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PRELIMINARY STUDIES OF DYNAMIC PARAMETERS IN MULTI-MATERIAL STRUCTURES WITH THE ADDITION OF ZEOLITE

The aim of this article is to present the results of preliminary research of the damping parameters of vibration in the constructions with the addition of zeolite. The first part of the article deals with the characteristics and application of zeolite. It describes mainly the impact of the addition of zeolite on the concrete parameters. The main part of the article presents the research outcomes of the damping parameters of the three models of plate-beam. The models contain modified binder in which the part of the concrete is replaced by the zeolite (with more than 85% content of the clinoptilolite). The values of the damping coefficients of vibration are determined by the collocation method as well as the method based on the estimation of kinetic energy of the vibrating system. The damping coefficients of the first three models of model vibration are determined.

Key words: damping parameter of vibration, zeolite, clionoptilolite, concrete.

Подано результати попереднього дослідження демпфірувальних параметрів вібрації у конструкціях з додаванням цеоліту. Перша частина статті стосується характеристик та застосування цеоліту, описано вплив додавання цеоліту на конкретні параметри. Основна частина статті – це результати вивчення демпфірувальних параметрів трьох моделей пластини балки. Моделі містять модифіковане зв'язувальне, в якому частину бетону замінено на цеоліт (з понад 85 % вмістом клиноптилоліту). Значення коефіцієнтів загасання вібрації визначаються колокаційним методом, а також методом, основаним на оцінці кінетичної енергії коливальної системи. Коефіцієнти загасання перших трьох моделей вібрації визначаються.

Ключові слова: параметр загасання вібрації, цеоліт, клиноптилоліт, бетон.

Introduction

While designing more complex bridges, overpasses, viaducts with substantial spread and low stiffness, it is significant to determine correctly the dynamic response of the structure. The operation life of

the structure is also relevant, and especially its condition which can significantly increase the dynamic effects (e.g. defects in the roadway). Therefore, when designing structures composed of many materials (frequently made of steel, reinforced concrete, wood and other), and determining the values of damping coefficient of vibration, such materials must skillfully be combined, however, simultaneously looking for new materials and modifying already applied. Following this line of thought, it was decided to recognize the dynamic characteristics of the modified reinforced concrete. The modification consists in replacing the part of cement with a zeolite, thus a new component of the cement mix. Strength characteristics of such concretes are already partially recognized, but there is no research concerning the dynamic characteristics, such as the aforementioned damping coefficient of vibration. To test the level of damping, the complex models of reinforced concrete and steel were used. The study consisted of vibration excitation of these models and the determination of the size of damping on the basis of the analysis of vibration waveforms. (collocation method). The second method determines the damping coefficient based on the estimation of the kinetic energy associated with the material model. The first three modes of free vibration of models were taken into account. The identification of the dynamic parameters of the models was performed by using Algor MES program. The calculation considered only a small range of free vibration.

Preliminary information on the use of zeolite as an additive to concrete.

The properties of zeolite and its possible uses are described in such works as [1, 2, 3, 4, 5]. The name "zeolit" (from Greek: boiling stone) was used in 1765 by Swedish mineralogist Axel Freiherr von Cronstedt. Zeolites are crystalline, hydratedaluminosilicates especially such metals as Ca, Mg, Na, K, Sr and Ba. Natural, modified, and synthetic zeolites can be distinguished.

Natural zeolites are formed mainly as hydrothermal forms. They most commonly appear in crevices and voids of eruptive rocks (e.g. basalt) or as the products to transform feldspar and feldspathoid. The process of zeolite creation from volcanic ash at the increased temperature and pressure, under natural conditions, lasts for several thousand of years.

The group of natural zeolites comprises about 40 minerals, among which the most common and used are,

- Clinoptilolite $Na_6[(AIO_2)_6(SiO_2)_{30}]\cdot24H_2O$,
- Chabazite $Ca_2[(AIO_2)_4(SiO_2)_8]\cdot13H_2O$,
- Mordenite $Na_8[(AIO_2)_8(SiO_2)_{40}]\cdot24H_2O$.

The diagnosis of zeolite synthesis processes under natural conditions has created the opportunity to take action on a laboratory scale. Initially, the volcanic ash was employed for this purpose. Later, the attempts were made to use fly ash from coal combustion.

Zeolites are distinguished by a number of unique physico-chemical characteristics, among which are,
- a high a absorption capacity
- molecular – sieve ability
- selectivity
- ion exchange capacity
- acid and elevated temperature resistance
- highly developed surface of up to 1.5 thousand $m^2\cdot g\text{-}1$

The study of concrete samples with the addition of zeolite shows considerable effectiveness of natural zeolite acting on:
- water and ion chloride penetration
- the degree of corrosion and concrete shrinkage
- the increase of strength and durability
- corrosion resistance

Research on models

Three slab-beam models were made, differing in the composition of concrete mix, ie with 5%, 20%, and 40% of zeolite instead of cement. Zeolit of the fraction up to 200μm of more than 85% clinoptilolite

content. Each model consisted of a plate having a thickness of 8cm, the horizontal dimensions of 2.64 m to 2.64 m, leaned on double T-bars of a height of 100mm spacing of 2m. Steel beams were jointly supported at the ends. In order obtain material characteristics of modified concrete, tests on cubic concrete samples (15cm x 15cm x 15cm) were performed. On the basis of the studies, the compressive strength of concrete and Young modulus were, inter alia, obtained. Scanning microscope photos of concrete samples are shown in Figure 1a (5% zeolite), Figure 1b (20% zeolite), 1c (40% zeolite), and the parameters of concrete are listed in Table 1.

