Estimation of the Dynamic Characteristics of the Foam Concrete

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Abstract. Dynamic properties of the building materials are not often under investigation because of complexity and difficulty of the dynamic problems, which need to be solved. Foam concrete (FC) is a material that has wide application and utilization in the civil engineering structures. FC is a mixture of cement, water, additives and technical foam and principle of fabrication is well known for more than 30 years. Currently, it is mainly used in the floor structures of the buildings, thus static parameters are investigated. Its usability can be much wider thanks to its specific properties. A research aimed at the application of the foam concrete in the pavement structures takes place at our workplace. FC could be utilized as a sub-base layer at the road reconstructions, excavations or as a structure layer of the new pavements. This paper presents the preliminary outputs of the experimental and numerical analyses of the selected dynamic properties of the FC. Results were obtained from the dynamic hammer testing and the Finite Element (FEM) simulation as a background for the design procedure of the pavement structures. Relevant dynamic parameters such as dynamic modulus of elasticity at low strain or damping parameters were determined in this article. This paper is also aimed at the estimation of the Rayleigh damping coefficients. For the Rayleigh damping coefficients, a half-power bandwidth method was selected. Conclusions indicate some dispersion of the observed quantities and further testing and analysis to increase the reliability of the determined characteristics is required. Obtained dynamic parameters will be a background for the pavement design using the FC.

1. Introduction

FC is a mixture of cement, water, additives and technical foam and principle of fabrication is well known for more than 30 years. It is a material with good mechanical properties [1, 2], low thermal conductivity and simple and high technological treatment, [3-5]. FC consists of closed void pores what allows to achieve low bulk density and spare of input materials. Thanks to its properties, it is usable as a replacement of conventional granular or bounded sub-base layers of the industrial floors, the transport areas or as a part of the foundation structures of the buildings. The foam concrete can be used as a sub-base layer at the road reconstructions, excavations or as a structure layer of the new pavements [6, 7]. Following the preparation of the large scale physical tests, preliminary numerical simulations will be carried out to identify the boundary condition of the design procedure for the application in the pavements. Relevant dynamic parameters such as dynamic modulus of elasticity at low strain or...
damping should be determined. This paper is aimed at the estimation of the Rayleigh damping coefficients.

2. Material damping
Material damping in engineering practice is defined as a reduction of the movement caused by the passive resistance of the material. It is the ability of the system to dissipate the energy during structure movement. Throughout the dissipation, the kinetic energy transforms to other energy types that dispersed into the structure. This process causes the attenuation of the vibrations and impacts what provides a certain safety level against dynamic loading of the structure except the specific situations such as the resonance.

2.1 Rayleigh damping
Rayleigh damping is a convenient way to take into account the damping of particular materials of the model in the numerical simulation but determining the relevant parameters with sufficient reliability requires experimental measurements [7, 8]. Due to complexity of the large scale physical models with several uncertainties in the boundary conditions, foam concrete specimens were separately tested in the laboratory to obtain foam concrete parameters at defined boundary conditions.

The damping proportional to the mass and the stiffness, normally referred to as Rayleigh damping, is commonly used for linear and nonlinear dynamic analysis. It is suitable for an incremental approach of a numerical solution. In the discrete systems, especially when FEM method is utilized, Rayleigh's damping is introduced. Rayleigh damping is expressed using a Rayleigh damping matrix which is given by:

\[
[b] = \alpha \cdot [m] + \beta \cdot [k],
\]

where \([m]\) is a mass matrix and \([k]\) is a stiffness matrix. The first member on the right side of the equation expresses attenuation proportional to the displacement velocity. The second member expresses attenuation of the velocity of the deformation [9, 10].

