SOME TECHNICAL ASPECTS RELATED TO VALUATION OF TECHNICAL AGEING LEVEL OF USED CONSTRUCTION MACHINERY

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Abstract. The current paper deals with important technical issues that arise when construction companies are providing used construction machinery and equipment. The present development is focused on the main characteristic data of construction machinery (e.g. useful technical characteristics), which determine the real level of technical ageing and residual life of construction machinery for the needs of construction companies, as well as the prospects for further successful marketing of used construction machinery. An analysis of the technical characteristics of one of the most used machines for conventional construction – immersion vibrators for concrete compaction – is carried out, based on which the main useful technical characteristics for this type of machine are established. As a result of the surveying performed, there are mathematical models obtained, by which can be calculated the real technical ageing level of used construction machinery, depending on the variation of their useful technical characteristics. Finally, a specific numerical example for calculating a real level of technical ageing of an immersion vibrator for concrete compaction is solved, and important recommendations are made, which are related with the process of providing the construction companies with used construction machinery and equipment.

Keywords: construction machinery, second-hand mechanization, useful technical characteristics, technical ageing level.

1. INTRODUCTION

The significant progress of the construction industry in Bulgaria and Europe over the last 30 years testifies to the achievement of higher quality levels of construction management by contractors in general. Along with the implementation of new structures and technologies for construction, new con-

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DOI: 10.7546/EngSci.LX.23.04.05

struction materials, the use of increasingly modern and energy-efficient construction machines with high performance, which contribute for reducing the time of execution of construction processes and achieving a higher quality of construction in general, the progressive jump in construction is also due to the correct and effective policy of construction companies regarding the renewal of the aging machine park (so-called "second-hand mechanization"). The pursuit of equipping with newer, more modern, and more efficient machines goes hand in hand with finding customers on the market for realization of the outdated equipment used by construction companies, because of which many specialized supplier companies (intermediaries) provide services for sale (or rental) of suitable, but used, second-hand construction equipment. This requires making of adequate decisions by the construction companies regarding the purchase and sale of used construction equipment (second-hand) to ensure the necessary efficiency of the machinery park management policy.

The assessment of actual level of technical ageing of used construction equipment (second-hand) is one of the important engineering issues facing the management of construction contractors, which determines the remaining resource/life of the machine for future operation and usefulness of the machine for construction purposes, as well as the user value and market price of the machines. This leads us to pay particular attention to methods for assessing the actual (real) level of technical ageing of used construction machinery (second-hand). This question is by no means unimportant, given the relatively high price level of construction equipment nowadays, as well as the significant share of the costs of construction mechanization and maintenance of the machine park in the mix of total costs of construction companies.

2. RELATIONSHIP BETWEEN THE MAIN USEFUL TECHNICAL CHARACTERISTICS OF CONSTRUCTION MACHINERY AND TECHNICAL AGEING LEVEL

The technical ageing level of used construction equipment (second-hand) determines the remaining resource/life of machine, and hence its residual capacity to satisfy future needs of consumer companies/users for construction purposes (the so-called "usefulness of machine"). The usefulness of machine is determined mostly by its operational capabilities, which find a direct quantitative expression through the main operational technical parameters of machine (the so-called "useful technical characteristics"). These are such basic technical parameters of construction machine that are directly related to its productivity, energy consumption or work quality/manufacturing. It is the nature and degree of change of the "useful technical characteristics" of used construction machine (second-hand) in relation to the design/initial values for a new machine that should be the main and leading factor, based on which the real/actual technical ageing level of used construction machinery (second hand) is determined. For this reason, the machine's useful technical characteristics can also be called "technical ageing parameters".

