521. Experimental identification and optimization of the concrete block vibropressing process

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Abstract. Material testing machine Instron 8802 was used for experiments with raw concrete vibropressing. The experiments were conducted according to the Mean Square Error Latin hypercube design. Influence of pressing force, force amplitude and frequency on the pressing process was investigated. The registered displacement and force curves were smoothed and approximated with 1- 3 parameter functions. The dependence of these parameters on the pressing force constant component, force oscillation amplitude and frequency was determined by means of nonparametric kriging approximations. The approximations were validated with additional physical experiments. The estimated relative prediction error was 15%. Developed approximated models were applied for multiobjective optimization of the vibropressing process. Optimization criteria were: compacting rate, consumed energy, pressing cycle length. Pareto frontier surfaces were constructed and analyzed.

Keywords: raw concrete, rheological model, parametric identification, multiobjective optimization.

Introduction

Vibropressing technology is generally used for compaction of high-strength concrete blocks such as paving bricks, and the blocks are immediately demolded, unlike poured concrete constructions. A large range of block making machines is available on the market from manufacturers like “Poyatos”, “Prensoland”, “Masa-Henke”, “HESS” and many others. They are based on the following principle: the pressure is combined with forced vibrations, and for some models with vibro-impact as well, see QFT8-15 Brick Making Machine [18] for example. A two-side vibro-impact press was also patented and investigated by the authors [13, 14], see Fig. 1. The most important characteristics of such blocks are strength and freeze-thaw durability. Both of them increase by increasing the density of the block using the same raw concrete composition – sand, cement, water and chemical additives.

Point-mass systems and continuous medium models are used to describe the concrete vibration process. Consolidation by vibration is mostly described as consisting of two stages - the first comprising subsidence or slumping of the concrete, and the second - deaeration (removal of entrapped air bubbles). A different model should be used for each stage [6].

The analysis of literature indicates that at present time an exact model of the rheological behavior of vibropressing of raw concrete does not exist as too many factors are involved in this process. The change of viscosity of raw concrete under the influence of vibration is well known phenomena. I. Blekhman introduced the name vibrorheology for the field of science which operates with rheological models subject to a vibration [4, 5]. Vibrorheological properties of raw concrete are analyzed in [15]. Different authors classified different factors as key factors. By

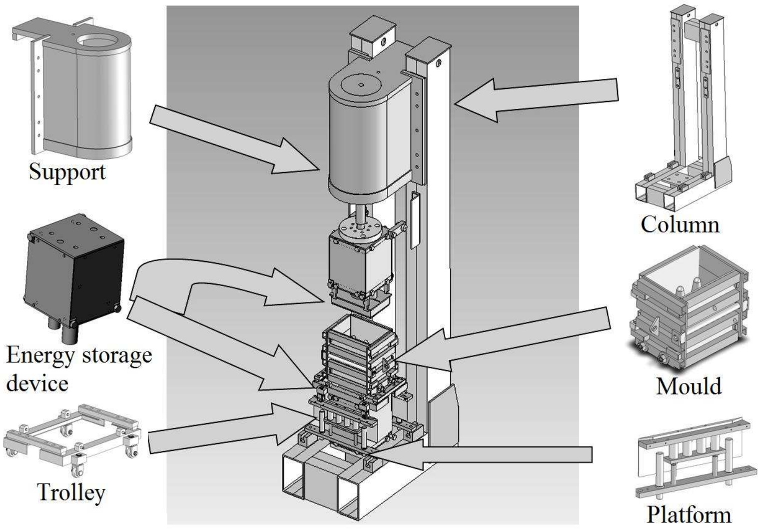

Fig. 1. Two-sided vibro-impact press

example, in the work [23] two factors are qualified as main factors: finest particle surface area and the mass of coarse aggregate. Most works about vibrorheology are related to self-compacting concrete mixes [8, 21, 22]. The experience of concrete block producers indicates that the construction and use of models on the basis of formal universal rheological theory should be avoided. In [12] the experimental investigation of vibropressing of large quartzite cement blocks was implemented. The properties of concrete blocks depend on recipe, chemical and granulometric characteristics of concrete mix components as well as on the dynamic action on the raw material during the forming process – the constant pressure component, amplitude and frequency of forced vibration and length of the forming cycle.

