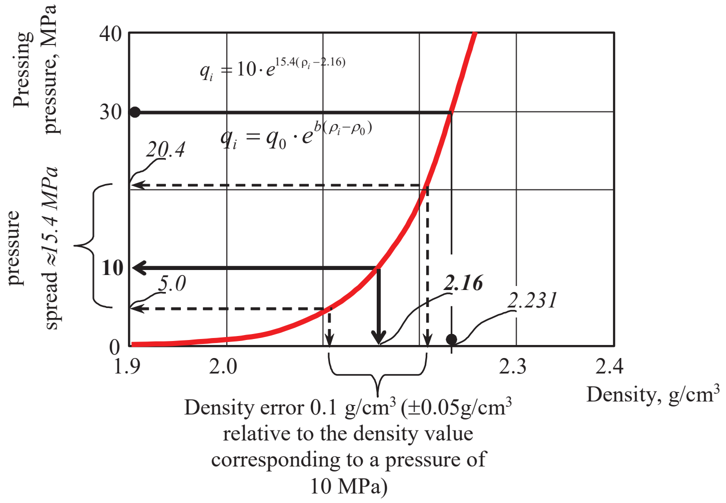
The most convenient criterion for assessing the CC steepness is to use the coefficient $b$, cm$^3$/g, determined from dependence (3), because, to determine $b$, it is sufficient, for each mixture, to experimentally determine only two pairs of quantities.

The first pair $q_0$ and $\rho_0$ is the so-called base pressure $q_0$, which is conveniently represented by the pressure of the lower boundary of the interval of real working pressures, and by the mixture density $\rho_0$ corresponding to this pressure. The second pair $q_{\max}$ and $\rho_{\max}$ is the pressure of the upper limit of the interval of real working pressures $q_{\max}$ and the corresponding mixture density $\rho_{\max}$.

We denote the maximally possible difference $\Delta\rho$ in the density of SP articles molded from the same mixture. This difference is determined by an error in the volumetric dosing and does not depend on the level of density. With this difference $\Delta\rho$, the difference in pressure $\Delta q$ (pressure spread) is equal to:

$$\Delta q = q_0 \cdot \left(e^{b \cdot \Delta\rho} - e^{(-b \cdot \Delta\rho)}\right). \tag{4}$$

The minimum margin of error for the volumetric dosing of SP molding presses can be taken as ±2.5 %. For an imaginary mixture whose base pressure and density are equal, respectively, to $q_0 = 10$ MPa and $\rho_0 = 2$ g/cm$^3$, the maximum possible difference in density is $\Delta\rho = \pm 0.05$ g/cm$^3$. In this case, the equality of numerical values of $\Delta q$ and $b$ holds (the numerical value of criterion $b$, cm$^3$/g, is equal to the numerical spread of pressure $\Delta q$, MPa, in the vicinity of the point on CC with a pressure of 10 MP with a margin of error in the volumetric dosing of ±2.5 % – Fig. 4).



$$b = \frac{\ln\left(\frac{q_{\max}}{q_0}\right)}{\rho_{\max} - \rho_0} \approx \frac{\ln\left(\frac{30}{10}\right)}{2.231 - 2.16} \approx 15.4 \text{ cm}^3/\text{g}$$

Fig. 4. Illustration of the physical essence of the coefficient '$b$' (cm$^3$/g), which characterizes the CC steepness and is numerically equal to the maximally possible spread of pressure $b \approx \Delta q$ with a margin of error in the volumetric dosing of ±2.5 %

The coefficient $b$ [16, 17] can be used not only as a *criterion for steepness* but also as a *suitability criterion* of mixtures for SP, including at molding presses with multi-cavity molds. For most mixtures used to produce articles using SP molding presses, the range of working pressures is (10÷30) MPa, so these boundary values, $q_0 = 10$ MPa and $q_{\max} = 30$ MPa, should be accepted when determining $b$ of each mixture. Then the suitability criterion of mixtures for SP is determined from the following dependence:

$$b = \frac{\ln\left(\frac{30}{10}\right)}{\rho_{30} - \rho_{10}} \approx \frac{1.1}{\rho_{30} - \rho_{10}}, \tag{5}$$

where $\rho_{30}$ and $\rho_{10}$ is the density of the examined mixture measured by using the proposed small mold at pressures $q_0 = 10$ MPa and $q_{\max} = 30$ MPa.

## 5. The study results

### 5. 1. Results of studying the effect of error in the bulk dosing of the mixture into a mold cavity of the molding press on the error of pressure in the process of the SP of articles made from various raw mixtures

Our analysis of the CC set has revealed that a CC shape and, accordingly, its steepness in the area of working pressures primarily depend on the nature of the main filler. The degree of influence of the humidity and content of additives, including the content of binders, may differ and it is poorly predicted. Sometimes even a relatively slight change in the content of an additive can significantly deform the CC with a change in its steepness (as evidenced by curves 1 and 2 in Fig. 2), or only with a shift along the axis of density, with an almost intangible change in its steepness.

Errors in the mass of the batch, poured into the cavity of a mold by a volumetric dispenser, are adequate to variations in density in the process of SP. With the constant run of converging punches, for a single-cavity molding press, these errors would lead to a spread in the density and pressure of articles molded during different SP cycles, for a multi-cavity molding press – of articles from different cavities within a single SP cycle. Subsequently, when analyzing CC, a margin of error of the volumetric dosing is taken equal to ±2.5 % – this level is close to the minimum achievable one at volumetric dosing.