If the damping ratios for the \(i\)-th and \(j\)-th modes are \(\zeta_i\) and \(\zeta_j\), then the Rayleigh coefficients \(\alpha\) and \(\beta\) are calculated from the solution of the two algebraic equations:

\[
\begin{bmatrix}
\frac{1}{\omega_i} & \omega_i \\
\frac{1}{\omega_j} & \omega_j
\end{bmatrix}
\begin{bmatrix}
\alpha \\
\beta
\end{bmatrix}
=
\begin{bmatrix}
\zeta_i \\
\zeta_j
\end{bmatrix}
\]

2.2 Experimental estimation of coefficients \(\alpha\) and \(\beta\)
To estimate the Rayleigh coefficients, two damping ratios with the corresponding frequencies need to be determined. If we assume that these frequencies are the natural frequencies of the dynamic system, we must excite the system with a specific way to obtain the peak frequencies for the first significant vibration modes. This could be sometimes difficult to achieve so another approach was adopted in this paper.

Two methods to determine the material damping ratio were considered: logarithmic decrement method and half-power bandwidth method, [10]. In this case a half-power bandwidth method was selected because only one successful peak should be achieved and this peak can be related to the dominant frequency of the system. Frequency response function (FRF) of the system must be obtained to use this method. Hammer or shaker tests can be performed to obtain FRF function. Peaks at the FRF show natural or dominant frequencies of the system \(\omega_n\). Two points that correspond to the half-power bandwidth are selected, 3 dB down from the top of the peak, as shown in the figure 1.
The damping ratio $\zeta$ for the corresponding natural or dominant frequency $\omega_n$ ($\omega_i$ or $\omega_j$) can be calculated once the corresponding frequencies $\omega_i$ and $\omega_j$ are read. Material has more damping potential if the frequency range between investigated points is wider [8]. The damping ratio can be expressed as:

$$\zeta = \frac{\omega_1 - \omega_0}{2\omega_n}$$

(3)

The Rayleigh coefficients are then calculated as follows:

$$2\zeta_i\omega_i = \alpha + \beta\omega_i^2, \quad 2\zeta_j\omega_j = \alpha + \beta\omega_j^2$$

(4)

$$\alpha = \frac{2\omega_i\omega_j(\zeta_j\omega_j - \zeta_i\omega_i)}{\omega_j^2 - \omega_i^2}, \quad \beta = \frac{2(\zeta_j\omega_j - \zeta_i\omega_i)}{\omega_j^2 - \omega_i^2}$$

(5)

3. Experimental testing

Inputs for the analysis were obtained from experimental observations in the laboratory. The foam concrete specimens with the age of 28 days were prepared for the selected nominal bulk densities. Bulk density represents the density of the dry specimen after drying procedure. A total of 4 samples for each density were tested. The nominal dimensions of the test blocks were 100 × 105 × 400 mm. To obtain a frequency response function (FRF), each block was at one side bonded to the heavy stand with the large clamp so the cantilever with the free length of 300 mm was created. The vertical hammer test at the upper free end of the block was then performed and the response of the foam concrete specimen was recorded via accelerometers.

4. Numerical simulation

To verify the observed dominant frequencies of the foam concrete specimens, numerical simulation in the software ADINA using the Finite Element Method (FEM) was carried out [9]. The dynamic response of the system in the time domain was solved. For this reason, the dynamic properties of the systems such as natural frequency and shape of the natural vibration are very important. Used method transforms the solution of the continuous systems, to the system with the finite degree of freedom. The basic properties necessary for creating the computational model are the mass and stiffness of the element.
These properties are described by the matrices $[m]$ and $[k]$, which are included in the equation of balance:

$$[m] \dot{\{r\}} + [k] \{r\} = \{0\}$$

(6)

where $r$ is the vector of generalized node displacements $j$ and $h$.

This equation is satisfied by the following particular solution:

$$\{\varphi_{(j)}\} = \{\varphi_{(j)}\}^* \cdot \sin(\omega_{(j)} \cdot t)$$

(7)

If the conditions of orthogonality are fulfilled, the basic characteristic of the natural mode is:

$$\langle \{\varphi_{(j)}\}^T \cdot [m] \cdot \{\varphi_{(h)}\} \rangle = 0 \text{ for } j \neq h,$$

(8)

$$\langle \{\varphi_{(j)}\}^T \cdot [k] \cdot \{\varphi_{(h)}\} \rangle = 0 \text{ for } j \neq h.$$  

(9)

5. Results and discussion

5.1 Experimental testing

The first three dominant frequencies were determined following the response of the foam concrete specimens with the nominal bulk densities 300, 500, 700 and 900 kg/m$^3$ (Figure 2.). Measured bulk densities at the natural moisture content are higher by approximately 100 kg/m$^3$ which is a normal phenomenon.