In this study the influence of dynamic parameters on the forming process was analyzed on the basis of mathematical models, identified from natural experiments without application of classical rheological hypotheses. The material testing machine Instron 8802 that can implement the given time-force function up to 250 kN was used instead of a specialized forming machine. A special cylinder-piston construction with the diameter 0.15 m was built for the experiments. The variable factors were the values of the constant pressure component, the frequency and amplitude of vibration force and the duration of vibration. The same amount of sand and cement was used for all experimental trials; only the cement-water ratio was varied. The experiments were conducted according to the Mean Square Error experimental design [1].

The mathematical model of system dynamics was identified in several ways. First, the dependence of summary resistance force on the moving average density, deformation and the deformation speed was determined using smoothed registered values of force and piston displacement (and numerically calculated velocity) in parametric (polynomial) and nonparametric kriging approximation. The second way – identification of variable coefficients in the linear second order differential equation. Both approaches yielded similar results. The constructed mathematical models were used for multiobjective optimization of the vibropressing process. The three objectives were the density of the formed block (greater is better), applied energy (less is better), and forming duration (less is better). Nonparametric kriging response surface method was applied to obtain a set of Pareto optimal solutions. Additional natural experiments confirm some of the best solutions. At this time the work is still in progress, because the variation of composition of raw concrete and additives as well as the variable (increasing) vibration frequency must be considered in the optimization research.

In the paper [22] it is claimed that vibrations with the displacement amplitude $A\omega^2$= 130-200 m/s^2 provide the greatest decrease of viscosity by vibration of self-compacting raw concrete. In our experiments the vibration displacement amplitude was incomparably smaller – about 10 mm/s^2, but compacting was sufficiently effective. So the inertia forces of concrete particles excited by vibrations were also negligible.

Experimental equipment

The INSTRON 8802 material testing machine [10, 24] was used for conducting raw concrete vibropressing experiments instead of real pressing machine, because of the possibility to realize various dynamic modes with very accurate measurement of process parameters. In a dynamic mode this machine can implement a load up to 250 kN according to the given time function with a very high accuracy of displacement and load value measuring and registering. Universal hydraulic wedge action grips with a set of wedge elements ensure reliable fixation of the specimen, element, or structural component and enable quick mounting of interchangeable devices for compression tests. The rigid frame of the INSTRON 8802 machine minimizes the influence of deformation of the machine load unit on the test results. The digital control system offers a wide range of choices when designing an experiment.

A cylindrical mold and piston-plunger with a diameter of 15 cm were built for forming experiments, see Fig. 2. The pressing mold and plunger were fixed in the machine hydraulic grips, see Fig. 3.

Fig. 2. Pressing plunger, mold and compacted concrete block specimen

Fig. 3. Mold and plunger fixed in testing machine grips

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Methodology of vibropressing experiments

The aim of experiments with raw concrete vibropressing was the examination of the influence of vibropressing characteristic parameters (pressing load, vibration force amplitude and frequency, duration) on the quality of pressing. Therefore the chemical and granulometric parameters in all experimental runs were the same - see Tab. 1.

Table 1. Concrete mix composition (5% air)

Constituent material	Density (kg/m^3)	Composition (kg/m^3)
Cement, CEM I 52.5 (400)	3160	742
Water	1000	185
Sand (0/4) mm	2618	1392

Usually vibropressing is implemented so that the raw concrete is filled in the mold with a vibrating base and the hydraulically-driven plunger pushes the raw concrete material downright like a cylinder piston. The plunger also vibrates. The vibrations are usually induced by means of an electric vibration exciter operating with power supply frequency of 50 or 60 Hz.