The varying extent of the effect of this error on pressure is illustrated in Fig. 5 for real mixtures whose CCs demonstrate different steepness. For comparison, the level of the expected average pressure of 20 MPa was selected. For mixture '1', the spread of pressure is $\Delta q_1 = 28 - 14 = 14$ MPa; for mixture '2' – there is twice as much pressure spread ($\Delta q_2 = 40 - 10 = 30$ MPa), and the spread is one and a half times higher than the average pressure level. The description of CC (Fig. 5) is significantly different in the indicator ($b = 6$ for curve 1; $b = 15.4$ for curve 2).

Fig. 6–8 show the examples of mixtures' CCs illustrating the different steepness of the work area. For the convenience of comparing the CC by the range of pressure variation due to the error of volumetric dosing of ±2.5 % (0.1 g/cm$^3$), we selected for the entire spectrum of the analyzed mixtures the level of the expected average pressure to be $q = 10$ MPa.

Fig. 6 shows the mixtures' CCs with a relatively low steepness (the expected spread of pressures is from –25 % to +35 %). The CC steepness in Fig. 7 is higher (the expected spread of pressures is from –38 % to +44 %). Fig. 8 shows an example of the CC curves 3, 4, and 5 of the actually used mixture «cement+sand+fine screening of limestone crushing» with an increase in the screening content from 10 to 60 %. This adjustment of the composition led to a significant increase in the CC steepness – for CC5, the expected spread of pressures is generally catastrophic: from –50 % to +100 %. It should be noted that at a higher pressure (exceeding 10 MPa), necessary to mold articles of the predefined strength, the spread of pressures could be even greater.

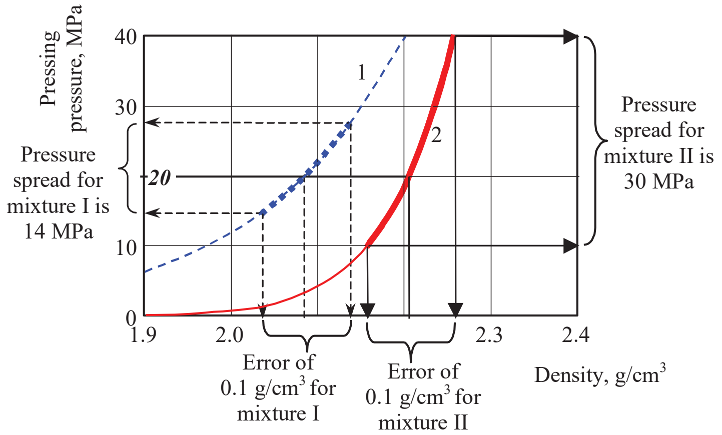


Fig. 5. Illustration of pressure spread in two mixtures with a different steepness of the compression curve (base pressure $q_0$= 10 MPa): 1 – a mixture for the production of silicate bricks (sand+7.5 % lime+7 % water); $b$=6; $\rho_0$=2.0; 2 – a mixture based on limestone (filler – sand and 60 % limestone screening, a fraction less than 0.63 mm+10 % Portland cement, grade 500+8 % water); $b$= 15.4; $\rho_0$=2.16

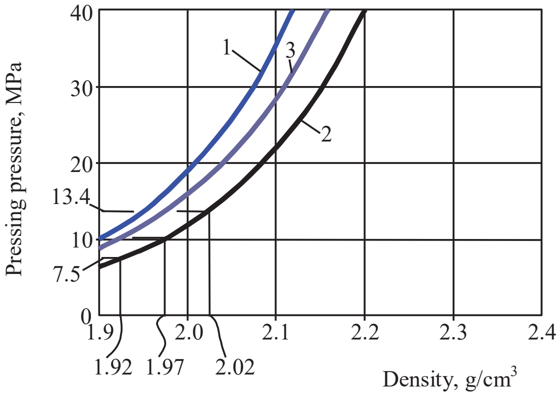


Fig. 6. Compression curves for silicate mixtures with a 7.5 % activity and a humidity of $W$=5, 7, 9 % (base pressure $q_0$= 10 MPa): 1 – $b$=6.37; $\rho_0$= 1.93; $W$=5 %; 2 – $b$=6; $\rho_0$=2.0; $W$=7 %; 3 – $b$=5.73; $\rho_0$= 1.95; $W$=9 %

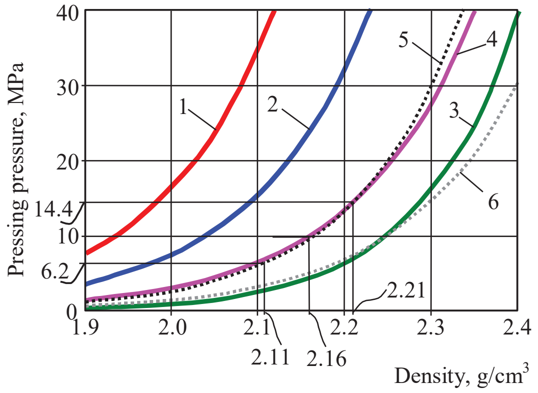


Fig. 7. Compression curves for cement-sand and cement-dolomite mixtures; base pressure $q_0$= 10 MPa: 1, 2, 3, 4 – for cement-sand mixtures: cement content, 10 %, 20 %, 30 % (humidity $W$= 10 %), and 30 % ($W$=8 %); 5, 6 – for cement-dolomite mixtures: cement content, 9 % and 17 %; 1 – $b$=7.5; $\rho_0$= 1.93; 2 – $b$=7.3; $\rho_0$=2.04; 3 – $b$=9.2; $\rho_0$=2.25; 4 – $b$=7.3; $\rho_0$=2.16; 5 – $b$=8.1; $\rho_0$=2.16; 6 – $b$=7.5; $\rho_0$=2.25

Fig. 9 shows the examples of mixtures' CCs based on scale (containing iron waste of metallurgical production), which, unlike conventional mixtures for SBA, have about twice the high level of density (that is, shifted to the right on the density scale) and are built at about twice the range of pressures.

