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The influence of concrete composition on Young's modulus

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Abstract

This paper presents a dynamic method of concrete testing using Young’s modulus. The advantages of the method are compared with the static method and the possibilities of application in practice are discussed. The procedure for concrete dynamic Young's modulus testing is presented. Young’s modulus of concrete samples of different compositions have been tested by static and dynamic methods. Conclusions related to Young's modulus of concrete values obtained from static and dynamic testing methods and the influence of concrete composition on these values, have been drawn.

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1. Introduction

Young's modulus is a very important material property due to its influence on strains of material under load, and hence displacement of structure. Engineers need to know the value of this parameter to conduct any computer simulation of structure behavior. In the case of concrete, Young's modulus value is connected to compressive strength, which increases with the progress of the hydration process of cement, in a similar way. Monitoring this parameter is therefore important.

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Vibration monitoring is one of the most important nondestructive testing (NDT) methods of structural health monitoring. In this method, the mode shapes of a structure are used as a simple and efficient means of characterising resonance vibration. Resonance vibration is caused by the interaction between the inertial and elastic properties of a material. Vibration monitoring could be useful since nearly all engineering structures can be made to resonate [1].

The advantage of the vibration monitoring method is the global nature of the identified frequencies [2], but the most important benefit it is that vibration monitoring is non-destructive testing method and it can be applied many times to the same test object. Structural damage in an engineering system leads to modification in vibration modes. Changes in resonate frequency values, mode shapes and modal dumping indicate possible damage of tested system. A change of modal characteristics depends on the nature, location and severity of damage [2]. The use of vibration monitoring method to assess damage of concrete is presented, for example in [3,4,5].

Compressive strength is the indicator of the Young's Modulus of concrete. There are a few experimentally achieved equations showing relationships between those two parameters [6]. It should be noted that the value of Young's modulus of concrete depends on many other factors such as moisture, the percentage of aggregate volume, density, and aggregate type.

Assuming that the relationship between the dynamic Young's modulus of the concrete and its compressive strength is determined, the vibration monitoring method can be useful for continuous monitoring of concrete compressive strength increases. It is important due to the pressure exerted on civil engineering to provide shorter schedules of building [7]. Continuous monitoring of compressive strength increases could be beneficial in prefabrication plants. The necessary curing time before form removal could be specified based on the vibration monitoring method. The proposal for the continuous monitoring of the Young's modulus of concrete since casting was presented by the authors in [8,9]. Another innovative application of the vibration monitoring method is stiffness reconstruction using rotation rate sensors. The preliminary results of the application of this method are presented in [10].

There are a few normalised methods of assessing the elastic properties of material using the vibration monitoring of specimens such as the American Society for Testing and Materials [11], Deutscher Ausschaussfür Stahlbeton [12] and Polish/European standard [13]. It should be noted that the latter is dedicated to refractory product testing. These standards use nearly the same procedures of testing, the main difference is in using various correction factors which depends on sample dimensions.

In this paper, Young’s modulus for different compositions of concrete was tested using static and dynamic methods. Effects of the kind of aggregate and compressive strength class were taken into consideration. A comparison of Young's modulus values obtained from static and dynamic testing were made. The correctness of the theoretical relationships between Young's modulus and compressive strength was also investigated.

2. Materials

For the purpose of this investigation, three concrete mixes were designed: Self-Compacting Concrete (SCC) and High Performance Concrete (HPC). The mixes varied significantly in aggregate content. The HPC mix was characterized by higher aggregate content compared to SCC. HPC mix (C3) was made using basalt aggregate. In the case of SCC mixes two kinds of aggregate were used: basalt (C1) and natural (C2). SCC mixes were contain ant-washout admixture which makes them appropriate for underwater use.

The concrete mixes were prepared using cement CEM III A 42.5N (concretes C1 and C2) and CEM I 42.5R (C3). The chemical composition of the cements is given in Table 1. The phase composition of cement CEM I 42.5R, calculated according to Bogue formulae was as follows: C3S-53.3%, C2S-17.7%, C3A-11.5%, C4AF-10.2% by mass. The specific surface area of CEM I and CEM III were 4230 cm²/g and 4280 cm²/g respectively.
Table 1. Chemical composition of cements (% mass.).

|             | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | K₂O | Na₂O | SO₃ |
|-------------|------|-------|-------|-----|-----|-----|------|-----|
| CEM I 42.5  | 17.9 | 5.8   | 2.9   | 63.1| 1.2 | 0.8 | 0.1  | 2.1 |
| CEM III 42.5| 28.8 | 6.8   | 1.8   | 51.2| 5.3 | 0.6 | 0.7  | 1.9 |

The polycarboxylate superplasticizer (SP) and anti-washout admixture (AWA), based upon the polyoxyethylene cellulose ether were used as admixtures.

Compositions of C1 and C2 mixes were calculated according to Okamura’s and Ozawa’s method [14] as a self-compacting concrete. Mix C2 has a similar volume percentage of components as C1 but contains natural aggregate. Appropriate self-compacting concrete slump flows of C1 and C2 mixes were obtained by using adequate amount of superplasticizer. The composition of concretes C1, C2 and C3 is presented in Table 2.