In our experimental machine both pressing and vibration were implemented using hydraulically-driven plunger acting from one side – downwards.

The vibropressing experimental regime

The main focus of this paper is the study of the vibropressing regime. In industrial vibropressing machines [18] the raw concrete is filled in the mold with a vibrating base and the hydraulically-driven plunger pushes the raw concrete material downright like a cylinder piston. The plunger also vibrates. The vibrations are usually generated by an electric vibration exciter. The vibropressing usually is implemented by pressing the plunger according to the given law of force or displacement variation $f = f(t)$ (here t - time) and simultaneously vibrating the mould and plunger according to some given displacement law $x = x(t)$, for example $x = a\sin(\omega t)$. Experimental equipment on the basis of the testing machine Instron cannot implement such a dynamic regime. Since we are interested mainly in the dynamics of vibration under pressure, the following force function was applied:

$$f = f_0 + f_1 \sin(2\pi\omega t) \tag{1}$$

where f_0 – the constant pressing force, f_1 – the force oscillation amplitude and ω - the frequency in RPM. At the beginning of the process this pressure cannot be applied since the raw concrete has a low compacting rate and accordingly a low resistance force. Therefore before applying vibration, the two-stage pressing without oscillations was used, see Fig. 4.

Due to technical characteristics of the testing machine Instron, the initial pressing stage was implemented with some inaccuracy that contributed to increasing the result dispersion. The testing machine was also not capable of implementing high frequency (ω > 50Hz) force vibration with high pressure force amplitude (f_1 > 0.5 kN). In such cases the vibrations were nearly chaotic and only Fourier analysis showed the prevalence of required frequency, but the realized amplitude is much less than required amplitude.

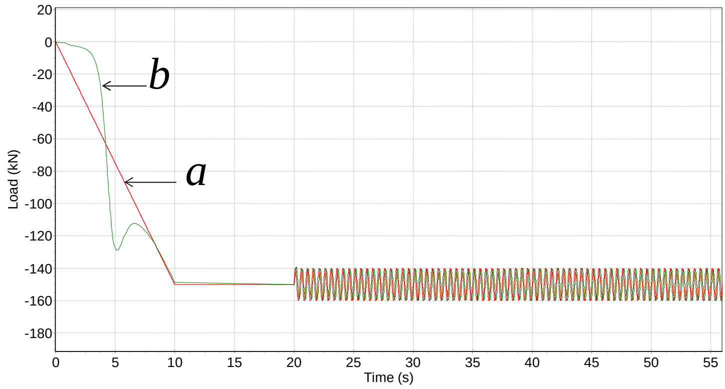

Fig. 4. The example of required (*a*) and implemented (*b*) pressing force function