Table 1

Material parameters of cubic concrete samples

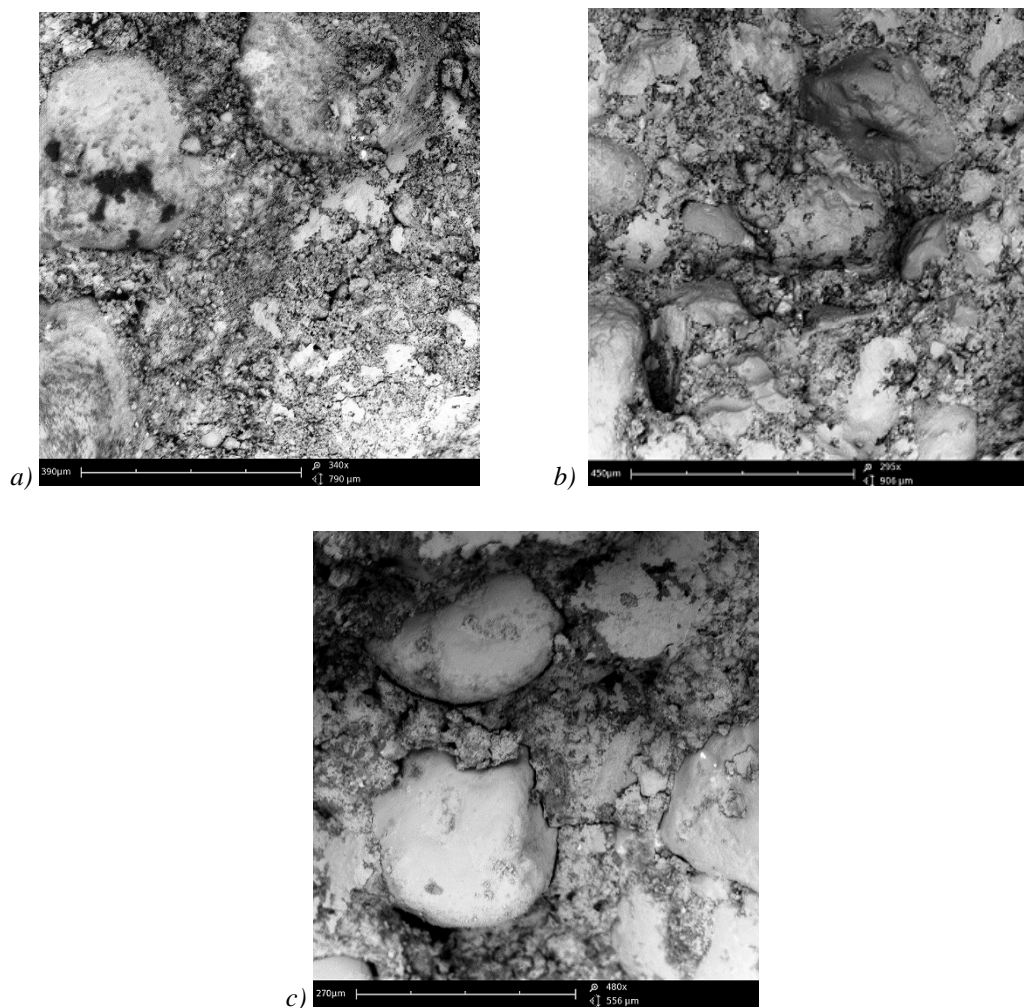| No. of sample model	$f_{c,cube}$ (MPa)	E_{cm}(GPa)
1 (5%)	13,24	28,0
2 (20%)	15,76	30,6
3 (40%)	9,96	23,4

Fig.1 The photos of concrete samples (a) 5%, b) 20% and c) 40% content of clinoptilolite)

The damping level of vibration of models was determined by the collocation method, described later in [10]. The collocation method requires taking the measurements of free vibrations of models. For this purpose, tests were performed with the use of HBM equipment: accelerometers B200, Spider analyzer, and controlling program Catman 5.0. Vibrations were excited by hitting with a wooden beam, and the models used in the study are shown in Fig. 2.