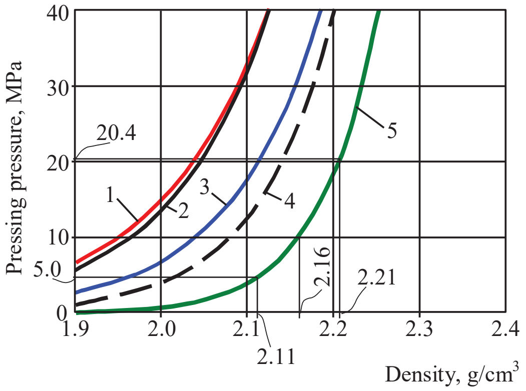


Fig. 8. Compression curves for cement-sand mixtures with limestone screening additive; base pressure, $q_0$= 10 MPa: 1, 2, 3, 4, 5 – cement-sand mixtures with a humidity of $W$= 10 % with the addition of different amount of limestone screening (1, 2 – fractions of limestone less than 2.5 mm in the amount of 10 % and 20 %; 3, 4, 5 – a fraction of limestone less than 0.63 mm in the amount of 10 %, 30 % and 60 %); 1 – $b$=7.9; $\rho_0$= 1.95; 2 – $b$=8.66; $\rho_0$= 1.96; 3 – $b$=9.56; $\rho_0$=2.04; 4 – $b$= 11.5; $\rho_0$=2.08; 5 – $b$= 15.4; $\rho_0$=2.16

In this case, an increase in the cement content (a significantly lighter additive in comparison with the scale) shifts the CC not to the right, as is the case for the mixtures for SBA, but to the left, to the region of lower density. However, the CC regularities described above are also retained for such mixtures.

Thus, our compression studies of a wide range of mixtures, using the proposed procedure:

– have shown that the shape and location of CC primarily depend on the nature of the main component of the mixture but can, sometimes to a large extent, be adjusted by the humidity or content of various additives, including binders;

– have confirmed significant differences in the steepness of the section of working pressures (from 10 to 40 MPa), characteristic of the SP molding presses;

– have demonstrated that the error of the volumetric dosing mixture used in SP molding presses, which has a minimum of ±2.5 %, leads to a pressure error, which is determined by the steepness of the working area of the CC;

– have established that the error of pressure at CC high steepness can exceed a hundred percent; when the working pressure increases, the possible error of pressure grows;

– have confirmed the feasibility of comparing the CC steepness at the chosen and the same level of pressure for different mixtures, for example, 10 MPa.

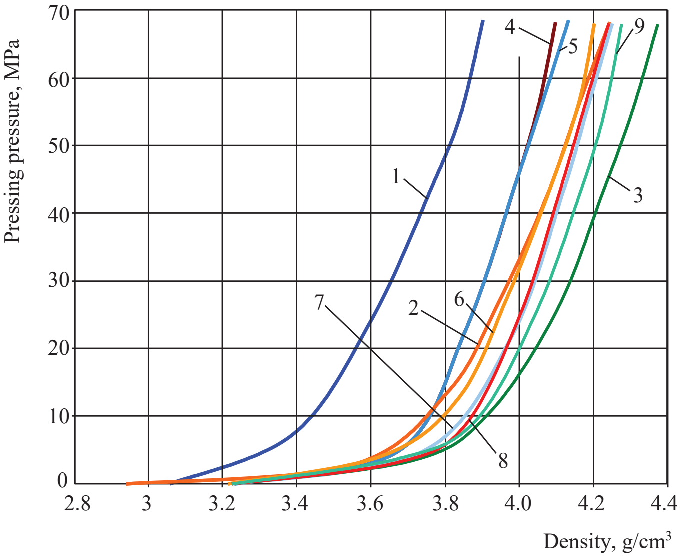


Fig. 9. Compression curves for scale-based mixtures (metal production waste): 1 — without cement; humidity *W*=0 %; sample height, 28 mm; 2 — without cement; humidity, *W*=4 %; sample height, 28 mm; 3 — without cement; humidity, *W*=8 %; sample height, 28 mm; 4 — cement 5 %; humidity, *W*=8 %; sample height, 28 mm; 5 — repeated mixture «4»; 6 — cement 5 %; humidity, *W*=5 %; sample height, 50 mm; 7 — repeated mixture «6»; 8 — cement 5 %; humidity, *W*=5 %; activation of the mixture in a high-speed roller-type activator; sample height, 50 mm; 9 — repeated mixture «8»

### 5. 2. Results of assessing the effect of error in the volumetric dosing of the mixture into the mold cavity on the strength of articles and the probability of the occurrence of an overpressing defect

Fig. 10 shows an example of some of the specified dependences $\sigma=f(q)$, derived during molding in a small mold. The curve $\sigma=f(q)$, acquired in a small mold, together with the CC of the same mixture, makes it possible to determine the minimum article strength $\sigma_{\min}$ at the maximum minus dosing error (at $q_{\min}$), and to decide whether it is acceptable to reduce the strength and suitability of the mixture for SP. Typically, the regulated maximum reduction in strength from the rated $\sigma_{rated}$ is 20 %, that is, the condition $\sigma_{\min}>0.8\cdot\sigma_{rated}$ must be met. Obviously, if this condition is not satisfied, then there is no sense in the further testing of such a mixture – it should be recognized as problematic; one must take measures to improve its suitability for SP, and then repeat the measurements on the improved mixture.