![Figure 2. First three dominant frequencies with overall trend stripes for each dominant frequency](image)

Results show increase of the dominant frequencies with increasing bulk density. The gap between adjacent peaks is also larger at higher bulk density. On the contrary, lower bulk densities show lower dispersion of the values for particular test specimens. Damping ratios were estimated for the first two dominant frequencies using half-power bandwidth method and their values varied from 1.4 to 3.8% without significant dependency on the bulk density and with smaller dispersion of the values for the second dominant frequency (Figure 3.).
Figure 3. Damping ratio / measured bulk density relation

Calculated values of the Rayleigh coefficients related to the measured bulk densities with some moisture content are plotted in the Figures 4 and 5.

Figure 4. Alpha / measured bulk density relation

Figure 5. Beta / measured bulk density relation

A large dispersion of the Rayleigh coefficients occurs, especially of alpha at lower bulk densities, but overall trend leads to smaller dispersion at higher densities. Generally, relatively high values of alpha
and very small values of beta were determined. Alpha coefficient represents the damping proportional to the material mass. We assume that porous structure of the foam concrete with large amount of air closed in the pores allows to achieve higher damping what results in higher values of alpha. Beta is related to the damping proportional to the material stiffness which is very low in this case. Obtained values of beta oscillate slightly above the zero value. The results seem to be reliable in terms of overall trend but further measurements need to be carried out to verify the reliability of the estimated values.

5.2 Numerical simulation

These mathematical solutions are directly integrated in ADINA software. At given Poisson’s ratio of 0.25 determined by the laboratory testing, the dynamic modulus of elasticity was iterated to match the first dominant frequency obtained from the experiment. Linear elastic material model was adopted. The typical first six undamped vibration modes are plotted in the Figure 6.

![Figure 6. First six vibration modes of the specimen and corresponding undamped natural frequencies, \(f_1 = 133.6\) Hz, \(f_2 = 136.8\) Hz, \(f_3 = 409\) Hz, \(f_4 = 621.7\) Hz, \(f_5 = 642.4\) Hz, \(f_6 = 663.4\) Hz for the nominal bulk density of 500 kg/m\(^3\).](image)

Computational simulation shows, that the natural frequencies for the first two vibration modes are very close to each other what is caused by the similar cross section dimension in both of horizontal and vertical direction. The small gap between the first two natural frequencies is determined by the mass action in particular directions of vibration (Figure 6.). Despite of matching the spectrum peak related to the first natural frequency, others do not fit the frequency spectrum obtained from the experimental testing. This phenomenon occurred because probably only second vibration mode of the specimen was achieved during vertical load of the hammer test when mostly vertical vibrations took place. Higher modes required combined loading including torsion and sufficient density of the accelerometers. It can be supposed that this type of loading does not occur in the sub-base layer of the pavement. Higher vibration modes have also less influence on the formation of the resonant states of the structure because of lower probability of occurrence of such type of dynamic loading. Frequencies determined from the experiment should be then considered as dominant frequencies rather than natural (Figure 2.).

6. Conclusions

The aim of the experimental testing and numerical simulation was to determine the dominant frequencies for selected bulk densities of the foam concrete and calculate the Rayleigh damping coefficients. These characteristics can be utilized for dynamic analyses of the structures with the foam concrete [7,8,11-13].
Estimated values of the Rayleigh coefficients $\alpha$ and $\beta$ indicate good damping potential of the foam concrete at lower frequencies what can be a benefit at the pavements in the built-up areas. Together with the decent stiffness properties, when static modulus of elasticity reaches 1.2 GPa for the compression loading and 0.6 GPa for the flexural loading at nominal bulk density of 500 kg/m$^3$, the FC can substitute the conventional upper sub-base layers of the pavements, even bounded one. Results presented in this paper show some dispersion of the observed quantities and further testing and analysis to increase the reliability of the determined characteristics is required.

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