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ANALYSIS OF THE GRANULOMETRIC COMPOSITION OF A THREE-FRACTION CHARGE FOR VIBROPRESSED PRODUCTS

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Using developed equipment and a methodology for experimental studies on the workability of the grain composition of three-fraction charges under load in a cylindrical container during vibrational impact after a series of blows from a compactor, the optimal fraction content was determined to meet the conditions for achieving a high degree of compaction. The analysis of experimental results identified charges with high bulk density and compaction coefficients, highlighting the following optimal fraction composition for further research (wt.%): 20–50% of 5–10 mm granite gravel, 25–40% of 2–5 mm granite gravel, and 25–40% of 0–0.3 mm sand. All experimental results were processed using the simplex-lattice method of mathematical modeling, applying the Scheffe methodology to derive regression equations in the form of fourth-degree polynomials. The analysis of graphical interpretations of the regression equations revealed patterns in bulk density changes under load and the compaction coefficient of three-fraction charges depending on their composition.

Keywords: workability, three-fraction charge, granite gravel, sand, mathematical modeling, Scheffe methodology, regression equation.

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Introduction

Currently, the building materials science of Ukraine is particularly in need of energy-efficient technologies for the production of a wide range of products[1]. A significant range of individual building products can be manufactured using the method of vibropressing polydisperse cement-containing charges with variations in pressure and temperature during subsequent steam curing, and even transitioning to natural drying modes. In many cases, such technological solutions are implemented in small enterprises for the production of non-load-bearing products: single and one-and-a-half bricks for the construction of low-rise buildings and structures (garages, agricultural buildings, non-pressure hydraulic structures, etc.), paving slabs, channels for drainage of sewage, etc. [1]. To ensure competitive properties of such products (mainly compressive strength, open porosity, and frost resistance), granite gravel of the fraction of 5–10 mm is used as a hydraulically inert coarse component, while either granite gravel of the fraction of 2–5 mm or a broader fraction of such gravel, granite screenings (often of the fraction of 0–3.5 mm), serves as a medium-coarse component. For the fine component, local inexpensive sands with varying fineness modulus are chosen.

The hydraulically active component of the charge is Portland cement of various types, usually no less than grade M400. Portland cement is the most

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[1] Pro osnovni zasady (stratehiyu) derzhavnoyi ekolohichnoyi polityky Ukrainy na period do 2030 roku: Zakon Ukrainy vid 28.02.2019. No. 2697-VIII. https://zakon.rada.gov.ua/laws/show/2697-19#Text. (date of application 15.07.2024).

expensive component of the charge, and its content is typically limited (usually 12–15%) or replaced with an alternative material, such as slag-alkaline binders [2,3]. Given a constant binder content in the charge at 12%, the granulometric composition of its hydraulically inert part can vary significantly: coarse fraction 15–35%, medium fraction 25–75%, and sand 10–45%. Consequently, issues arise with workability and packing density of the grains during vibropressing, which directly affects compliance with technical requirements for key operational properties [4]. Rationalizing the granulometric composition of the charges is a complex multi-parameter function, for which a significant number of mathematical models have been developed, and graphical dependences of the fractional composition range on the content of fractions in the charge have been proposed [5].

In specific cases, the choice of a rational granulometric composition requires systematic empirical verification of the workability of experimental charges, followed by clarification of the optimum composition range under real production conditions and taking into account the specifics of the equipment used, the conditions of mass preparation operations, vibropressing modes, technological tooling, and other factors. These circumstances give rise to a number of complex technical challenges that are difficult to resolve in small enterprises, resulting in charges that significantly differ in composition from optimal ones and a failure to fully utilize the technical and economic reserves of production.

The goal of this work was to develop tooling and an experimental methodology for selecting a rational granulometric composition of three-fraction charges made from hydraulically inert fillers for vibropressed products, in accordance with their workability indicators.

