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# The influence of specimen size on the dynamic properties of lightweight concrete determined by the resonance method

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**Abstract.** The paper examines the way specimen size influences measurements by the resonance method. The experiment was performed with a lightweight concrete with a porous aggregate (Liapor). Several sets of specimens were made; they differed both in size and type (drilled cylindrical cores, cast prisms). All the specimens were tested for the natural frequency of longitudinal, transverse, and torsional vibration, which were then used to calculate values of the dynamic modulus of elasticity. The outcome of this experiment is a statistical analysis of the test results.

## 1. Introduction

Concrete, being the most widely used building material, is subject to strict requirements set by the modern society. For some time now, its quality has not been assessed on the basis of compressive strength only. Today, there are also environmental factors or matters of sustainability to consider [1, 2], which is naturally reflected in the requirements. Both the industry and researchers are still more frequently concerning themselves with properties that have to do with concrete durability (and by extension the service life of concrete structures), such as surface permeability or shrinkage [3, 4].

The modulus of elasticity (Young's modulus) plays an important role in this regard. A current trend in civil engineering is to build very slender and elegant structures, something which cannot be achieved without prestressing. Whole structures or their parts are thus susceptible to various strains and may experience vibrations, deflections, cracking, or creep. Young's modulus is closely linked with all these phenomena [5, 6]. Young's modulus also functions in the most advanced model of concrete shrinkage, which is a numerical model designed by a team led by professor Z. P. Bažant [7].

Thanks to a wide choice of available lightweight aggregate (with a broad range of bulk density, particle size, and strength), a high-quality lightweight concrete can be designed with a great spectrum of compressive strength and bulk density. Lightweight concrete can be used as an open-structure concrete for thermal insulation as well as dense lightweight structural concrete [8, 9]. Lightweight concretes have been used in Scandinavia and Canada for decades; however, in recent years lightweight concrete structures have been spreading all over the world [8, 10, 11]. One of the benefits of lightweight concrete is that it reduces the vertical load of the structure, precast elements are less costly to transport, requiring less heavy machinery for handling. Its other strong points are good thermal insulation properties (proportional to bulk density), better durability (determined by less severe shrinkage and lower permeability, stronger interfacial transition zone, and excellent freeze-thaw resistance), and, when the lightweight aggregate is made from industrial by-products, it is more eco-friendly. On the other hand, some downsides are that the concrete can be brittle if designed as a structural concrete with higher



strength (due to the high strength of the cement paste), higher temperature during ageing due to more hydration heat, or difficulties with pouring or pumping because of the high water absorption of the lightweight aggregate [8, 12].

## 2. Experiment

The experiment used the resonance method to determine selected dynamic parameters of lightweight concrete using specimens of varying size. The goal was to ascertain to what extent the specimen size can affect the value of the modulus of elasticity.

### 2.1. Material

A lightweight concrete with a lightweight aggregate (Liapor) was designed. Both fractions of this aggregate were pre-soaked in water for 24 hours prior to mixing. The composition of the lightweight concrete is detailed in table 1. The water/cement ratio was 0.46 and the concrete was defined using fresh-state and 28-day properties; see table 2.

**Table 1.** Fresh concrete composition.

Component	Content per 1 m <sup>3</sup> of fresh concrete (kg)
Cement CEM II/B-S 32.5 R	450
Sand 0/4 mm (Bratčice)	776
Aggregate Liapor 1/4 mm	52
Aggregate Liapor 4/8 mm	198
Admixture Sika VZ 10	0.68
Admixture Sika Stabilizer-4R	0.45
Water	208

**Table 2.** Concrete properties in fresh state (FS) and hardened state (HS) at 28 days of age; the number in brackets is the sample standard deviation.