We have studied an overpressing defect to determine the level of pressure $q_{threshold}$ for each examined mixture at which this defect occurred.

It has been established for many mixtures that it is not possible to register this level on a small mold, even in the case of the most favorable conditions for the manifestation of overpressing: one-sided pressing; low humidity; a pressure of 60 MPa, significantly larger SP working pressures; the sample height of 75 mm, which corresponds to the similarity criterion $K_{simil}=h_{article}/R_{hydr}=6$ instead of the usual $K_{simil}=2\div4$. When molding samples in a large mold (Fig. 4) from the same mixtures, it was possible to register the overpressing already at a pressure of $q_{threshold}=25$ MPa (at one-sided pressing and the article height of 120 mm, which corresponds to the real similarity criterion $K_{simil}=h_{article}/R_{hydr}=4$). Thus, it has been established that it is advisable to test the mixture for the possibility of overpressing using a large mold although this leads to a significant increase in resource consumption.

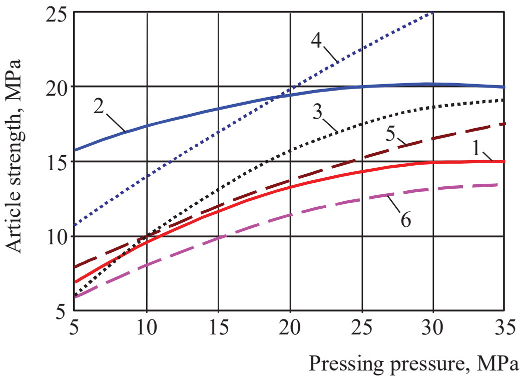


Fig. 10. The dependence of article strength at compression σ (MPa) on the pressing pressure *q* (MPa): 1, 2 — cement-sand mixtures with the addition of 20 % of chalk (cement content, 10 %; in moistened condition and after drying); 3 — a mixture based on limestone (filler — sand and 60 % of the limestone screening with a fraction less than 0.63 mm — 10 % of the Portland cement, grade 500, +10 % water) after hardening for 7 days of normal hardening followed by drying; 4 — cement-dolomite mixture (the content of the Portland cement, grade 500 — 17 %,) after 7 days of normal hardening followed by drying; 5, 6 — cement-dolomite mixtures with a cement content of 8 % after hardening for 28 days of normal hardening, activated and not activated. Description of the curves $\sigma=f(q)$: 1 — $\sigma=3.8+0.68q-0.01q^2$; 2 — $\sigma=13.93+0.42q-0.007q^2$; 3 — $\sigma=1.55+0.98q-0.014q^2$; 4 — $\sigma=7.5+0.68q-0.003q^2$; 5 — $\sigma=5.53+0.5q-0.005q^2$; 6 — $\sigma=3.3+0.55q-0.007q^2$

The test pressure $q_{test}$ tests during the check should be set at least 20 % larger than the pressure $q_{\max}$, determined from CC, which is maximally possible at the greatest plus margin of error of volumetric dosing. The mixture passes the test if the crack due to overpressing has not been detected, that is, $q_{test}<q_{threshold}$.

The mixture should be recognized as problematic when the samples molded from it revealed the defect of overpressing; one must take measures to increase its suitability for SP, and then repeat the measurements on the improved mixture.

It should be noted that the defect of «overpressing» at a relatively low level of pressure of $q_{threshold}=(20\div25)$ MPa was typical of the mixtures with a high content of dusty particles, for example, when briquetting the dust-shaped waste of metallurgical production. Moreover, increasing the consumption of cement by such mixtures shifted $q_{threshold}$ to the region of even lower pressures, making it useless to apply a conventional way to improve the strength of articles by increasing the content of cement in the mixture.

Taking into consideration the high resource intensity of the experimental check for the absence of overpressing, we studied the possibilities of an indirect assessment of its probability based on the indicators of the $\sigma=f(q)$ curve, acquired on a small mold.

The $\sigma=f(q)$ curves of most examined mixtures are accurately enough described by the parabolic dependence $\sigma=A+B\cdot q-C\cdot q^2$ whose peak is at a conditional pressure of $q_y=B/2C$, where $A$, $B$, $C$ are the coefficients determined experimentally. As the pressure increases, its impact on strength decreases – the derivative $K=d\sigma/dq=B-2\cdot C\cdot q$ is increased, which characterizes the steepness of the $\sigma=f(q)$ curve and numerically equals the increase in strength while increasing pressure by 1 MPa.

The $K=d\sigma/dq$ derivative at $q=20$ MPa (a typical SP molding press pressure) was used as a criterion for assessing the steepness of the $\sigma=f(q)$ diagram. The mixtures 1–6 in Fig. 10 at $q=20$ MPa are characterized by the steepness values $K=d\sigma/dq$ from $K=0.14$ (curve 2) to $K=0.56$ (curve 3). Our experience in evaluating these and other mixtures shows that at $K\geq0.4$ the overpressing is unlikely, so a laborious check of its absence is not necessary. In the value range of $0.25\div0.4$, such a check is desirable, and at $K\leq0.25$ – mandatory.