Materials and methods

For the experimental studies, granite gravel of two fractions was used: coarse (5–10 mm, subsequently referred to as X) and medium (2–5 mm, referred to as Y), as well as sand (commercial dispersion degree, fraction less than 0.3 mm, referred to as Z). The granite gravel (Poltava region, Shmatkivske field) and sand (Kremenchuk, Kremenchuk River Port JSC) were not dried or sieved. The components of the charges were dosed using electronic scales (Constant brand, model 14192-640C), with a weighing accuracy of 0.05 g for samples of 500 g. The mixing of the components was carried out in a porcelain bowl with a spherical bottom using a porcelain spoon with intensive stirring for 30 seconds. The filling of the charges into the measuring device was done from the mixing bowl using a conical plastic funnel with a lower opening diameter of 45 mm, an upper opening diameter of 80 mm, and a height of 85 mm. The measuring device was made from steel grade 45 and consisted of three following parts:

1. A cylindrical container with a height of 265 mm, an internal diameter of 50 mm, and a wall thickness of 3.5 mm. The inner surface was polished, and external threads were cut on the lower part of the cylindrical container for screwing in a plug.
2. The plug has flat inner and outer bottoms, internal threads for screwing onto the lower part of the cylindrical container, and a textured outer surface for ease of unscrewing.
3. A cylindrical weight (diameter of 49 mm, and height of 40 mm) with a rod-scale (millimeter scale). The cylindrical container with the screwed-in plug weighs 1.315 kg, while the weight with the rod-scale weighs 0.815 kg. The weight with the rod-scale is designed to be placed inside the cylindrical container above the layer of poured charge, completing the assembly of the measuring device for conducting experiments. For experiments, the assembled measuring device was placed on a massive concrete base with a metal anti-slip support against the plug. Coaxially with the cylindrical container at a height of 1240 mm, a pendulum in the shape of a sphere (weight of 328 g, made of dispersion-filled composite with a polypropylene matrix) was suspended; the distance from the suspension point to the center of the sphere was 1200 mm. For testing, the pendulum was moved away from the vertical axis by 400 mm (between the center of the sphere and the intersection center with the axis of the cylindrical container on the concrete base) and released, resulting in a point impact of the sphere against the outer part of the measuring device and shaking the charge within it. After every 0, 5, 10, and 15 impacts, measurements were taken of the height of the charge layer in the cylindrical container. Based on these measurements, the corresponding bulk density of the charge under load (ρ_i, where i=0, 5, 10, 15 is the number of impacts) and the packing coefficient of particles in the respective charge were calculated as the ratio of the maximum value of the charge layer height to its minimum value (K_y).

For the convenience of analyzing the test results, the compositions of the charges were graphically represented by points on a three-component concentration triangle. The coordinates of each point are indicated by subscripts (k, l, m) in the formula notation $X_kY_lZ_m$, which correspond to the content of the respective fraction (in mass percent) in a specific charge.

To generalize the patterns of changes in ρ_i and

K_y with varying compositions of the studied charges, the method of mathematical planning of experiments was used: the simplex lattice method by Scheffe [6]. The choice of this method is due to its convenience for processing experimental data from three-component charges, whose compositions are displayed on the concentration triangle and establish a planning matrix that describes the relationship «composition vs. property» in the form of polynomials of the second, third, and fourth degrees, including incomplete orders when data is lacking for some of the compositions. In this case, the property under investigation is represented as a continuous function of changes in the argument: the composition of the charges, which allows for the prediction of the property at any point in concentration space by calculating it according to the obtained regression equations in accordance with the applied polynomial. Despite the complexity of the regression equations, the results of computer calculations allow for their graphical interpretation for ease of analysis.

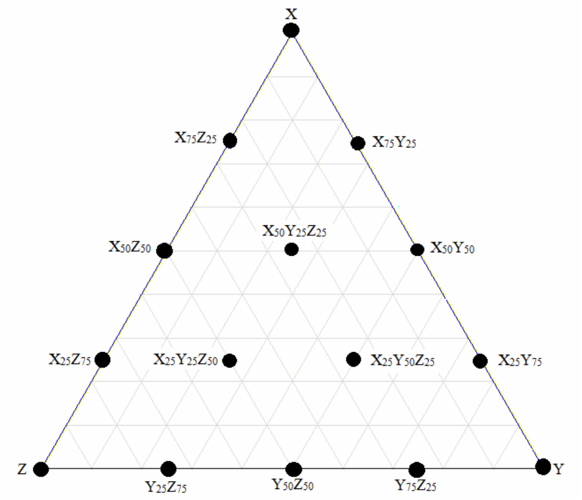

Fig. 1. Points and formulaic representation of the charges for tests on the concentration triangle

Results and discussion

For the first stage of testing, 15 charges were selected, with their composition points displayed on the concentration triangle by corresponding formula notations (Fig. 1). The results of ρ_i and K_y values for these charges are presented in Table 1.