Property	Value
Flow value (FS)	450 mm
Bulk density (FS)	1,620 kg/m <sup>3</sup>
Cubic compressive strength (HS)	23.4 (1.0) N/mm <sup>2</sup>
Cubic tensile splitting strength (HS)	2.40 (0.08) N/mm <sup>2</sup>
Bulk density (HS)	1,640 (28) kg/m <sup>3</sup>
Water content (HS)	13.4 (0.1)%

### 2.2. Test specimens

The experiment used 6 cubes of 150 mm, 8 prisms with the nominal dimensions of 100 × 100 × 400 mm (henceforth P100), 3 prisms of 150 × 150 × 600 mm (P150) and one prism of 300 × 300 × 900 mm (P300). All the specimens except for the largest prism were compacted on a vibration table; prism P300 was compacted with an immersion vibrator (figure 1). When the moulds were filled with the fresh concrete, they were covered with a PE sheet and stored on a level surface under standard laboratory conditions. The concrete aged in the moulds for 3 days, after which it was removed and placed under water. The exception was once again prism P300, which was left in the mould - it was thoroughly sprinkled with water, covered with several layers of wet fabric and wrapped in a PE sheet. At the age of 28 days all the specimens were removed from the water and prism P300 was demoulded.



**Figure 1.** Manufacturing of a prism of  $300 \times 300 \times 900$  mm (P300).



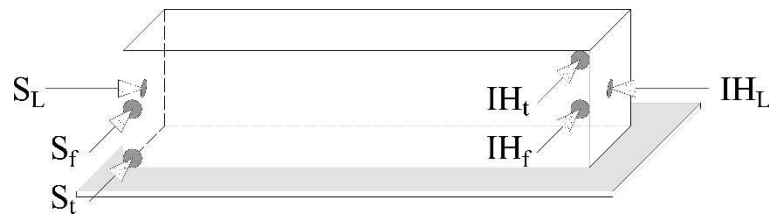
**Figure 2.** Drilling cores from prism P300.

Next, 3 cube specimens were tested for compressive strength and the other 3 for shear splitting strength; the strength data was supplemented with a determination of bulk density. Moisture content was also measured on all 6 cubes after the strength tests. Table 2 lists all this data. The other specimens were left in standard laboratory conditions without any curing for 15 more months; the dynamic properties were therefore measured at the age of approximately 16 months. After the measurements by the resonance method, core samples were drilled from prism P300 - 6 had the nominal dimensions of  $150 \times 300$  mm (figure 2), 6 of  $100 \times 300$  mm, and 6 of  $75 \times 300$  mm. The cores were left in laboratory conditions for a week so that all the water that was used during the drilling could evaporate. Afterwards the cores (henceforth CS) were tested by the resonance method.