It is also noted that the increase in pressure, for mixtures with a low $K$ value, produces a slight increase in strength but increases the risk of overpressing; for mixtures with a high $K$ value, it makes it possible to significantly improve strength without overpressing; therefore, it is effective.

In the process of assessing the propensity of mixtures to overpressing, we formulated another condition meeting which renders the overpressing unlikely, so a resource-intensive check of its absence is impractical. Condition (6) includes a conditional pressure $q_y=B/2C$ – the pressure of the peak of the parabola describing a $\sigma=f(q)$ diagram:

$$q_y>1.2\cdot q_{\max}, \tag{6}$$

where $q_{\max}$ is the maximum pressure that is achieved at the maximum plus margin of error in the bulk dosing of a mixture into a mold cavity. If condition (6) is not met, then such a mixture must be checked for the absence of overpressing.

Let us consider the application of condition (6) using an example of mixtures whose $\sigma=f(q)$ diagrams are shown in Fig. 10. These mixtures 1–6 are characterized by the values of conditional pressure from $q_y=30$ MPa (curve 2) to $q_y=113$ MPa (curve 4). By determining the $q_{\max}$ value for each mixture from a CC, we find out that condition (6) is met with a large margin for mixtures 4 and 5; for mixture 3, it is not satisfied ($q_y=35$ MPa$<<1.2\cdot q_{\max}=1.2\cdot40=48$ MPa). Our experimental check revealed the presence of an overpressing defect on this mixture 3 at a pressure of 48 MPa, thus confirming the adequacy of condition (6).

Thus, the diagram of the $\sigma=f(q)$ dependence, acquired on a small mold in the pressure range of $10\div30$ MPa, makes it possible, when jointly considered with the CC for the mixture under study:

– to confirm or deny the possibility of an unacceptable reduction in strength at a maximal minus margin of error in volumetric dosing;

– based on the study of a $K$ steepness and when meeting the $q_y>1.2\cdot q_{\max}$ condition, to decide on the need for this mixture to be further checked for the level of risk of overpressing.

It should be noted that the relatively resource-intensive check of the absence of overpressing, conducted on a large mold at a pressure corresponding to the maximum plus dosage error ($q_{test}=1.2\cdot q_{\max}$) in the process of analyzing a wide range of mixtures, was necessary quite rarely, for mixtures with a large content of cement and dusty fractions of fillers.

### 5. 3. Analysis of methods to improve the suitability of mixtures for SP, including multi-cavity molding presses

The shape of a compression curve of the mixture may indicate the mixture's suitability for SP, especially at multi-cavity molding presses. As an example, consider curve 2 in Fig. 5. A normal density spread (from 2.11 g/cm$^3$ to 2.21 g/cm$^3$, curve 2, Fig. 5), associated with the margin of error of dosage ($\Delta\rho=\pm0.05$ g/cm$^3$), produces a deviation of pressure from the rated level of $q_{\max}=20$ MPa for this mixture: minus, to the level of $q_{\min}=10$ MPa; plus, to the level of $q_{\max}=40$ MPa. Such a spread of pressure $\Delta q_2=30$ MPa, exceeding 100 %, leads, in accordance with curve 2 in Fig. 13, leads to a spread in the strength $\Delta\sigma_2=18-9=9$ MPa. In this case, samples with a minimum strength of $\sigma_{\min2}=9$ MPa go far beyond the strength, claimed for this mixture, of $\sigma_{claimed}=15$ MPa (grade 150). A given mixture cannot be used for SP at a multi-cavity molding press. However, it is likely that the low cost of the filler (this is an anthropogenic waste) makes one look for such methods that would ensure that a given mixture could be used for SP.

Such special SP methods, which make it possible to produce articles from cost-effective but problematic mixtures, based on anthropogenic products without improving them, is the use of small single-cavity molding presses with the necessary tracking systems, for example, made by the Chinese firm «Titan Machinery» [21] instead of a single high-performance molding press with a multi-cavity mold. Similar Ukrainian molding presses were used to produce bricks by the company «Fagot» (facial brick from the mixture based on shell rock). When molding articles using such a molding press, the formed raw brick can be discarded in two cases – at the greatest errors of volumetric dosing, both towards reducing the mass of the batch and towards its increase. The discard signal is triggered by the height and pressure sensors in the following cases: at the minimally allowable height of an article, the minimally permissible pressure is not reached, which could have ensured the necessary density and quality indicators; at the maximally allowable height of an article, the maximal permissible pressure is exceeded and the overpressing is likely. The measurements reported in study [22] showed that the density of filling is subject to the law of normal distribution, so the number of such rejected bricks is negligible. The use of mobile mini complexes with such molding presses can be very effective in the development of relatively small dumps of anthropogenic products whose properties vary widely. However, if it is necessary to ensure a high enough performance, the cost of operating such mixtures is the use of a fleet of molding presses with numerous staff of operators and brick stackers, or with complex and expensive stackers, as well as increased costs for the maintenance and repairs of molding presses. Therefore, operating a fleet of single-cavity mini molding presses has no prospect of widespread application.

Among the measures to improve the suitability of mixtures to semi-dry pressing (SP) of articles from them, most often used is increasing the consumption of a binder, which makes it possible to reach the necessary level of the strength of the least dense articles while strengthening the facets of articles. Increasing the content of a dust-like binder in most mixtures does not reduce the criterion *b* to a critical level (curves 1–5 in Fig. 7) but makes it possible to reduce the rated level of pressure $q_p$ thereby reducing the probability of overpressing. However, the binder is the most expensive component of mixtures, so the production of articles from most anthropogenic products at the increased consumption of cement becomes uncompetitive. Instead of increasing the consumption of cement, one can ‘improve’ the mixtures by a variety of inexpensive additives, including of the anthropogenic nature, such as blast pellet slag, but it complicates the separation of the mixture and increases the cost of articles.