It is known that the long-term operation of construction machines leads to a gradual deterioration (change with a negative trend) of their useful technical characteristics, which is expressed in an increase in the technical ageing level of machine. A very important fact here is that the technical ageing level of machine usually increases non-linearly (usually at much faster rate) relative to the rate of change (deterioration) of the machine's useful technical characteristics. For example: if the main useful technical characteristics of a motor grader (hourly production P [m^2/h], fuel consumption $k2$ [ltr/kW.h], grading quality, etc.) have only changed/deteriorated with about 30% compared to the design values of a new machine, it could be assumed that such motor grader is completely unfit for further operation, and therefore its technical ageing level should be considered equal to 100% (i.e. its further successful realization on the secondary market for suitable construction equipment is impossible, in which case the most correct solution would be to scrap the machine – transfer it for secondary raw materials or use it only for spare parts). There is a non-linear relationship between the change/increase in technical ageing level of the machine and the change/deterioration of the machine's useful technical characteristics (the so-called "technical ageing parameters").

The non-linear dependence between the user utility (remaining resource) of the machine and its main technical parameters was studied as early as the 70s of the 20$^{\text{th}}$ century by the American researcher Chilton. From research done, it was found that the non-linear relationship between the user usefulness of the machine (expressed by the "value of the machine") and its main technical parameters can be expressed by an exponential function (power index). This power index is called "Chilton's coefficient", which characterizes the power of influence of the main technical parameter of the machine on its value (consumer usefulness). A similar "Chilton's coefficient" can be established for each individual group of machines, considering that the value of this coefficient for a particular type of machine and its corresponding technical parameter can be considered sufficiently stable over time [1].

In general, the simpler design of a construction machine, the fewer in number should be the main technical parameters on which its remaining resource/life R will depend. If it is assumed that the remaining resource/life R

of a construction machine is mainly determined by only one of its technical parameters Y (hereinafter referred to as the "basic ageing parameter"), then the level of physical ageing "K_{phys}" will be able to calculated based on the ratio of the value of the basic technical parameter for a new machine (i.e. the design value set in the technical specification of the machine as new) and the actual measured value of this basic parameter on the date of the assessment. In doing so, the degree of non-linearity in changing the level of physical ageing relative to the change in the basic ageing parameter, which is expressed by the "Chilton's coefficient" – "b", should also be taken into account. In this case, the following dependence can be used to calculate the coefficient of physical ageing "K_{phys}":

$$K_{phys} = 1 - R, \tag{1}$$

where: $R = (Y_{assess}/Y_{basic})^b$ is the remaining resource/life of the machine, relative to the basic ageing parameter; Y_{assess} is the actually existing (measured) meaning/value of the basic technical parameter of ageing of the machine on the date of assessment; Y_{basic} is design meaning/value of the basic technical ageing parameter for a new machine (i.e. the design value); b is coefficient of non-linearity (Chilton's coefficient).

3. EXAMPLE OF DETERMINING THE REAL LEVEL OF PHYSICAL AGEING FOR SELECTED TYPE OF CONSTRUCTION MACHINERY (IN THE CASE "IMMERSION VIBRATORS FOR CONCRETE COMPACTION") BASED ON ANALYSIS OF CHANGE IN THE BASIC TECHNICAL AGEING PARAMETER

3.1. Establishing basic technical parameter for determination of physical ageing in immersion vibrators

Mechanical methods of concrete compaction use vibration energy (expressed by the frequency and amplitude of vibrations) to remove air voids from the concrete mixture, which are formed during the process of placing the concrete [2]. Immersion vibrators have a housing, inside which rotating eccentric elements are mounted, which create a centrifugal inertial force that excites vibrations in the vibrator housing, with a certain frequency f [Hz] and amplitude A_1 [mm], which are subsequently transmitted to the concrete mixture. Centrifugal force F_V [N] depends on the mass of the unbalanced (eccentric) element m_{unbal} [kg], the eccentricity e [m] and the angular speed of rotation squared $\omega^2 = (2.\pi.f)^2$ [rad/sec] [3]. From the above formulas, it is clear that as the vibration frequency of the vibrator f [Hz] increases, the centrifugal force will increase. It is recommended that immersion vibrators operate within a specific revolutions (rpm)/oscillation frequency range that will achieve the greatest radius of action, efficiency, and performance in operation. The most commonly used immersion (poker) vibrators in conventional construction for compaction of reinforced concrete elements are those of medium size, which have a diameter of $D = 50\div90$ mm (vibrating head radius $R_1 = 25\div45$ mm), and their centrifugal vibration force is usually in the range $F_V = 3100\div8900$ N [9]. The American Concrete Institute (ACI) recommends vibrators with such vibration centrifugal force F_V [N] and with such diameter D [mm] to work with rpm/oscillation frequency "$n = 3000\div12000$ [rpm]" (i.e. $f = 50\div200$ Hz), but the most effective operating rpm/frequency is determined to be in the range "$n = 5000\div8000$ [rpm]" ($f = 83\div133$ Hz), since it has been found that at such frequency they work most efficiently, and achieve the greatest radius of action and productivity [4]. According to [4] and [8], it is evident that the radius of action of an immersion vibrator R_2 [mm] should be assumed to be approximately 8 times larger than the radius of the vibrating head. Therefore, for the purposes of the present development, $R_2 = 8.R_1$ (designed for a new vibrator) is assumed.