Fig. 2 Models used in research

Two accelerometers were mounted to each model (in half and quarter span between double-T bars). The measurements of accelerations as a result of excitation in three places where performed. The place of excitation and where the sensors were fixed is shown in Fig. 3.
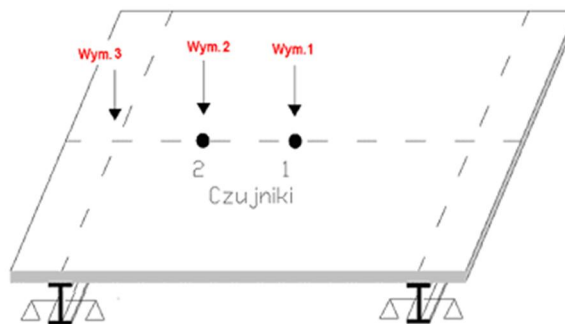

Fig. 3 The distribution of acceleration sensors and places of vibration excitation

The results of the measurements are the vibration accelerations at the time, sampled at a frequency of 1200 Hz with a bandwidth of 150 Hz for each of the three models. On the basis of time domains, the spectral analysis of vibration was carried out- with the use of Catman 5.0 program, FFT: Auto Power Spectrum- Amplitude.

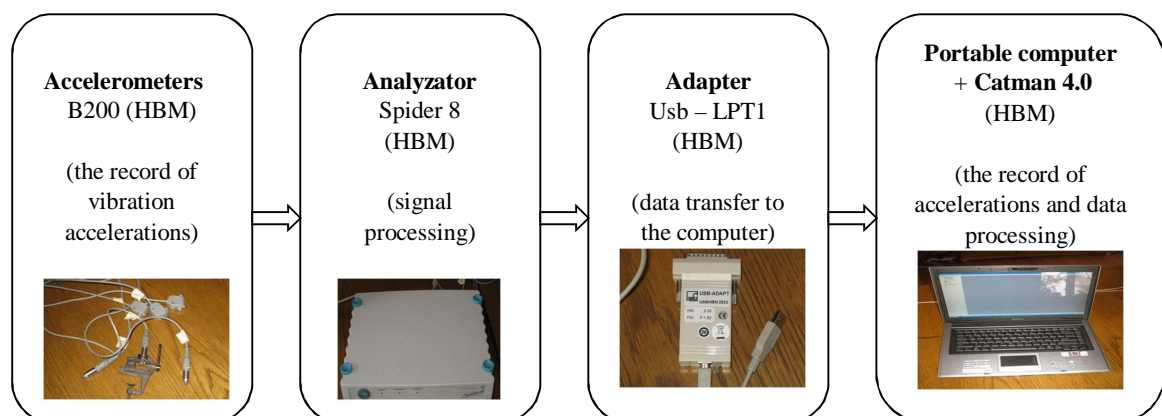The following block scheme of measuring system was used in the research (Fig. 4).

Fig. 4 The block diagram of measuring system

An example of the time domain of acceleration (Fig. 5) and amplitude spectrum are presented on the next page (Fig. 6).
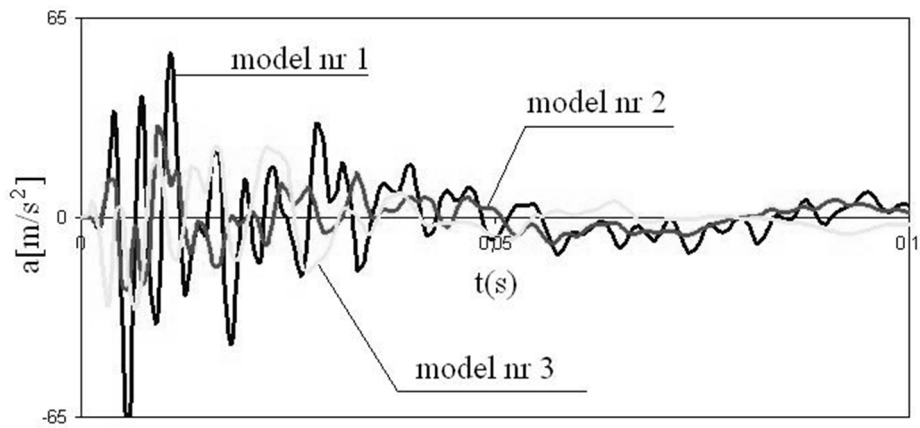
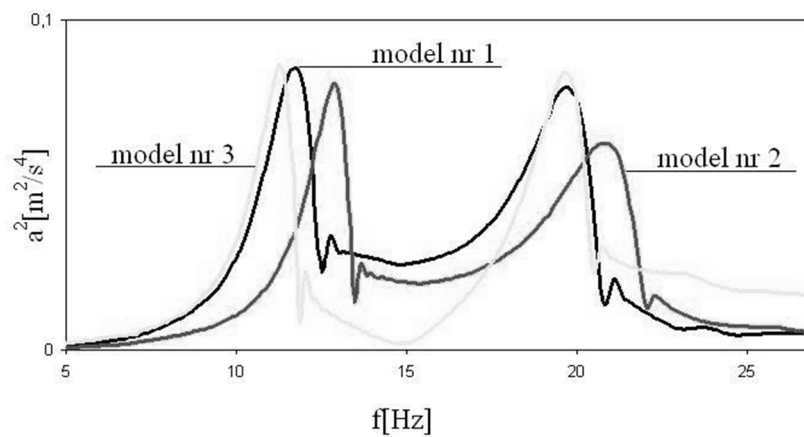*Fig. 5 An example of the time domain of vibration*

Fig. 6 An example of the amplitude spectrum of vibration acceleration

Natural frequencies obtained from the tests were verified by the calculations with the use of Algor (FEA program). The obtained modes of vibrations as well as the values of natural frequencies were very similar, with little divergence. Natural frequencies obtained from tests and calculations are shown in tab.2.