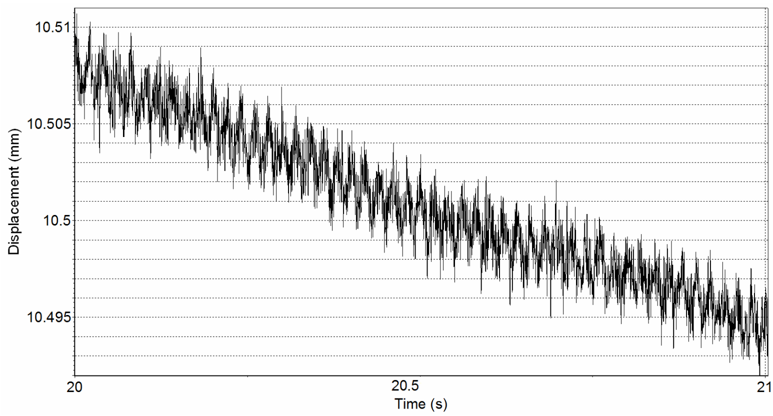

Fig. 5. Displacement graph, 50 Hz force oscillations

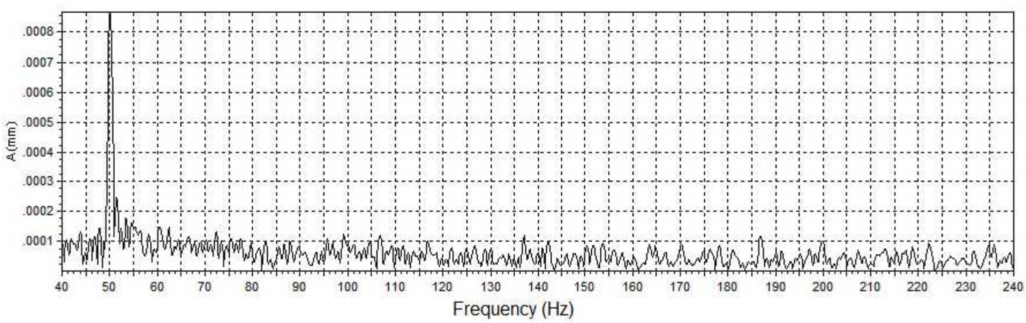

Fig. 6. Fourier spectrum of displacement oscillations with 50 Hz pressing force

In this study only the influences of vibration force frequency and amplitude on the compacting process were analyzed. The same cement (class 400), sand filling aggregate (0.3 – 2.5 mm, moisture 0.2%) and water-cement mass ratio (W/C) 0.25 were used for all experimental runs.

Concrete cylinder blocks with diameter 15 cm and height 20 cm were compacted.

The experiment for three variable factors f_0, f_1 and ω was planned according to the Mean Square Error experimental design [1], but since the Instron machine is incapable of implementing high-frequency high-amplitude vibration force, some experimental runs gave different input factor values.

During the experiments the values of the pressing force f and plunger displacement x were measured and registered with a small time step - 0.0002 seconds. The full pressing duration was 33s, including 12 second two-stage initial pressure without vibration. The measured processes involve error noise of various origins, see Fig. 5. In this experiment try the required constant force component was 75 kN, but as can be observed at the beginning of vibration the mean force value was about 79 kN. This also influenced the displacement curve.

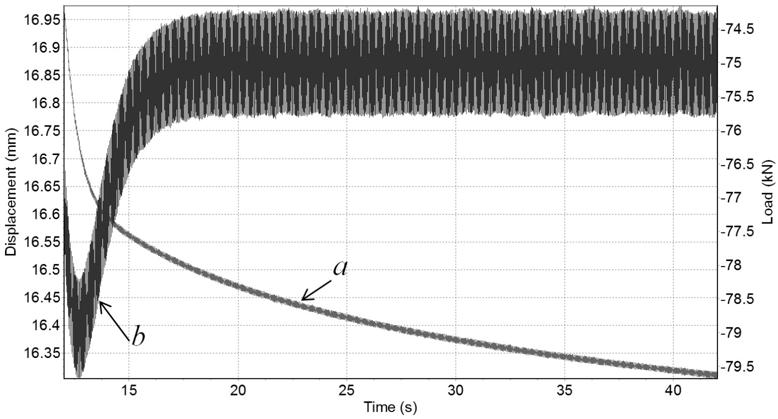

Fig. 7. Registered plunger displacement (*a*) and force graphs (*b*)

Further analysis requires velocity values and numerical differentiation of measured functions; therefore the registered data must be smoothed. The testing machine implements the required frequency very accurately, therefore a locally weighted sinusoidal approximation with Gaussian weighting function [1, 3] was used for smoothing and numerical differentiation of the registered functions. Figure 8 presents measured and smoothed displacement graphs. In the same way the force graph can be smoothed. Simultaneously the smoothed first and second time derivation graphs can be calculated. Figure 9 shows the numerically calculated plunger acceleration graph. As can be noticed the acceleration of the plunger and correspondingly of the top part of the raw concrete mass is relatively small, so the inertia forces of mass parts are also small in comparison with the pressing force. Therefore the wave process in the compressed raw material is not significant. Finite element analysis gives the lowest eigenfrequency – approximately 2000 Hz in the compacted cylinder.