Harmonic vibrations excited by the immersion vibrator are propagated in the concrete mixture up to a certain radius of action. The maximum radius of action at which the concrete can practically be considered fully compacted R_2 [mm] represents the distance from the axis of the immersion vibrator to a certain point in the concrete to which the vibrator delivers a sufficient amount of vibration energy that is capable of reducing internal friction between the concrete particles to such an extent that the air voids/bubbles can move up to the surface of the concrete, thus being removed. According to Kolek [5], the minimum necessary amplitude of the concrete, at which it is considered that there is an effective compaction process, can be assumed: $A_{min,adm} = 0,04$ mm.

When immersed in the concrete mixture, the amplitude of the surface of vibrator A_1 [mm] is reduced by about $15\div20\%$, compared to the vibration amplitude in free (air) environment. The vibration amplitude of the vibrator surface A_1 [mm] depends mostly on the magnitude of the centrifugal force, but also on the total own mass of the entire immersion vibrator [4].

When pouring concrete with a low consistency, an average air content of about 5–20% is generally obtained. The total effect of compaction work on the concrete of a particular construction site (performance plus vibration quality) will depend not only on the frequency f [Hz] and the vibration amplitude

A_1 [mm], but also on the perceived radius of action (and hence the offset distance) of the vibrator R_2 [m] when planning the technology of work, as well as from the duration of the vibration time at any given point of the concrete mixture [4]. As a rule of thumb to achieve a good quality compaction work, the concrete mixture should be vibrated until the air content throughout the concrete is reduced to about 1.5% or less [6].

Productivity of immersion vibrator can be calculated according to the following dependence [7]:

$$P = 3600.\left(2.R_2^2.h\right)/\left(t_1 + t_2\right),\ [\mathrm{m}^3/\mathrm{h}], \tag{2}$$

where: R_2, [m] is the adopted radius of action of the vibrator; h, [m] – the height of the compacted concrete layer depending on the length of the vibrating head of vibrator; t_1, [sec] – the time required to compact/vibrate the concrete at one installation/location of the vibrator, which depends on the consistency of the concrete mixture; t_2, [sec] – the time required to move the vibrator from one installation/location to another. It usually takes about 10÷20 seconds.

According to development [10], it was found that the vibration amplitude at a certain measured point of the concrete mixture gradually decreases with the distance of the measuring point from the surface of immersion vibrator, which was again studied at different consistencies of the concrete – Fig. 1. It

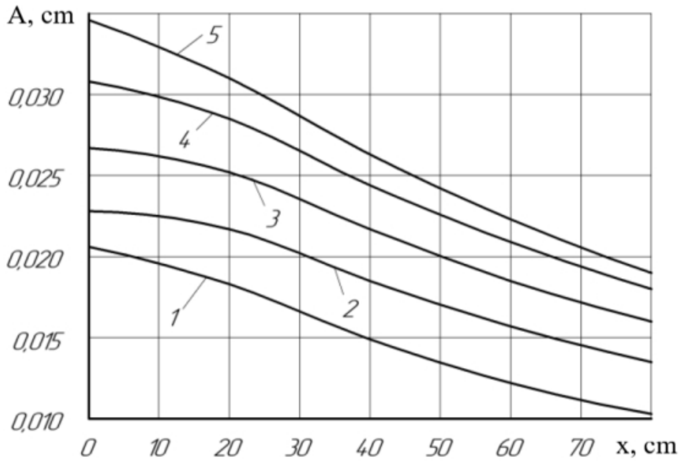

Fig. 1. Variation of the oscillation amplitude of compacted concrete mixture of different consistency depending on the distance from the source of vibration: 1 – at the mixture rigidity $S = 6$ sec; 2 – at $S = 30$ sec; 3 – at $S = 60$ sec; 4 – at $S = 90$ sec; 5 – at $S = 120$ sec [10]