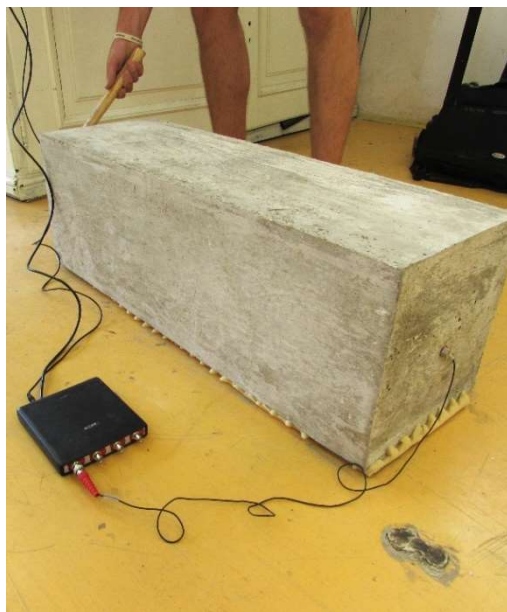
### 2.3. Resonance method

Any solid body begins to vibrate when excited by an external impulse. This vibration can take several forms; however, the assessment of the dynamic material properties of regular bodies is performed only with the natural frequencies of longitudinal ( $f_L$ ), torsional ( $f_t$ ), and flexural ( $f_f$ ) vibration [13, 14]. During resonance the amplitude of the vibration in the specimen rapidly increases at the moment when the excitation force frequency is identical to the natural (i.e. resonance) frequency of the specimen – this holds as long as the external impulse is continuous (it lasts for a longer time). However, the basic resonance frequently can also be determined using interrupted (impulse) vibration – in this case the impulse is typically a mechanical strike of an impact hammer [15]. Using an accelerometer and a Fourier analyzer the natural frequency of the specimen's vibration can be easily determined. The position of the accelerometer and the point of impact is shown in figure 2.

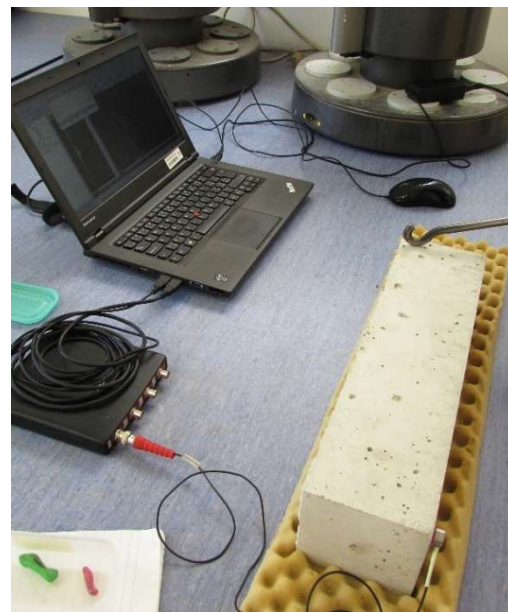
The actual measurement of natural frequencies was performed using a Handyscope HS4 oscilloscope with an acoustic emission sensor. The frequencies were evaluated using a software (an accessory to the oscilloscope), which operates on the basis of fast Fourier transformation. Figure 4 shows the determination of  $f_L$  on prism P300, figure 5 shows the determination of  $f_t$  of prism P100. Following the standard ČSN 73 1372 [16], Young's modulus  $E_{crL}$  the dynamic shear modulus  $G_{cr}$  were calculated.



**Figure 3.** Position of the sensors (S) and the impact hammer strike point (IH) during the measurement of the natural frequencies of longitudinal (L), flexural (f), and torsional (t) vibration.



**Figure 4.** Determination of the natural frequency of longitudinal vibration in prism P300.



**Figure 5.** Determination of the natural frequency of torsional vibration in prism P100.

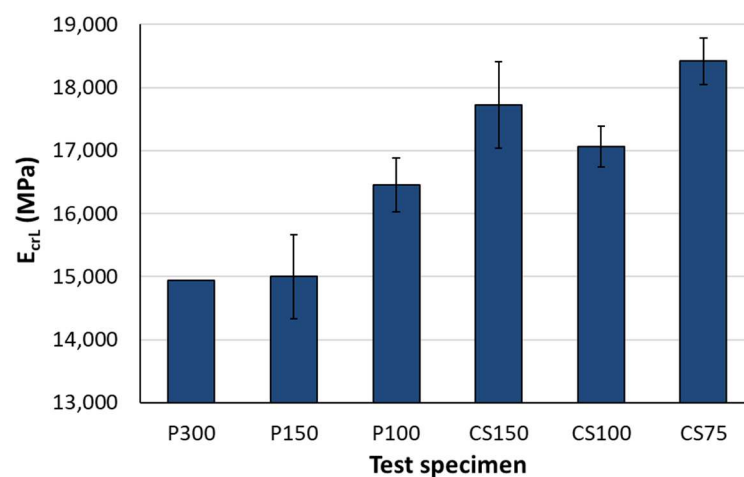
### 3. Results

The values of the dynamic modulus of elasticity  $E_{crL}$  and  $G_{cr}$  for the lightweight concrete with Liapor are plotted in figure 6 and 7. Results for the prism of  $300 \times 300 \times 900$  mm are only represented by one value, because there was only one specimen of these dimensions. Results for the prism of  $150 \times 150 \times 600$  mm are represented by three values, results for prism P100 by eight values, and results for all the cores are represented by six values. The graphs show the average values for each specimen set and the error bar represents sample standard deviation (except for prism P300, of course).