Another universal technique is based on activating the materials to change their properties when used in various industrial areas, for example, the steel industry [23]. There is reason to believe that this technique is the most promising one. The technique is to use mechanical activators, in particular, high-speed activators of the roller type [24]. They are used for the additional processing of the mixture already prepared for molding before feeding it to a molding press [25]. Repeated compaction of a thick layer by a roller and the subsequent loosening of this layer exposes the active surfaces of the mixture particles [26]. Due to this and other beneficial effects, not only does the strength of the articles increase without increasing the consumption of cement but also the required pressure and the CC steepness decrease (Fig. 11).

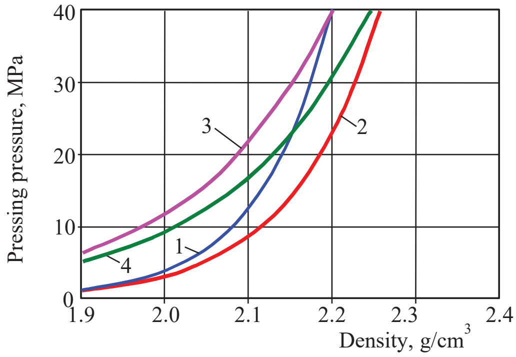


Fig. 11. Illustration of a change in the compression curves for mixtures after mechanical activation; base pressure, $q_0$= 10 MPa: 1, 2 — cement-sand mixtures without activation ‘1’ and after activation ‘2’ (cement content, 10 %; the limestone fraction less than 5 mm, 20 % (remaining — sand); humidity, 10 %); 3, 4 — silicate mixtures without activation ‘3’ and after activation ‘4’ (lime content, 7.5 % (remaining sand); humidity, 7 %); 1 — $b$=11.6; $\rho_0$=2.06; 2 — $b$ =9.66; $\rho_0$=2.09; 3 — $b$=6; $\rho_0$=2.0; 4 — $b$=5.73; $\rho_0$=1.95

## 6. Discussion of the study results and the development of a simplified low-cost preliminary express assessment of the suitability of raw mixtures for semi-dry pressing

It is a very interesting fact that the coefficient *b* is numerically close (coinciding) with the numerical value of the pressure spread in the vicinity of the compression curve point with a pressure of 10 MP (the example is shown in Fig. 4). The numerical value of the coefficient is $b$=15.4 cm$^3$/g. If we take the average density error to be ±2.5 % (that is, ±0.05 g/cm$^3$), the pressure spread along the curve in Fig. 4 would equal 15.4 MPa. Such a match (or proximity of values) was observed for all compression curves that we considered in this article.

An analysis of the results from studying the suitability of a set of real mixtures for SP, as well as from special measurements of the range of samples’ strength at a variation in the mass of the mixture batch in a mold cavity, equal to the error of volumetric dosing of ±2.5 %, makes it possible to recommend the following gradation of mixtures into three types based on criterion *b*.

For mixtures of type I, whose criterion is $b \leq 8$ cm$^3$/g, the spread of pressure and quality indicators is typically not critical, including the multi-cavity molding presses. These mixtures include, for example, silicate mixtures (curves 1, 2, and 3 in Fig. 6), as well as some cement-sand mixtures (curves 1, 2, and 4 in Fig. 7). The usual density spread (for example, from 1.92 g/cm$^3$ to 2.02 g/cm$^3$, curve 2 in Fig. 6) for mixtures of type I leads to a slight variability in pressure (in the example, from 7.5 MPa to 13.4 MPa, that is, from – 25 % to +34 % relative to a base pressure value).

The measurements confirm that the spread of pressure (from $q_{\min}$ to $q_{\max}$) for mixtures of type I does not cause either unacceptable reduction in strength or overpressing. An example of executing a procedure of checking the absence of a negative pressure spread is illustrated in Fig. 12 relative to the standard silicate mixture from the Kuryazhsky plant of silicate products (Kharkiv, Ukraine). This mixture’s CC, shown in Fig. 5 (curve 1) and in Fig. 6 (curve 2), is described by the exponent, whose power is $b$=6<8 cm$^3$/g. For the case of the maximum margin of error in the volumetric dosing ($\Delta\rho$=±0.05 g/cm$^3$), pressure deviations from the rated level of $q_p$=20 MPa for this mixture are in the range from the level (minus) of $q_{\min}$=14 MPa to the level (plus) of $q_{\max}$=28 MPa (CC 1 in Fig. 5).

This spread in the pressure ($\Delta q_1$=28–14=14 MPa) results in the spread in strength $\Delta\sigma_1$=17–11=6 MPa (for mixture 1 in Fig. 13). In this case, condition (1) is met: samples with a minimum strength of $\sigma_{\min 1}$=11 MPa do not deviate beyond the limits of the rated strength $\sigma_{rated}$=12.5 MPa (grade 125) to larger than 20 % ($\sigma_{\min}$=11 MPa>0.8·$\sigma_{rated}$= =10 MPa). Thus, the strength of the considered mixture would not demonstrate an unacceptable reduction due to the error of volumetric dosing.