can be seen that the vibration amplitude of the vibrator surface is reduced on average by about 25÷30% due to the gradual compaction and increase in the density of the concrete mixture from 75% to 100%.

According to [7], an approximate value of the radius of action R_2 $[cm]$ of immersion vibrator can be determined based on the following dependence:

$$A = A_1.\sqrt{(R_1/R_2)\,.e^{-\beta.(R_2-R_1)}} \gg A_{min,adm}, \qquad (3)$$

where: $A_{min,adm}$ [cm] is the minimum admissible amplitude of vibration of the concrete particles at which there is effective compaction; A_1 [cm] – amplitude of vibration of the concrete particles immediately next to the vibrating part of the vibrator (i.e. on the surface of vibrator); A [cm] – vibration amplitude of concrete particles located at a distance from the axis of the poker (immersion) vibrator; β [cm^{-1}] – damping coefficient of the amplitude of the oscillatory movement of concrete mixture. It is usually taken in the range of: $\beta \approx (0,028\div 0,055)$ [cm^{-1}]; R_1 [cm] – radius of poker (immersion) vibrator (i.e., radius of vibrating head); R_2 [cm] – the distance from the axis of the vibrating head to the point in the concrete mixture for which the vibration amplitude A [cm] is calculated.

It follows from the above dependence that it is the amplitude of oscillations on the surface of a poker vibrator A_1 [mm] is the main parameter/factor that affects the size of the radius of action of the vibrator R_2 [mm], and hence on its performance P [m^3/h], operational capabilities and user usefulness.

In general, two main types of immersion vibrator displacement (offset) patterns/schemes are recommended for compaction of concrete: square vertices and rhombus vertices, which are shown in Fig. 2 [4 and 8]. The presented data of the scheme in Fig. 2 refer to vibrators that have an average size (approximately $R_1 = 25\div 45$ mm).

According to the development [10], it was found that the vibration amplitude of the surface of immersion vibrator A_1 [mm] gradually decreases in the process of compaction (and increase in density) of the concrete mixture, which was studied for different consistencies of the concrete – Fig. 3. It can be seen from the figure that the vibration amplitude of the vibrator surface is reduced by about 25÷30% on average when compacting and increasing the density of concrete mixture from 75% to 100%.

In the process of using the immersion vibrator, it is normal to expect the development of various degradation processes in the materials and structure of the vibrator as a result of long-term operation, which are mainly related to ageing of friction surfaces, mechanical ageing of bearings, physical ageing of hinged connections, widening of design clearances, development of backlashes