The analysis of ρ_i values for the pure components of the charges (X, Y, and Z in Table 1) indicates a trend towards their monotonous increase with an increasing number of blows from the rammer. The maximum bulk density is noted for sand (Z), while the minimum workability is characteristic of the coarse fraction of granite gravel (X), which reaches a bulk density of 1.439 g/cm^3 under load after 15 blows from the rammer. The compaction coefficients for pure components correlate with the noted results for ρ_i and increase in the order X–Y–Z.

Two-fraction charges, the composition points of which belong to the sides of the concentration triangle (Fig. 1) and are indicated in Table 1 with No. 4–12, exhibit a tendency for monotonous growth in bulk density under load with an increasing number of impacts from the pile driver.

The maximum bulk density is noted for the two-fraction charge of coarse gravel and sand in a ratio of 1:1 ($X_{50}Z_{50}$ in Table 1). A charge of medium

Table 1

Results of calculations according to the experimental design (Fig. 1)

No.	Formulaic representation of the compounds	ρ_0	ρ_5	ρ_{10}	ρ_{15}	K_y
1	X	1.377	1.408	1.423	1.439	1.045
2	Y	1.517	1.554	1.573	1.592	1.050
3	Z	1.526	1.592	1.623	1.644	1.077
4	$X_{25}Y_{75}$	1.517	1.544	1.563	1.582	1.043
5	$X_{50}Y_{50}$	1.526	1.563	1.573	1.582	1.037
6	$X_{75}Y_{25}$	1.464	1.499	1.517	1.535	1.048
7	$X_{25}Z_{75}$	1.633	1.745	1.782	1.807	1.106
8	$X_{50}Z_{50}$	1.710	1.790	1.820	1.846	1.080
9	$X_{75}Z_{25}$	1.644	1.699	1.733	1.757	1.069
10	$Y_{25}Z_{75}$	1.592	1.699	1.733	1.757	1.103
11	$Y_{50}Z_{50}$	1.676	1.757	1.807	1.833	1.094
12	$Y_{75}Z_{25}$	1.623	1.654	1.699	1.710	1.054
13	$X_{25}Y_{50}Z_{25}$	1.613	1.654	1.687	1.710	1.060
14	$X_{50}Y_{25}Z_{25}$	1.710	1.757	1.807	1.820	1.064
15	$X_{25}Y_{25}Z_{50}$	1.794	1.833	1.873	1.887	1.052

gravel and sand in a ratio of 1:1 ($Y_{50}Z_{50}$ in Table 1) compacts somewhat less effectively. All charges with variations of coarse and medium gravel compositions (No. 4–6) compact significantly worse compared to other two-fraction compositions. The compaction coefficients do not have direct correlations with the values of ρ_i. This circumstance is explained not only by the influence of numerous factors (such as the size and shape of particles within each fraction, the friction forces between homogeneous particles and particles of different mineralogical compositions against each other and against the inner surface of the cylindrical container, the tendency of charges to segregate during filling, etc.), but also by the difference in the physical essence of the indicators ρ_i and K_y. This implies that the bulk density of the charge under load determines the ability to fill intergranular spaces with polydisperse particles and their ease of placement during shaking as a result of pile driver impacts, while the compaction coefficient determines the peculiar rate of possible density growth during vibrations until a limiting value characteristic of the individual charge composition is reached. Both indicators are important to consider in subsequent experiments with variations in vibropressing modes, as K_y will determine the sensitivity of the formed masses to vibrational acceleration and the magnitude of pressing forces, while ρ will dictate the ease of packing granular components until achieving their maximum possible dense packing in the formed product. At this stage of research, a more valuable insight is provided by analyzing the maximum values of r achieved in specific charge compositions. It should be noted that there is an indirect correlation between the values of ρ_{max} and K_y for two-fraction charges. The charges with maximum values of ρ_{15} (No. 11 and 8 in Table 1) have relatively high values of K_y but are inferior to the charges (No. 10 and 7) with average values of ρ_{15}.