Table. 2

The comparison of natural frequencies

Model	f (Hz) test	f (Hz) Algor	No. / mode of vibration
No 1	11,62	12,23	1 / rotation of the beam and the vertical displacement of the plate
	19,63	19,94	2 / symmetrical bending of beam and plate
	32,17	36,31	3 / antisymmetric bending of plate and beam
No 2	12,92	12,65	1 / the rotation of beam and the vertical displacement of plate
	20,90	22,43	2 / symmetrical bending of beam and plate
	33,87	38,13	3 / antisymmetrical bending of plate and beam
No 3	11,36	12,09	1 / the rotation of beam and vertical displacement of plate
	19,85	20,68	2 / symmetrical bending of beam and plate
	-	35,03	3 / antisymmetrical bending of plate and beam

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The first, second and third mode of free vibrations obtained in Algor is presented below (Fig. 7,8,9).
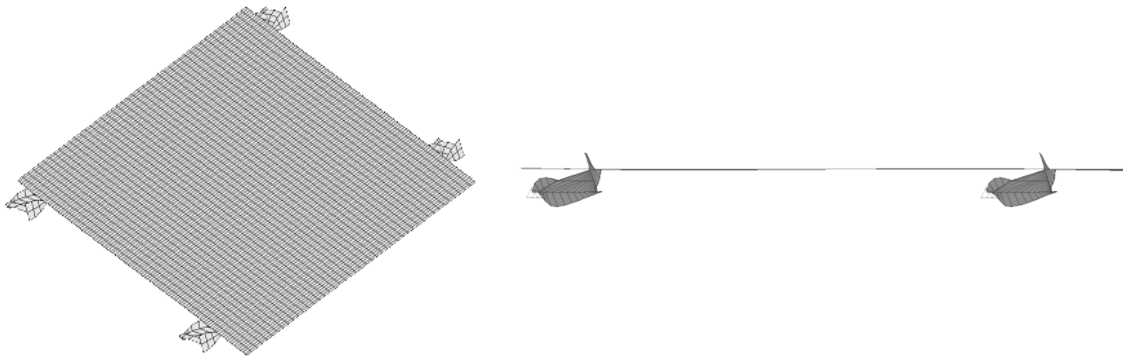

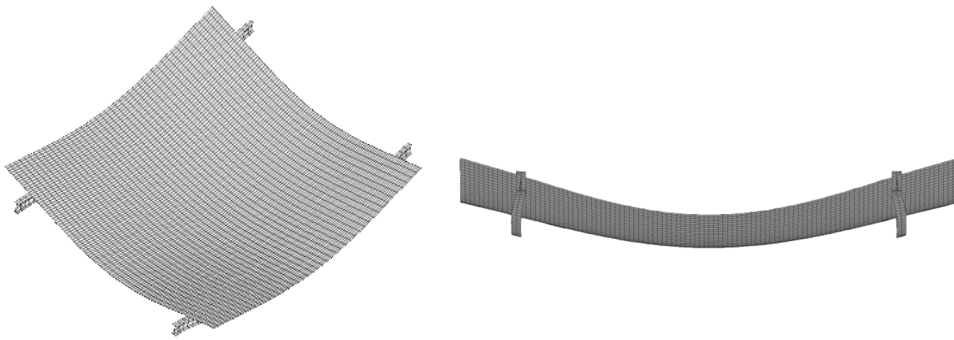*Fig. 7 The first mode of free vibrations of models (f1=12,23Hz, 12,65Hz, 12,09Hz)*

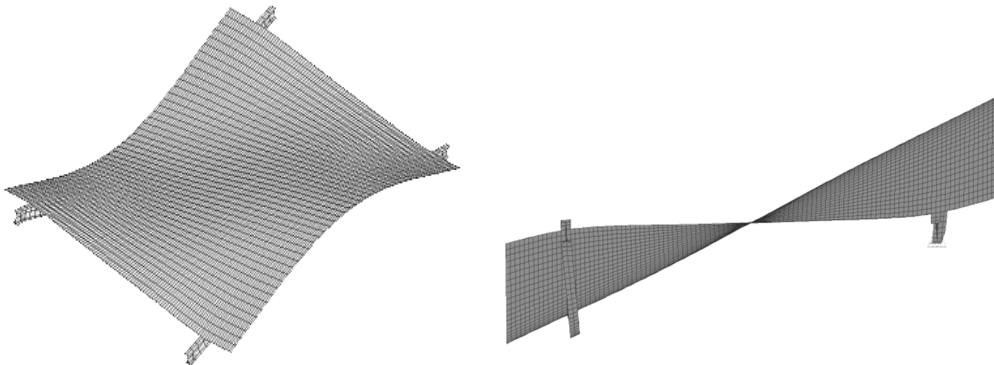*Fig. 8 The second mode of free vibration of models (f2=19,94Hz, 22,43Hz, 20,68Hz)*