For the analysis and optimization the response curve (more than 300000 points), obtained by fixed compacting force parameter values f_1 and f_2 must be characterized with a small number of parameters. For this purpose the displacement curve approximation was used. Fig. 10 illustrates a typical compacting displacement curve. The first attempt of approximation was made with exponential approximation using the non-linear method of least-squares. However this 3-parameter approximation did not give very accurate approximations. The approximation with a power function was used in the form:

$$\hat{x}(t) = x_0 + R(t - t_0 + \Delta)^p \tag{2}$$

with four parameters x_0, R, Δ and p for curve fitting according to least-squares method. This approximation gives very accurate approximation of displacement curves, see Fig. 10.

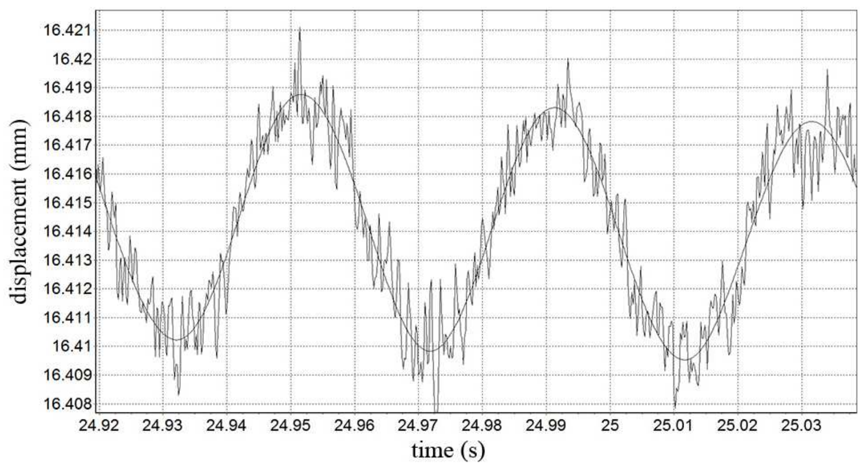

Fig. 8. Registered and smoothed plunger displacement graphs

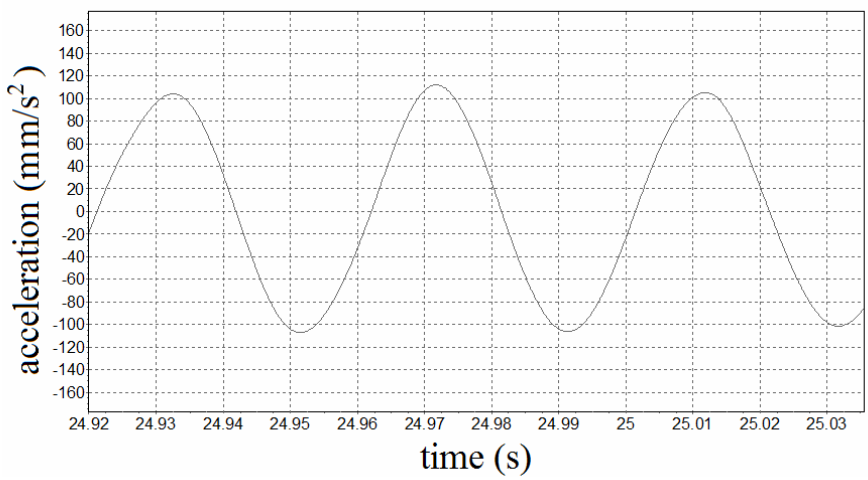

Fig. 9. Numerically calculated plunger acceleration

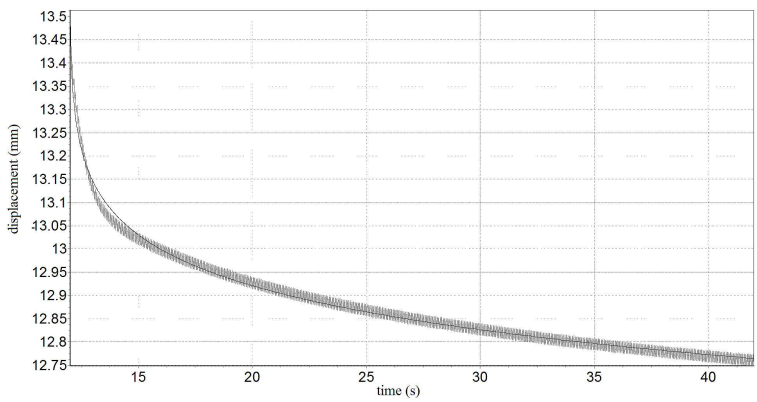

Fig. 10. Registered and approximated plunger displacement graph

Furthermore, quite good approximations for all our experimental runs could be obtained using fixed values of $x_0 = x(t_0)$ and Δ =0.02, p = 0.05 and fitting only the one value - coefficient R. By determining the value of R the compacting process can be entirely characterized in the given time interval. So the approximation of the dependence $R = R(f_0, f_1, \omega)$ gives the possibility to analyze and to optimize the vibropressing process.