For three-fraction charges, whose composition points lie within the concentration triangle (Fig. 1) and are presented in Table 1 (No. 13–15), the charge with 50% medium fraction gravel (No. 13 in Table 1) shows the least compaction. The trend of monotonous growth in values of ρ_i with an increasing number of pile driver impacts is preserved for each charge. The values of K_y do not have a direct correlation with ρ_i, similar to the situation with two-fraction charges. This latter circumstance is significantly influenced by the low tendency of charges No. 13–15 (Table 1) to segregate during filling into the cylindrical container, which results in high values of initial bulk density under load (ρ_0).

For the experimental data on ρ_{15} and K_y (Table 1), a simplex lattice design method was used based on obtaining a mathematical model in the form of a fourth-order polynomial. The corresponding regression equations are as follows:

$$\rho_{15}=1.439x+1.592y+1.644z+0.266xy+ \\ +1.218xz+0.86yz+0.157xy(x-y)+ \\ +0.28xz(x-z)-0.112yz(y-z)- \\ -0.147xy(x-y)^2+0.259xz(x-z)^2- \\ -0.976yz(y-z)^2+4.091x^2yz-8.168xy^2z+ \\ +4.605xyz^2, \qquad (1)$$

$$K_y=1.045x+1.05y+1.077z-0.042xy+0.076xz+ \\ 0.122yz+0.04xy(x-y)-0.112xz(x-z)- \\ -0.189yz(y-z)+0.125xy(x-y)^2+0.261xz(x-z)^2- \\ -0.168yz(y-z)^2+1.171x^2yz+1.413xy^2z- \\ -3.901xyz^2. \qquad (2)$$

The graphical interpretation of Eqs. (1) and (2) are presented in Figs. 2 and 3, respectively. Here, it should be noted that concentrations X, Y, and Z are represented not in mass percentages but as fractions of one, while maintaining the normalization condition X+Y+Z=1 for any composition point within the triangular lattices representing the corresponding concentration triangles.

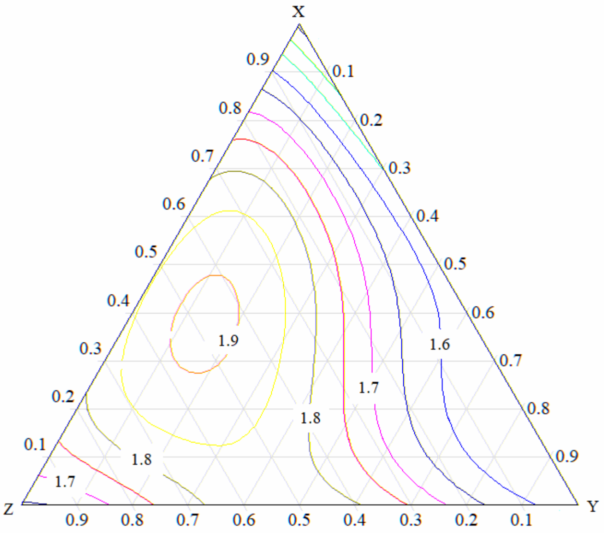

Fig. 2. Isolines of values ρ_{15} according to the regression equation (1) for the studied charges

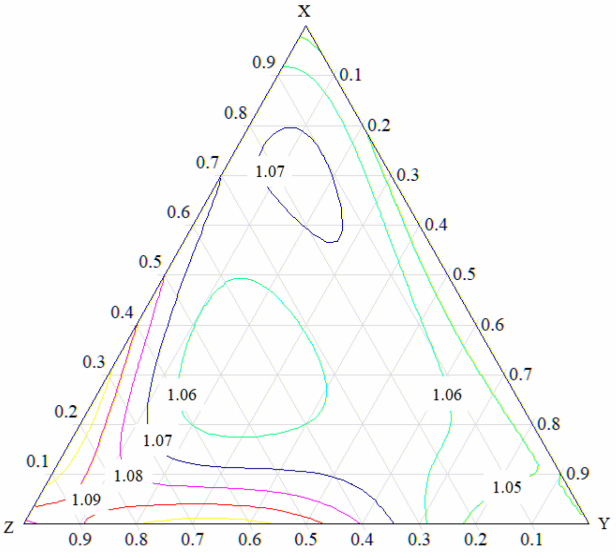

Fig. 3. Isolines of K_y values according to the regression equation (2) for the studied charges

It can be seen from Fig. 2 that there is a strictly delineated concentration area of charges with a high degree of compactability, outlined by the isoline ρ_{15}=1.9, under the conditions of the experiments. The boundary concentrations of components in this oval-shaped area correspond to the following approximate values (wt.%): 28–48, 8–21, and 39–58 for X, Y, and Z, respectively.