Fig. 9 The third mode of free vibration of models (f3=36,31Hz, 38,13Hz, 35,03Hz)

Damping characteristics

The values of logarithmic decrement of damping of the first three modes of vibrations were estimated by using the collocation method [10] and energy method [6, 7, 8, 9]. In the case of collocation method, the damping parameter related to the mode of vibration without information on the impact of a particular material on the damping level of vibration of the structure. For this reason, the energy method was used, in which damping coefficients of vibration related to a particular component material of a structure. Obviously, the influence of the structural and external damping on the overall result of damping coefficient cannot be forgotten. Nevertheless, their impact in these models is small.

Thus, only the simultaneous use of collocation and energy method allows for determining damping parameters associated with the appropriate material, in this case modified concrete.

The average values of damping of material vibration, expressed by the logarithmic decrement of damping are presented in Tab. 3.

The values damping of material vibration [9]

Material	The average value □
Weakly strained reinforced concrete (not scratched)	0,054
Average strained reinforced concrete (scratched)	0,157
Heavily strained reinforced concrete (scratched)	0,141
Compressed concrete	0,035
Partially compressed concrete	0,063
Composite structure	0,017
Wood	0,079
Steel	0,010

Collocation method

The instruction while determining the damping parameter with this method:

1. The measurements of free vibration of damped structures by using displacement sensors (also accelerometers, strain gauges, etc.), by which the time histories of displacements of structure ($u_i(t)$)were obtained. The example of the vibration history is shown in Fig. 10.
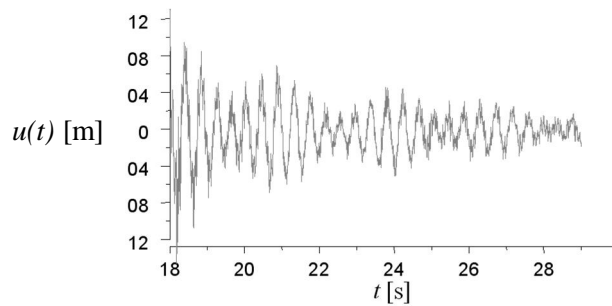

Fig. 10 An example of time history of vibration

2. The analysis of spectral time histories u(t) e.g. by using FFT (Fast Fourier Transform), by which circular frequencies of free vibrations corresponding to local extremes of this function are obtained. The function, obtained in such a way, is transformed to the form of square module:

$$F_u^{\,2} = \left|FFT\{u(t)\}\right|^2$$

(1)

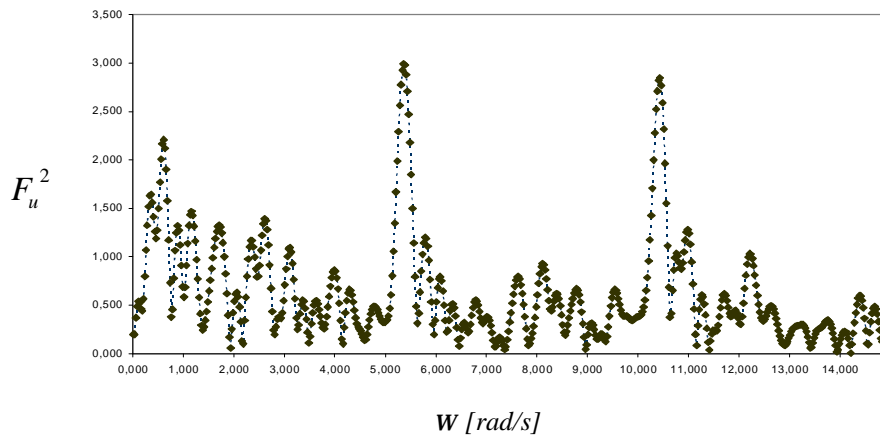The sample graph of the square module of transform is presented in Fig. 11.

Fig. 11 The sample square module of transform of vibration time history

3. The assumption that the vibration of tested structure is the sum of damped harmonic vibrations of different frequencies (damping was described by the replacing viscous model).

$$y(t) = \sum_i \{A_i e^{-b_i t} \sin(w_i^* t) + B_i e^{-b_i t} \cos(w_i^* t)\} ,$$ (2)

$$(w_i^*)^2 = (w_i)^2 - (b_i)^2 ,$$ (3)

4. The approximation of the function history $F_u{}^2$ with the function $F_y{}^2$ described by the following relation:

$$F_y{}^2 = \left(\left| \int_{-\infty}^{\infty} y(t) \frac{1}{\sqrt{2p}} e^{-iwt} dt \right| \right)^2$$ (4)