The procedure for checking the absence of overpressing for this mixture was carried out as follows. The criterion of steepness ($K$=0.64≫0.4) indicated with a large margin that there was no danger of overpressing. The conditional pressure $q_y$ was also greater than the maximal $q_{\max}$ ($q_y$=36 MPa>1.2·$q_{\max}$=1.2·28=33.6 MPa), that is, condition (6) was met. Thus, both checks confirmed that there is no need for experimental confirmation of the absence of overpressing in a large mold for this mixture. However, the control measurements showed that the crack of overpressing occurs when samples from this mixture are molded at a much higher pressure – $q_{threshold}$=(50÷55) MPa.

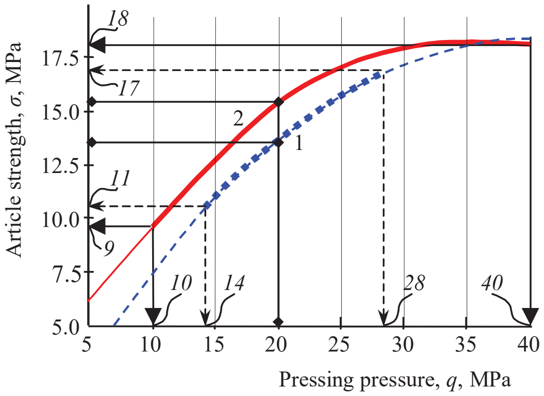


Fig. 12. Dependence of the article strength σ (MPa) on pressure $q$ (MPa): 1 – a mixture for the production of silicate bricks (sand+7.5 % lime+7 % water), $\sigma=-7.547+1.4q-0.019q^2$; 2 – a mixture based on limestone (filler – sand and 60 % limestone screening, a fraction less than 0.63 mm+10 % the Portland cement, grade 500+10 % water), $\sigma=1.55+0.98q-0.014q^2$

This example, as well as the experience of evaluating many other mixtures, confirms the possibility of a preliminary positive rapid assessment of the suitability of type I of mixtures for SP based only on criterion $b$, calculated according to formula (5), based on the results of the simplest measurements, by using a small mold, the density of the studied mixture $\rho_{30}$ and $\rho_{10}$ at pressures $q_0=10$ MPa and $q_{\max}=30$ MPa. The same simplified rapid evaluation should be applied to the mixture derived from the examined mixture, taking into consideration the possible errors in the dosage of its components. These include mixtures with the least favorable combination of humidity, the content of the binder and additives, as well as the granulometric and mineral composition of the main filler, such as an anthropogenic product or cheap local raw materials. The resource intensity of such tests would be minimal as long as $b\leq 8$ cm$^3$/g.

As a result, a type I mixture will be tested for the absence of an unacceptable negative impact not only due to the error of volumetric dosing but also to the error in the dosage of the mixture components. Such a mixture should be then transferred to optimize the composition, pressure, and hardening conditions according to the conventional procedure.

Mixtures of type II, whose criterion is $b$=8...12 cm$^3$/g, should be additionally studied for the possibility of using for SP. The examples of such mixtures are cement-sand mixtures with the addition of limestone screening (curves 2, 3, and 4 in Fig. 8) and chalk (curves 2, 3 in Fig. 2), as well as a cement-dolomite mixture with a low cement content (curve 5 in Fig. 7). The usual density spread (from 2.11 g/cm$^3$ to 2.21 g/cm$^3$, curve 5 in Fig. 7) leads to a noticeable spread of pressure (from 6.2 MP to 14.4 MP; that is, from –38 % to +44 % relative to the value of base pressure), which can cause noticeable instability in the quality of SP articles. The mixtures of type II require one or two additional verification steps described above. In the first phase of the test, it is necessary to determine $q_{\min}$ and $q_{\max}$ based on CC, then, by using a small mold, to build a $\sigma=f(q)$ curve, and check compliance with the condition $\sigma_{\min}>0.8\cdot\sigma_{rated}$. If the condition is not met, then there is no sense in the further verification of such a mixture – it should be recognized as problematic, one must take measures to improve its suitability for SP, and then repeat the set of measurements on the improved mixture. When the condition is met, one should determine the coefficients of the parabolic description of the $\sigma=f(q)$ dependence, calculate the criterion of steepness $K$ and conditional pressure $q_y$. At $K\geq 0.4$, the overpressing is unlikely, so a laborious check of its absence is not necessary; the mixture should be attributed to mixtures of type I. At $K<0.4$, the condition $q_y>1.2\cdot q_{\max}$ should be checked, and, if it is met, the mixture should also be attributed to mixtures of type I. If this condition is not met, then such a mixture must be checked for overpressing by molding in a large mold. The success of the check would make it possible to attribute the mixture to mixtures of type I, while the failure would force you to recognize the mixture as problematic; one must take measures to improve its suitability for SP, and then repeat the set of measurements on the improved mixture.

The mixtures of type III, whose criterion is $b>12$ cm$^3$/g, is typically unsuitable for SP at multi-cavity molding presses. An example of a type 3 mixture would be a mixture with a filler in the form of fine limestone screening and sand (curve 5 in Fig. 8). It is important to note that in terms of conventional consideration this mixture is quite competitive in comparison with conventional silicate mixtures. It provides a perfectly acceptable strength of 15 MPa (brick grade 150) at the consumption of cement of 8 % and pressure $q_p=20$ MPa, and the product is even better than silicate on the water resistance. However, as the results of the proposed simplified rapid assessment show, the use of such a mixture for SP is impossible without special measures due to the instability of pressure and quality indicators, first of all, strength, as well as a high probability of overpressing.