Identification of stiffness and friction coefficients

The simplest Kelvin-Voigt rheological dynamic model of vibropressing process is provided in Fig. 11. In this model the stiffness coefficient c and internal friction coefficient k as well as the equilibrium position of the spring change during the compaction.

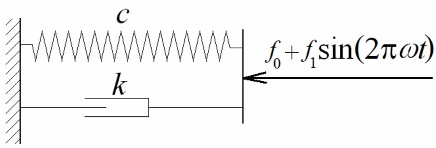

Fig. 11. The simplest Kelvin-Voigt dynamic model of vibropressing

Without regard for inertia forces the dynamic equation of Kelvin-Voigt model is:

$$k\dot{x} + c(x - x_{eq}) = f_0 + f_1 \sin(2\pi\omega t), \tag{3}$$

where k, c and x_{eq} are friction coefficient, stiffness coefficient and equilibrium position respectively. Authors of [7] used strain relaxation curves and least square regression method for determination of time dependent parameters of Burger's rheological model on the basis of experimental results. Here we used the registered time dependence curves which are more complicated because they involve oscillating components. Using locally weighted linear approximation for the recorded displacement x, pressing force f values and numerically calculated velocity values $\dot{x}$ we can calculate the Kelvin-Voigt model parameter values for each recorded time moment. As opposed to data smoothing, the bandwidth for local linear approximation in this case must be a multiple of the oscillation period. Fig. 12, 13 illustrates the time graphs of friction and stiffness coefficients.