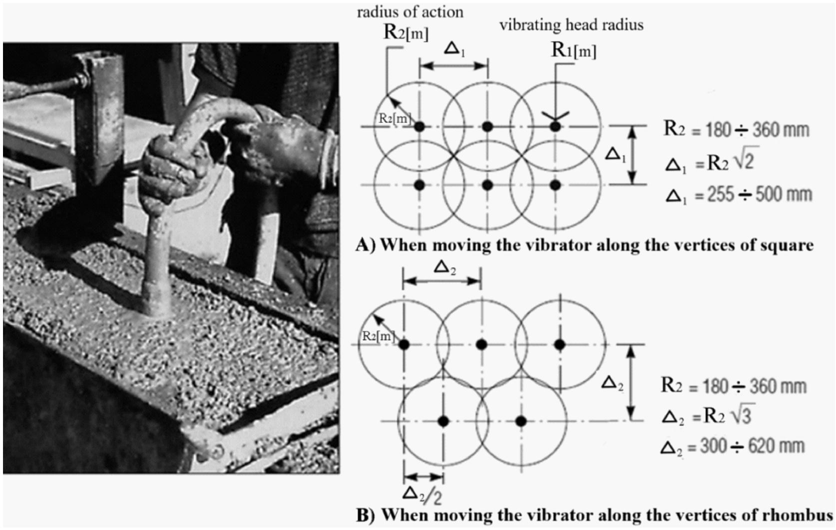

Fig. 2. Possible patterns/schemes of moving a poker (immersion) vibrator during concrete compaction: A) along the vertices of square; B) along the vertices of rhombus

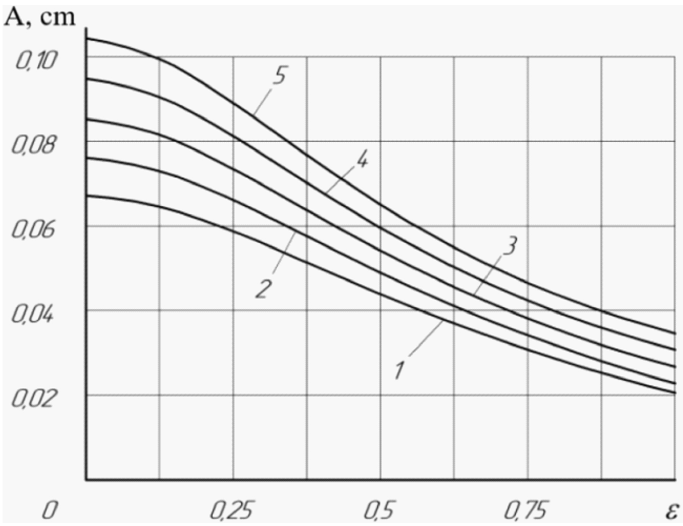

Fig. 3. Variation of the oscillation amplitude of immersion vibrator at its interaction with compacted concrete mixture of different consistency depending on the relative density of the concrete mixture (ε): 1 – at the mixture density $S = 6$ sec; 2 – at $S = 30$ sec; 3 – at $S = 60$ sec; 4 – at $S = 90$ sec; 5 – at $S = 120$ sec [10]

in joints, corrosion of metal, etc. Because of this, a number of deviations from the designed operational characteristics and mode of operation of the immersion vibrator are usually reached, in which its physical ageing increases and its operational capabilities are reduced. This is mainly due to a decrease in the amplitude of vibrations of the vibrator surface A_1 [mm] compared to the design values in the technical documentation (for a new vibrator), caused by the above-described degradation processes in the vibrator structure, which directly affects the performance of the vibrator and leads to its reduction.

For the purposes of the present development, it is assumed that the amplitude of oscillations on the surface of a poker vibrator A_1 [mm] is the "main useful technical parameter" for poker (immersion) vibrators, as well as a basic parameter for determining the ageing of this type of construction machinery.

Immersion vibrators, as well as other vibrators, generally do not have (are not factory-equipped) a pre-installed device/sensor to measure their frequency and/or amplitude of vibrations. For this reason, it is usually necessary to use additional measuring means in order to be able to measure the frequency and amplitude of the oscillations of a poker (immersion) vibrator. Some of the more modern mechanical concrete vibrators are equipped with an electronic display, on which the measured amplitude A_1 [mm] and vibration frequency f [Hz] of the vibrator are displayed in real time [2]. In laboratory conditions, standard test methods can be used to measure the oscillation amplitude of vibrator surface, using specialized measuring equipment (so-called "vibrometers"). To ensure the necessary measurement accuracy, it is recommended