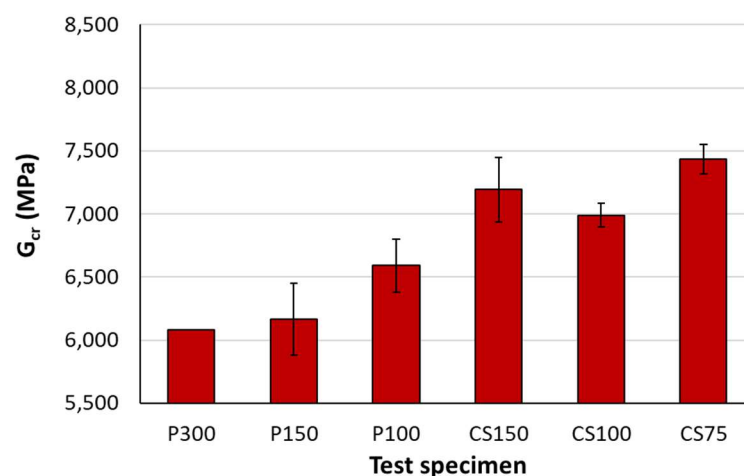
All data sets (i.e. the values of the dynamic parameters measured on all specimens – again with the exception of set P300, which consisted of a single prism) were first checked for data normality on a significance level of 0.05. The results for each set were statistically compared using a two-sample *t*-test, again on a level of significance of 0.05. The statistical test was set so as to compare the equality of the mean values of the test results. If the hypothesis is rejected, the result sets can be considered different with a statistical significance.

The statistical analysis shows that Young's modulus  $E_{crL}$  as well as the shear modulus  $G_{cr}$  measured on the core specimens are different with a statistical significance from the values measured on the prism specimens. Results for prism P300 could not be included in the statistical comparison – this is why it is only possible to say that the dynamic parameters reached the lowest values; however, when compared to prisms P150 this difference is only very small. Although the values of dynamic parameters measured

for prisms P100 are on average higher than prisms P150, they do not differ with a statistical significance. Similarly, the results for each test set of core specimens do not bear a statistically significant difference either. The above applies to both properties being examined. Basically the same conclusions were drawn by [17, 18], the only difference being that they determined the Young's modulus either by the ultrasonic pulse velocity test or the static test. The influence of specimen size was investigated e.g. by [19], and with similar results, only they used a different property as the evaluation criterion.



**Figure 6.** A bar chart of the average values of dynamic Young's modulus; the error bar represents the sample standard deviation.



**Figure 7.** A bar chart of the average values of dynamic shear modulus; the error bar represents the sample standard deviation.

#### 4. Conclusion

The experiment results indicate that the larger the prism specimen, the smaller (but only slightly) the value of  $E_{crL}$  and  $G_{cr}$  when measured by the resonance method. In cast specimens, this conclusion applies only to the mean values of the data sets, because this decrease is not statistically significant. It must also be emphasised that the difference in the specimen size was not particularly large – it would therefore be interesting to expand the experiment by specimens that have a volume in orders of cubic metres.

In the case where core specimens were drilled from a larger specimen (a prism with the dimensions of  $300 \times 300 \times 900$  mm), the influence of specimen size on the results is statistically significant on



a significance level of 0.05. The moduli of elasticity  $E_{crL}$  and  $G_{cr}$ , determined by the resonance method on the core specimens, reached 114 to 123% the value of the same parameter determined by the same method on prism P300, from which they were drilled.

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