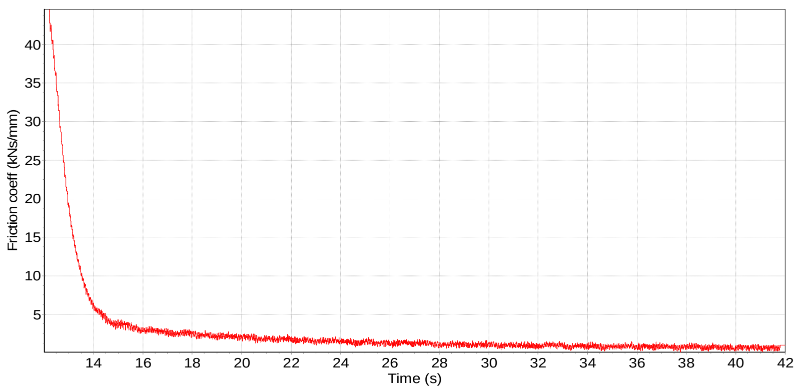

Fig. 12. Friction coefficient

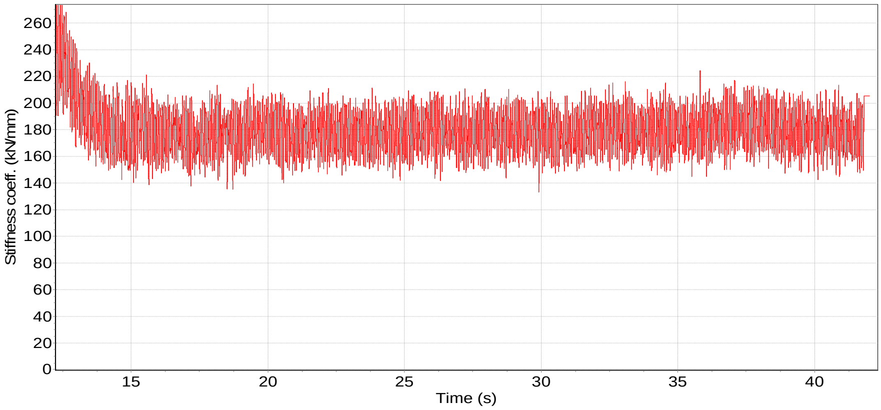

Fig. 13. Stiffness coefficient

It can be seen that the dynamic stiffness is nearly constant during compression but the dynamic friction (viscosity) significantly decreases. In such a way the Maxwell's and Burgers model [7] parameters can also be obtained.

Multiobjective optimization

The research approach is similar to the surrogate model building for composite panel buckling behavior [11]. First the measured responses are approximated with a small number of parameters and then the models of the dependence of these parameters on input factors are built. Knowing the dependence of the compacting curve characteristic R on the variable factors f_0, f_1, ω, one can calculate the objectives for multiobjective optimization.

The following criteria were involved for vibropressing process optimization.

1. The compaction C_r (measured in millimeters):

$$C_r = R\left[(t_1 - t_0 + \Delta)^p - \Delta^p\right]. \tag{4}$$

The greater compaction (and density, respectively) gives higher concrete block strength [16, 17, 19]. However C_r is limited by the granulometric characteristics of the filler material and cannot be infinitely increased.

2. Consumed energy W:

$$W = \int_{t_0}^{t_1} \dot{x}(t)(f_0 + f_1 \sin \omega t)dt \cdot \tag{5}$$

Here the approximated function of displacement cannot be used. But it is known that the total consumed energy is proportional to the force amplitude, frequency, internal friction coefficient of material and duration:

$$W = k_w \omega f_1 (t_1 - t_0). \tag{6}$$

It must be noted that the expression (6) gives the total value of absorbed energy. The total consumed energy can be considerably greater if the drive cannot recuperate the energy at the stage when the velocity is opposite to force direction, as it is in the case of our Instron machine.

Of course, less consumed energy is better.

3. Duration T:

$$T = t_1 - t_0. \tag{7}$$

Shorter duration means less cycle time and greater productivity of the forming machine.

4. Pressing force f_0.

Less pressure is better (if it gives good compaction), because it requires lighter construction and gives better reliability.

The software EDAOpt [2, 3] was used to analyze experiments and implement multiobjective optimization. This software uses several approximation methods (polynomial, custom polynomial, locally weighted polynomial, kriging) and allows multiobjective optimization using approximate objective and constraint functions. The program uses a simple modification of the multistart simulated annealing method [9], but works very fast and reliably finds the global optimum thanks to fast calculation of approximated functions. In the following case 7 experimental runs were used and an approximate model was built using the kriging method [3, 20]. The relative cross-validation error (relative to the standard deviation from mean value of response) of approximation was 15%.