The nature of the isolines K_y in Fig. 3 also distinguishes two closed concentration areas of the composition of the charge, but the K_y values in them are little different (1.06 and 1.07). The charges which are the most sensitive to shaking and quickly compacting under the loading (K_y>1.09) are shifted to the corner of the triangular lattice Z and, in fact, belong to the two-fraction compounds: X–Z with the Z>50 wt.% and Y–Z with the content of Z>47 wt.%. The absence of direct correlations between ρ_{15} and K_y was discussed above. From joint consideration of Figs. 2 and 3, it should be noted that the compounds of the charge with a high value of ρ_{15} are located in a wide concentration area of K_y values within 1.06–1.07 (in fact, the entire central part of the triangular lattice in Fig. 3).

To verify the relevance of the obtained regression equations and their graphical interpretations for predicting charges with predetermined values of ρ_{15} and K_y, a control experiment was conducted for the reference charge $X_{31.25}Y_{21.875}Z_{46.875}$, which belongs to the concentration area of the triangle $X_{25}Y_{25}Z_{50}$–$X_{37.5}Y_{12.5}Z_{50}$–$X_{37.5}Y_{25}Z_{37.5}$. For the reference charge, the following experimental values were obtained: 1.699; 1.782; 1.820; 1.846 and 1.087 for ρ_0; ρ_5; ρ_{10}; ρ_{15} (g/cm^3) and K_y, respectively. When calculating the values of ρ_{15} and K_y by using the most general regression equations (Figs. 2 and 3), deviations from the experimental values for the reference charge were found to be 2.8% and 3.2%, respectively. Such small deviations between calculated and experimental data limited further statistical analysis of the adequacy of the obtained regression equations, ensuring high accuracy in predicting the desired characteristics; therefore, the mathematical models are relevant.

Conclusions

Using the developed equipment and methodology for experimental studies on the compactability of three-fraction charges under load in a cylindrical container subjected to vibrational impact after a series of pile driver strikes, a rational content of fractions has been determined which correspond to conditions for achieving a high degree of compactability. Analysis of the experimental results sequentially narrowed down the concentration area of charges with high values of bulk density and compaction coefficients, highlighting a rational ratio of fractions for further research (wt.%): 20–50 of 5–10 mm grave gravel; 25–40 of 2–5 mm granite gravel and 25–40 of 0–0.3 mm sand.

All series of experimental results were processed using the simplex lattice method of mathematical modeling, employing the Scheffe method to obtain regression equations in the form of fourth-order polynomials. Analysis of graphical interpretations of regression equations established patterns in changes in bulk density under load and compaction coefficients of three-fraction charges depending on their composition.

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АНАЛІЗ ГРАНУЛОМЕТРИЧНОГО СКЛАДУ ТРИФРАКЦІЙНОЇ ШИХТИ ДЛЯ ВІБРОПРЕСОВАНИХ ШЛАКОЛУЖНИХ ВИРОБІВ

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Із застосуванням розробленого оснащення та методики експериментальних досліджень зручності зернового складу трифракційних шихт під навантаженням у циліндричній ємності при струшувальному впливі після серії ударів копра визначено раціональний вміст фракцій, що відповідає умовам досягнення високого ступеня ущільнюваності. Аналіз результатів експериментальних досліджень дозволив виділити складів шихт з високими значеннями їх насипної щільності та коефіцієнтів ущільнення, виділивши наступний раціональний склад фракцій шихти для подальших досліджень (мас.%): 37,5 – фракція 5–10 мм гранітного гравію, 25 – фракція 2 мм гранітного гравію та 37,5 – фракція 0–0,3 мм пісок. Усі серії результатів експериментів оброблені із застосуванням симплекс-решітчастого методу математичного моделювання, використовуючи методику Шеффе для отримання рівнянь регресії у формі поліномів четвертого порядку. Аналізом графічних інтерпретацій рівнянь регресії встановлено закономірності змін насипної щільності під навантаженням та коефіцієнта ущільнення трифракційних шихт залежно від їх складу.

Ключові слова: зручноукладальність, трифракційна шихта, гранітний гравій, пісок, математичне моделювання, плани Шеффе, рівняння регресії.

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