By approximating, it was assumed that the characteristic points are the extremes modules $F_u{}^2$ and the points lying at 0.5 of the height of these extremes (Fig. 12).
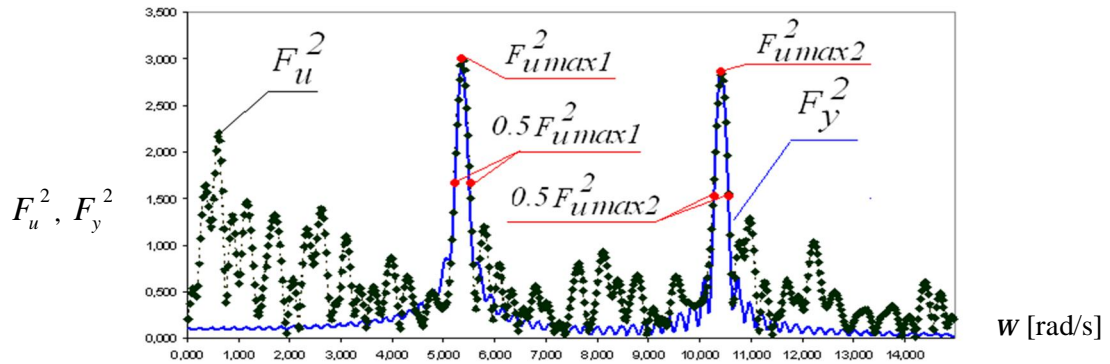

Fig. 12 Approximating function $F_y{}^{\tilde{}}$ and the characteristic points of method.

5. The determination of the following parameters: A_i, B_i, b_i

Markings: A_i, B_i – amplitude, b_i – damping parameter, w_{gi} – circular frequencies of free vibrations w_i^* - circular frequencies of damped vibrations.

As an example, taking into account the above relations, the system of nonlinear equations is obtained to determine the parameters A_i, B_i, b_i. Considering the spectrum with three peak values, nine nonlinear system of equation is achieved with nine unknowns of the form:

$$
\left| \left(\frac{b_1{}^2 \cdot B_1 \cdot 2 \cdot w_i + w_i \cdot B_1 \cdot (w_i^2 - w_{g1}^2) + 2 \cdot b_1 \cdot w_i \cdot A_1 \cdot \sqrt{w_{g1}^2 - b_1^2}}{\sqrt{2 \cdot p} \cdot (4 \cdot b_1{}^2 \cdot w_i^2 + w_i^4 - 2 \cdot w_i^2 \cdot w_{g1}^2 + w_{g1}^4)} \right) \cdot j + \frac{b_1 \cdot B_1 \cdot (w_i^2 - w_{g1}^2) + w_i^2 \cdot A_1 \cdot \sqrt{w_{g1}^2 - b_1^2} - w_{g1}^2 \cdot A_1 \cdot \sqrt{w_{g1}^2 - b_1^2} - w_i^2 \cdot 2 \cdot b_1 \cdot B_1}{\sqrt{2 \cdot p} \cdot (4 \cdot b_1{}^2 \cdot w_i^2 + w_i^4 - 2 \cdot w_i^2 \cdot w_{g1}^2 + w_{g1}^4)} \right) + \\
\left(\frac{b_2{}^2 \cdot B_2 \cdot 2 \cdot w_i + w_i \cdot B_2 \cdot (w_i^2 - w_{g2}^2) + 2 \cdot b_2 \cdot w_i \cdot A_2 \cdot \sqrt{w_{g2}^2 - b_2^2}}{\sqrt{2 \cdot p} \cdot (4 \cdot b_2{}^2 \cdot w_i^2 + w_i^4 - 2 \cdot w_i^2 \cdot w_{g2}^2 + w_{g2}^4)} \right) \cdot j + \frac{b_2 \cdot B_2 \cdot (w_i^2 - w_{g2}^2) + w_i^2 \cdot A_2 \cdot \sqrt{w_{g2}^2 - b_2^2} - w_{g2}^2 \cdot A_2 \cdot \sqrt{w_{g2}^2 - b_2^2} - w_i^2 \cdot 2 \cdot b_2 \cdot B_2}{\sqrt{2 \cdot p} \cdot (4 \cdot b_2{}^2 \cdot w_i^2 + w_i^4 - 2 \cdot w_i^2 \cdot w_{g2}^2 + w_{g2}^4)} \right) + = F_{ui}^2 \\
\left(\frac{b_3{}^2 \cdot B_3 \cdot 2 \cdot w_i + w_i \cdot B_3 \cdot (w_i^2 - w_{g3}^2) + 2 \cdot b_3 \cdot w_i \cdot A_3 \cdot \sqrt{w_{g3}^2 - b_3^2}}{\sqrt{2 \cdot p} \cdot (4 \cdot b_3{}^2 \cdot w_i^2 + w_i^4 - 2 \cdot w_i^2 \cdot w_{g3}^2 + w_{g3}^4)} \right) \cdot j + \frac{b_3 \cdot B_3 \cdot (w_i^2 - w_{g3}^2) + w_i^2 \cdot A_3 \cdot \sqrt{w_{g3}^2 - b_3^2} - w_{g3}^2 \cdot A_3 \cdot \sqrt{w_{g3}^2 - b_3^2} - w_i^2 \cdot 2 \cdot b_3 \cdot B_3}{\sqrt{2 \cdot p} \cdot (4 \cdot b_3{}^2 \cdot w_i^2 + w_i^4 - 2 \cdot w_i^2 \cdot w_{g3}^2 + w_{g3}^4)} \right) \right|^2
$$ (5)