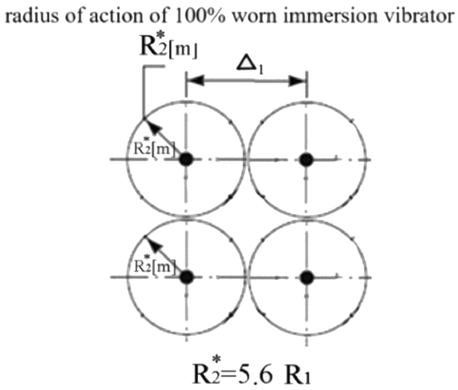

Fig. 4. Offset pattern/scheme and radius of action ($R_2 = 5.6\,R_1$ [mm]) of a poker vibrator assumed to be 100% level of physical ageing

that two vibrometers be attached to the immersion vibrator – one near the cap (lower end) of vibrating head and other near the base (upper end) of poker (vibrating head). The amplitude should be measured with a vibrating/running immersion vibrator when it is removed from the concrete (i.e., measuring vibrations in air). As the final obtained/measured value of the vibration amplitude on the surface of immersion vibrator A_1 [mm], the arithmetic average value of the two measured amplitudes (at the cap and at the base of vibrating head – i.e., at its lower and upper end) should be considered, which is calculated according to the following dependence:

$$A_1 = \left(A_{head\ cap} + A_{head\ base}\right)/2,\ \text{[mm]}. \tag{4}$$

3.2. Determination of screening criterion for a fully worn immersion vibrator for concrete compaction (i.e., 100% level of physical ageing, $K_{phys} = 1.0$)

As a criterion for a fully worn (100% level of physical ageing) immersion vibrator for concrete for the purposes of the present development, such a vibrator is taken that cannot reach the minimum required vibration amplitude of the concrete ($A_{min,adm} = 0.04$ mm) at a radius of action R_2[mm], equal to a minimum of 70% of its originally set design radius of action R_2 (i.e. not able to achieve vibration amplitude of the concrete $A_{min,adm} = 0.04$ mm and radius of action $R_2 = 0.7 \,.\, 8 \,.\, R_1 = 5.6R_1$). Considering the patterns/schemes of displacement (offset) of a poker vibrator “along the vertices of square” when compacting concrete (see Fig. 2 above), the following patterns/schemes of compaction is obtained by a similar 100% worn immersion vibrator – Fig. 4.

4. NUMERICAL EXAMPLE OF CALCULATING THE REAL LEVEL OF PHYSICAL AGEING OF IMMERSION VIBRATOR FOR CONCRETE COMPACTION

For the purposes of the present development, numerical example is considered with the following input data: To determine what is the real level of physical ageing of used immersion vibrator (second-hand vibrator) of medium size, which has vibrating head diameter $D = 50$ mm (radius $R_1 = 25$ mm). Average value of the vibration amplitude of the vibrator surface in air (free) environment equal to: $A_{1,meas.} = 0.4$ mm was previously measured. The design value of the same amplitude of a new vibrator in air (free) environment should be: $A_{1,design} = 0.6$ mm. The assessment of the level of physical ageing in the specific case is considered sufficient to be carried out by using only one basic technical ageing parameter – oscillation amplitude of the vibrator surface in free (air) environment – A_1 [mm]. For the purposes of the present development, Chilton's coefficient is adopted for the assessment of physical ageing of immersion vibrator for concrete compaction, relative to the basic technical parameter "oscillation amplitude of the vibrator surface": $b = 1.8$.

Solution: The actual level of physical ageing "K_{phys}" is calculated according to the dependence:

$$K_{phys} = 1 - R = 1 - \left(Y_{assess}/Y_{basic}\right)^{b} . \tag{5}$$

According to the above adopted screening criterion, the vibrator with diameter of $D = 500$ mm (vibrating head radius $R_1 = 25$ mm) considered in the example must not be able to achieve the minimum required amplitude of "$A_{min,adm} = 0.04$ mm" at minimum radius of action "$R_2 = 5.6\,R_1$ (i.e. $R_2 = 5.6 \times 25 = 140$ mm)" to consider such immersion vibrator as 100% worn. From Fig. 1 it can be seen that for such a medium-sized vibrator (diameter $D = 500$ mm, vibrating head radius $R_1 = 25$ mm) the reduction of the vibration amplitude of concrete at distance of 140 mm inside the concrete mixture, compared to the amplitude of surface of vibrator, is about 12÷16%, depending on the consistency of the concrete. This means that on the surface of such vibrator, amplitude of vibration in air (free) environment greater than $A_{1,meas.} > 0.04/\left(0.84 \times 0.8\right) = 0.06$ mm should be measured (in which also accounts the reduction of amplitude by about 20% after immersion of the vibrator in concrete mixture). In this way it is calculated: $Y_{basic} = 0.6 - 0.06 = 0.54$ mm and $Y_{assess} = 0.4 - 0.06 = 0.34$ mm.