The following procedure for executing the procedure of express testing a mixture for the absence of defects due to the errors in volumetric dosing using the suitability criterion $b$ is proposed. The initial step is to experimentally determine two density values of the examined mixture, $\rho_{30}$ and $\rho_{10}$, measured in the proposed small mold the size in the plan of 50×50 mm at pressures $q_0=10$ MPa and $q_{\max}=30$ MPa, and the calculation, using formula (3), of the $b$ criterion characterizing the CC steepness.

At this, the least labor-intensive, stage, it is advisable to specifically select a mixture with the most unfavorable combination of errors in the composition, which is possible under actual industrial conditions: with the largest and least content of a binder, with the highest content of small or dusty fractions of the filler, with the highest and lowest humidity, etc.

Next, the selected mixture with the highest level of criterion $b$ is categorized according to three types. If the mixture is categorized to be of type I, the express assessment of the suitability for SP is safely completed. The mixture is recommended for the conventional expensive and resource-intensive procedure of laboratory (regulatory) tests in order to determine the optimal composition of the mixture, the range of working pressing pressures, the hardening standard, as well as the verification of water absorption, frost resistance, and other rated quality indicators of small-piece articles.

If the mixture is categorized to be of type II, it undergoes a procedure of two stages of the simplified checks (unacceptable reduction in strength and overpressing), which may end positively, with the same recommendation to further regulatory tests, similar for the mixture of type I.

If a mixture of type II is tested unfavorably, it is necessary, similar to a mixture of type III, to carry out measures to improve its properties based on one of the methods described above. After the choice of a method and its implementation, the procedure of the proposed preliminary simplified express evaluation of the improved mixture is repeated, at the least favorable combination of factors (deviation for the worse of the binder content, granulometric and mineralogic composition, humidity, etc.). Iterations continue until the mixture fits a mixture of type I.

Thus, based on a set of studies into the effect of error in the volumetric dosing and other factors on the process of semi-dry pressing (SP), we have proposed and verified a procedure for the simplified preliminary express assessment of the raw mixtures' suitability for SP, including those based on anthropogenic products and local cheap natural fillers.

Using the procedure could reduce the cost of a set of laboratory tests. The application of the procedure opens up more opportunities for re-using in small-scale articles, made by a semi-dry molding method, a variety of anthropogenic products with heterogeneous properties, accumulated in increasing volumes, while contributing to resource preservation.

The most promising area of further research into expanding the scope of using anthropogenic products for small-scale articles is an in-depth study of the possibilities to improve the properties of such mixtures by processing them before molding in high-speed activators of the roller type.

## 7. Conclusions

1. For a set of mixtures for SP, we have verified an exponential description of CC, including a $b$ (cm$^3$/g) multiplier, which is part of the exponential power, characterizing the steepness of the CC working part. A simplified procedure has been proposed to experimentally determine «*b*» for each mixture at minimal cost at the level of base pressure $q_0$=10 MPa. It is shown that even the minimum possible error of ±2.5 % in dosage may lead to an unacceptable decrease in the quality of SP articles due to excessive variations in pressure. The ranges of «*b*» values for different mixtures have been determined, making it possible to judge the degree of stability of the pressure and quality indicators of SP articles made from them. The possibility and effectiveness of the use of a «*b*» indicator as a criterion for the express assessment of the suitability of a mixture for molding an article using an SP method have been proven. Mixtures with a numerical value of the criterion $b\leq8$ cm$^3$/g can be used for SP without additional measures, including in multi-cavity molding presses as the difference in quality indicators is typically within acceptable limits. Mixtures with $b\geq12$ cm$^3$/g are problematic and can only be used after a significant improvement in their suitability for SP. Mixtures with the intermediate '*b*' criterion values ($b$=8...12 cm$^3$/g) must be studied in detail for the possibility of using for SP.

2. We have tested the procedure and hardware for a simplified assessment of the effect of error in volumetric dosing of pressure spread on the strength of SP articles by molding samples in a small mold, followed by crushing them one after one after hardening and building the $\sigma=f(q)$ dependence in the study range of pressures of 10÷30 MPa. We have experimentally confirmed the suitability of the established $\sigma=f(q)$ dependence to decide that this mixture is not exposed to the negative impact of threshold pressure deviations from the rated level. The procedure has been proposed and verified for the experimental testing of a mixture for the absence of overpressing at the trial pressure $q_{test}$, set to be larger by the pressure $q_{\max}$, which is possible at the greatest plus margin of error in volumetric dosing. It has been revealed that for mixtures with a large content of dust-like components, including binders, the defect of overpressing can occur already at the pressure $q_{threshold}$=(20÷25) MPa, and the increase in the content of cement in such a mixture further reduces $q_{threshold}$.

3. In addition to conventional methods for improving the suitability of mixtures for SP, including at multi-cavity molding presses (increasing the consumption of a binder, the introduction of improving additives), we have proposed and verified a method for the mechanical activation of the mixture, in particular, using a high-speed activator of the roller type. The activation positive effect is achieved both by reducing the CC steepness and by significantly reducing the pressure without compromising strength and other quality indicators. A procedure has been suggested for the simplified preliminary examination of a mixture for the absence of defects due to the errors in volumetric dosing using an express assessment of the suitability criterion *b*. The procedure makes it possible to assess, at minimal cost, the impact of the spread of SP factors, inevitable under industrial conditions, on the stability of articles' quality. Expensive conventional tests of a raw mixture, planned to be used, especially based on anthropogenic products or local cheap raw materials with unstable properties, should be carried out only after obtaining positive results from the proposed rapid assessment.

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