where: $i = 1…9$, and $W_{g1} = W_2$, $W_{g2} = W_5$, $W_{g3} = W_8$ - resonant frequency, j- imaginary unit of complex number.

As it is can be seen from the above relations, in the following equations, the variables w_i i F_{ui}^2 assume the values listed in Tab. 4. The graphic illustration of the characteristic points is shown in Fig. 13.

Table. 4.

The values of variables w_i and F_{ui}^2 in a system consisting of nine nonlinear equations

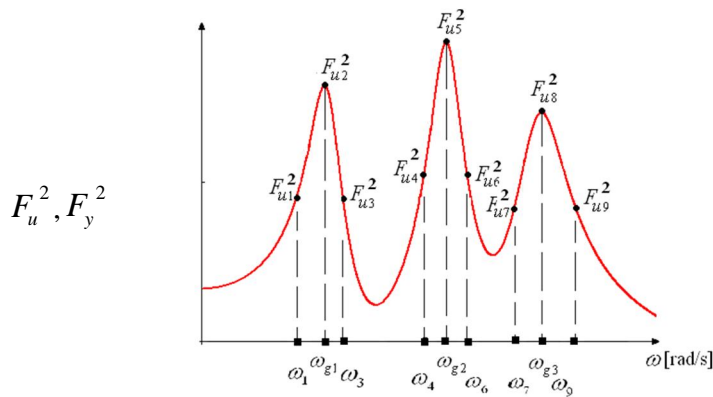| Equations	1	2	3	4	5	6	7	8	9
W_i	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9
F_{ui}^2	$0.5F_{u\max 1}^2$	$F_{u\max 1}^2$	$0.5F_{u\max 1}^2$	$0.5F_{u\max 2}^2$	$F_{u\max 2}^2$	$0.5F_{u\max 2}^2$	$0.5F_{u\max 3}^2$	$F_{u\max 3}^2$	$0.5F_{u\max 3}^2$

Fig. 13 The values of w_i i F_{ui}^2 in the case of three extremes

The systems of nonlinear equations were solved by using the program Mathcad 11. It contains three methods of solving the nonlinear equations, which are: compressed gradient method, Levenberg-Marquardta and Quasi-Newton ones.

The peak amplitudes of spectra not differing from the value of maximum peak of more than 30% were taken into account in the calculations. The results of logarithmic decrement of damping relating to the three models (5%, 20%, and 40% of zeolite content in the concrete mix) are presented in Fig. 14. The treatment of the data, used in the collocation method was performed in Catman program 5.0. The outcomes of the third mode of vibration associated with the third model were rejected due to its negligible share in the spectra.
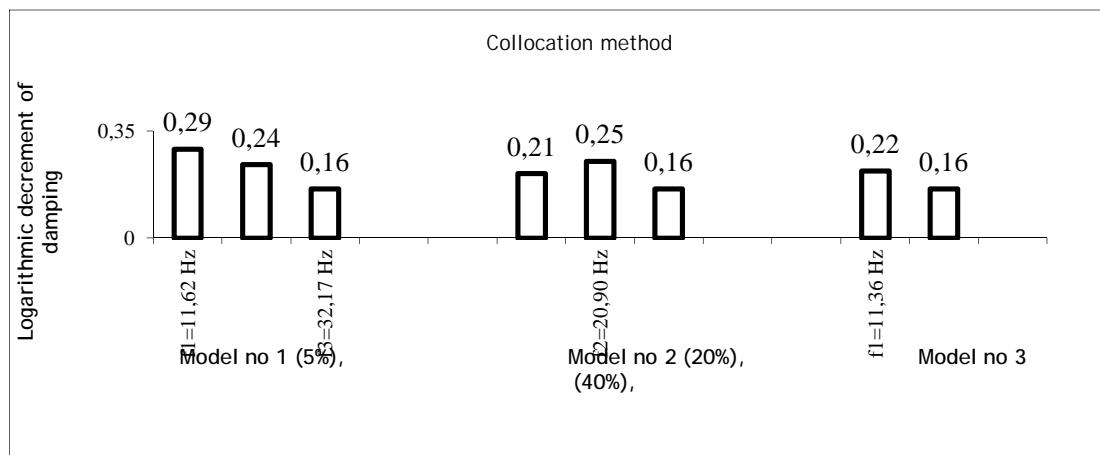

Fig. 14 The average values of the logarithmic decrement of damping of the first, second and third mode of vibration obtained by using the collocation method.