$K_{phys} = 1 - R = 1 - (0.34/0.54)^{1.8} = 1 - 0.43 = 57\%$ – i.e., the used (second-hand) immersion vibrator in question of medium size (vibrating head radius $R_1 = 25$ mm) with measured amplitude $A_{1,meas.} = 0.4$ mm (at design value: $A_{1,design} = 0.6$ mm) is more than half worn out (57%).

5. CONCLUSION AND RECOMMENDATIONS

This publication examines important technical issues that arise in the purchase and sale, and supply of construction companies with second-hand mechanization. The development is focused on analysis of the main technical parameters that determine the usefulness of the machines for construction activity (the so-called "useful technical characteristics").

Analysis of the technical characteristics of one of the most used machines for conventional construction – immersion vibrators for concrete compaction – is carried out, on the basis of which the main useful technical parameters for this type of machine is established, as well as a way to determine screening criterion for a fully worn immersion vibrator for concrete compaction (i.e., 100% level of physical ageing, $K_{phys} = 1.0$).

As a result of the analysis, a mathematical dependence is proposed, by which the real level of physical ageing of used construction machinery can be calculated, depending on the existing (measured) value of their useful technical parameter.

The main conclusion and recommendation that can be made is that when buying and selling second-hand construction equipment, it is advisable to also take into account the nature and degree of change of the main technical parameters (the so-called "basic ageing parameters") of the used construction machine, compared to the design/initial set values for a new machine, which should be the main and leading factors on which to assess the real/actual level of physical ageing of the machine.

REFERENCES

[1] R. Nedelchev, Chilton's coefficient in evaluation of machinery and equipment, in: Proceedings of the VII National Conference of Independent Appraisers, Sofia, Bulgaria (2021).

[2] S. Tymkowicz and R. Steffes, Vibration Study for Consolidation of Portland Cement Concrete, Final Report for MLR-95-4, Iowa Department of Transportation, Iowa, USA (1999).

[3] K. Radlov and G. Ivanov, *Construction machinery and mechanization*, Propeller publishing house, Sofia, Bulgaria (2022), ISBN: 978-954-392-681-7.

[4] American Concrete Institute, Guide for Consolidation of Concrete, ACI 309R-87, USA (1987), online: http://civilwares.free.fr/ACI/MCP04/309r_96.pdf.

[5] J. Kolek, Research on the Vibration of Fresh Concrete Reports, in: Conference on Vibrations – Compaction Techniques, Budapest, Hungary (1963).

[6] H. N. Walker, Petrographic Methods of Examining Hardened Concrete: A Petrographic Manual, in: VTRC Report No. 92-R14, Virginia Transportation Research Council, Virginia, USA (1992).

[7] Y. Petkov, L. Zarkova and Ch. Donchev, *Collection of problems and examples in construction technology production*, ABC Tehnika, Sofia, Bulgaria (2010), ISBN: 954-03-0287-0.

[8] CCAA, Compaction of Concrete, in: Cement Concrete and Aggregates Australia, Australia (2006), online:
https://ccaa.com.au/common/Uploaded%20files/CCAA/Publications/Technical%20Publications/PART_V_-_13_-_COMPACTION_GTCC_2020.pdf.

[9] I. A. Rahman and M. A. Rahman, Effect of Vibrations on Concrete Strength, A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Structural Engineering, University of Khartoum, Faculty of Engineering and Architecture, Department of Civil Engineering, Sudan (2007).

[10] A. Maslov et al., The determination of the parameters of a vibration machine for the internal compaction of concrete mixtures, in: International Journal of Engineering & Technology (2018) **7** (4) 12–19, DOI: 10.14419/ijet.v7i4.3.19545.

Received September 14, 2023