Fig. 14 provides the approximated dependence function of coefficient R on pressing force frequency and amplitude by fixed value of constant pressure force component f_1 = 75 kN.

Fig. 15 illustrates Pareto frontier surface for three criteria - compaction ratio C_r, consumed energy and duration T. The roughness of Pareto surface is caused by measurement and approximation errors.

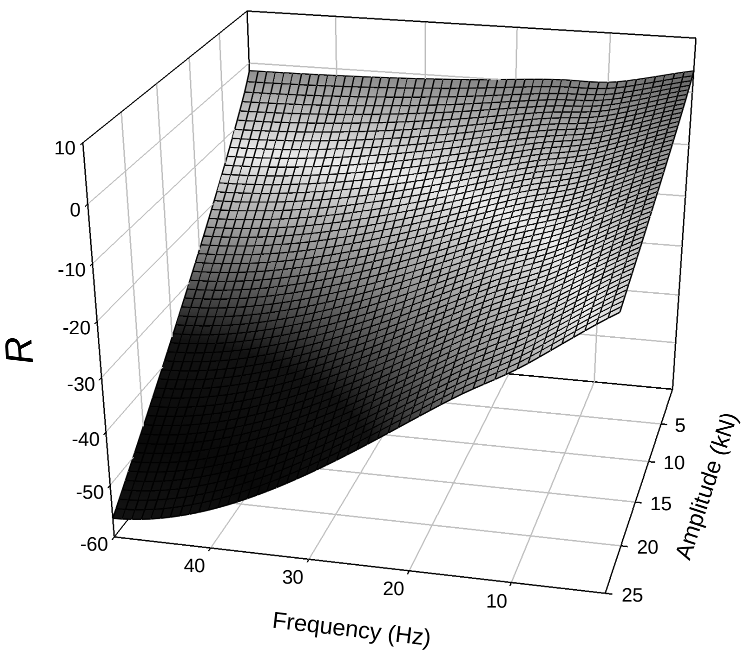

Fig. 14. Approximated dependence of coefficient R on vibration frequency and amplitude

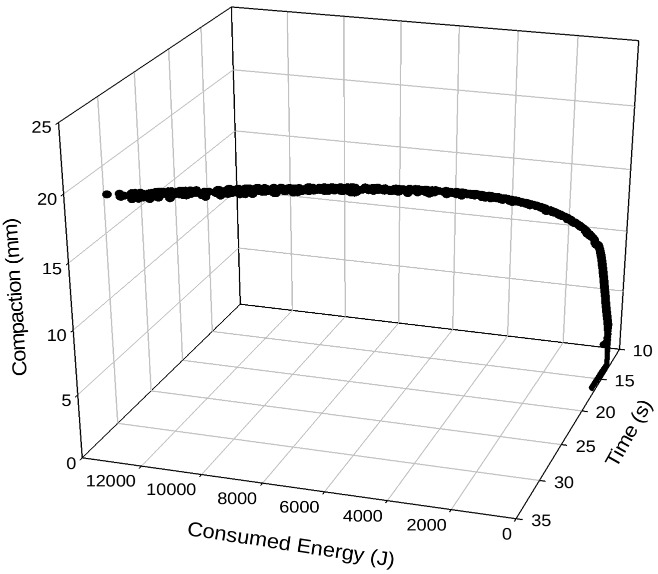

Fig. 15. Pareto frontier plot for 3 criteria

Conclusions

The presented methodology of simplification of load-displacement curves obtained from physical experiments with subsequent construction of approximate models for raw concrete behavior under the influence of vibropressing forces provides the possibility of multiobjective optimization. The prediction error of the constructed models is approximately 15% and can be reduced using a larger number of experimental runs and improved specific equipment. For practical application of this methodology it is necessary to involve the factors characterizing the properties and recipe of raw concrete components - granulometric parameters, water cement ratio and others, as well as to take into account the actual strength of the formatted blocks.

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