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The method based on the estimation of kinetic energy

The damping values were determined using the basic assumptions of the energy method [6, 7, 9] and basing on the kinetic energy of the system according to [8]. The damping coefficient is determined by taking into account the maximum kinetic energy E_{ij}. The kinetic energy can be expressed in the following form:

$$E_{ij} = \frac{1}{2} \varphi_i^T \mathbf{M}_j \varphi_i w_i^2 \qquad (6)$$

where: $\mathbf{M}_j$ - the inertia matrix of the j-th material in the structure (or the part of the structure); w_i - circular frequency of free vibration of i-th mode; φ_i - normalized eigenvector of the i-th mode of vibration

The value of the logarithmic decrement of damping with respect to the i-th mode of vibration is:

$$\Delta_i = \frac{1}{2} \frac{\sum\limits_j E_{ij} d_j}{\sum\limits_j E_{ij}} \qquad (7)$$

where: E_{ij} - the share of kinetic energy of the j-th material in the structure at i-th mode of vibration;

d_j - logarithmic decrement of damping associated with the material according to [9]

Logarithmic decrements of damping of vibration corresponding to the modified concrete in the energy method were assumed so that the values of damping coefficients of vibration corresponding to the particular mode of vibration, calculated considering the two methods, were similar. The second mode of free vibration of models was chosen because this mode of vibration was characterized by the vibration of a reinforced concrete plate mostly. Such a situation almost exclusively corresponds to the impact of the plate on vibration, and so on the damping of vibration. For the steel double-T bar, it is assumed that $d_s=0,05$, for reinforced concrete $d_z=0,24$ (model with 5% content of zeolite), $d_z=0,25$ (20% content of zeolite) $d_z=0,16$ (40% content of zeolite).

By using the formula (1), the energy values are obtained (Fig. 15), while Tab. 5 shows the values of three models for the second mode of free vibration.
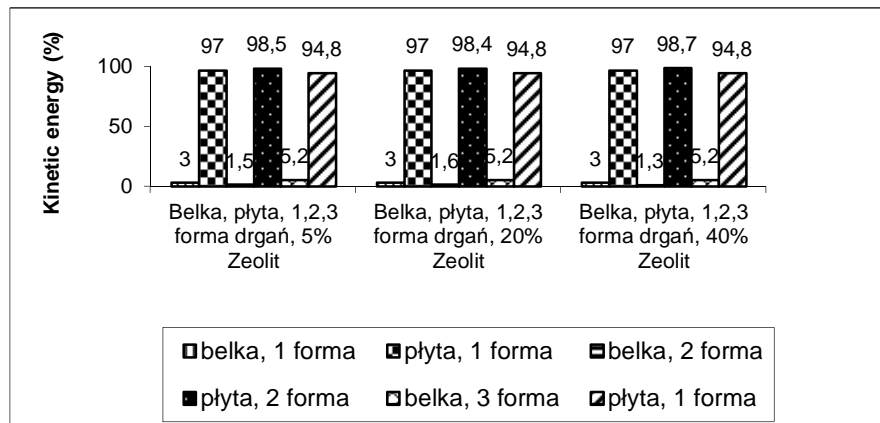

Fig. 15. The proportions of kinetic energy 1, 2, 3 modes of free vibrations of models with 5%, 20%, 40% content of zeolite.

Table 5.

The values of logarithmic decrement of damping, the second mode of vibration of three plate models.

Model	2 mode of vibration
Nr 1 (5% Zeolit)	0,237
Nr 2 (20% Zeolit)	0,247
Nr 3 (40% Zeolit)	0,158

As it can be seen, the above mentioned principle of determining the damping parameters is appropriate. In order to identify the effect of zeolite on the concrete more accurately, it is necessary to perform a larger number of models to conduct more research.

Summation

The first three modes of free vibration of models (collocation method) were taken into account while determining the damping. The first mode is characterized by the rotation of double-T bars and the vertical displacement of a plate which deforms in a small degree. The second mode of vibration is the symmetric vibration of a double-T bar and plate. The third mode is the antisymmetric vibration of a plate and double-T bar. Considering the results obtained by using the collocation method, it can be observed that there occurs a considerable decline in the value of the logarithmic decrement of damping of vibrations in the model no. 2 and 3, which refers to the first mode of vibration. Considering the second mode of vibration, which should show the impact of zeolite on the damping level of vibration the most accurately, there occurs the increase in the damping level of the second model, and a substantial decrease in damping for model 3. It seems that it relates to the irreversible changes in the structure of a model plate 3 by too much content of zeolite, which results in greater demand for water. This is also confirmed by the decrease in the compressive strength. Model No.2 with the increase in the compressive strength values is characterized by a slight increase in the value of logarithmic decrement of damping of vibration. Summing up, the models 1 and 2 show almost the same damping level, hence, the replacement of 5% or 20% of Portland cement with zeolite results in obtaining almost the same level of damping of vibration.

Further research will be conducted on models with the content of zeolite, not only as a binder but also as an aggregate.

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