The volume percentage of components in C1, C2 and C3 mixes were presented in Figure 1. As shown in Figure 1 the volume of aggregate in the case of SCC mixes (C1 and C2) was significantly lower than in the HPC (C3). Slight differences in ingredient volumes between C1 and C2 concrete are a consequence of various shapes of aggregate particles (crushed basalt and natural). These differences could be considered as negligible and in this investigation it was assumed that concrete C1 and C2 had the same volume composition with a different kind of aggregate.

![Figure 1. The volume percentage of concrete components.](image)

Table 2. Composition of concrete mixes (kg/m³).

| Concrete | Cement | Silica fume | Water | Aggregate (mm) | SP (wt. %) | AWA (wt. %) |
|----------|--------|-------------|-------|----------------|-----------|------------|
|          |        |             |       | 0/2  | 2/8 | 8/16 |       |           |
| C1       | 582    | -           | 232   | 846  | 338 | 508  | 2.0   | 1.0       |
| C2       | 585    | -           | 202   | 746  | 299 | 448  | 2.0   | 1.0       |
| C3       | 500    | 50          | 135   | 708  | 572 | 728  | 1.25  | -         |

3. Methods

3.1. Consistency

Fresh concrete mixes were subjected to the appropriate consistency tests. SCC mixes (C1 and C2) were tested...
according to PN-EN 12350-12:2012 (J-ring test). The flow diameter (d_1), flow time (T_{500}) and the difference in height level of the concrete mix in the middle and behind the testing ring (Δh) were measured. The consistency of the C3 mix was tested according to PN-EN 12350-2:2011 (slump test).

Specimens were prepared and cured in water at a temperature of 20±2°C, according to PN-EN 12390-1:2001.

3.2. Compressive strength

The compressive strength tests were performed according to the PN-EN 12390-3:2011 standard after 7, 14 and 28 days. The compressive strength of the concretes were tested using 150 mm cube samples, and 150 mm diameter and 300 mm high cylinder specimens.

3.3. Static Young's modulus

Determination of secant modulus of elasticity in compression was conducted according to PN-EN 12390-13:2014. Tests were performed on 150 mm diameter and 300 mm high cylinders. Parallelism of the top and bottom surfaces of the specimens was achieved by using the sand caps method as it is recommended by PN-EN 12390-13:2014. This method is adequate for both high and normal strength concrete. The loading cycle is presented in Figure 2. Specimens were subjected to pressure in the range of 10% (σ_b) to 30% (σ_a) of estimated failure stress (σ_f). Preloading stress was equal to 2 MPa in each test.

![Fig.2. The secant modulus of the elasticity loading cycle.](image)

3.4. Dynamic Young's modulus

The experimental setup was placed on a massive window sill. A concrete beam of length 500 mm and cross-section 100×44 mm was supported using steel tubes which provided pointed support. The supports were placed at 110 mm from each end of the beam. In this way the theoretical vibration nodes of the first free-free natural mode shape was acquired. This solution prevented interaction with the supports. To prevent high frequency interaction between the steel tubes and window sill thick rubber was applied. The experimental setup is shown in Figure 3.
To measure the translational vibrations two miniature accelerometers, PCB 333B52, were applied. The weight of each accelerometer was 7.5 gm, so the effect on the global mass was insignificant. The first was installed at the edge of beam and the second in the middle. The wires connecting the accelerometers with data acquisition card were fixed using vises to minimise their influence on vibrations.

The first resonant frequency of the beam was calculated using fast Fourier transform on the time history acceleration response. The dynamic Young’s modulus was calculated according to PN-EN ISO 12680-1:2008.

4. Results and discussion

The results of the concrete mixes testing are presented in Table 3. The properties of SCC mix (C1 and C2) meet the requirements for concrete mixes according to the guidelines for self-compacting concrete (EFNARC, 2002). Consistency testing results show that the C2 mix exhibits better flow properties with lower blockage risk (lower Δh) than the C1 mix, despite a lower water/binder ratio. Above mentioned are connected to the type of aggregate used. Applying a basalt aggregate requires a larger amount of water to reach the required flowability than when using natural aggregate. The consistency of HPC mix (C3) classifies it as S3 class according to PN-EN 206-1:2003.

Table 3. Concrete mixes investigations results.

| Concrete mix | Δh (mm) | d5 (mm) | T500s (s) | Slump (mm) |
|--------------|---------|---------|-----------|------------|
| C1           | 16      | 670     | 10        | -          |
| C2           | 11      | 700     | 12        | -          |
| C3           | -       | -       | -         | 130        |

The compressive strength testing results after 7, 14 and 28 days of curing are presented in Table 4. Cylinder samples were tested to check that the applied stress range was appropriate in the modulus of elasticity testing as the PN-EN 12390-13:2014 standard required. Compressive strength tests of the cylinders were conducted after static Young’s modulus testing. The concrete C2 reached an insignificantly higher compressive strength than C1. This is connected with the larger amount of water, that was necessary to achieve required the flowability of the C1 mix. Concrete HPC (C3) reached high compressive strength - over 100 MPa after 28 days.

Table 4. Compressive strength of concretes (MPa).

| concrete | 7 days | 14 days | 28 days |
|----------|--------|---------|---------|
|          | cube   | cyl     | cube    | cyl     |
| C1       | 36.9   | 30.6    | 51.5    | 43.8    |
| C2       | 40.4   | 35.1    | 52.9    | 49.0    |
| C3       | 84.8   | 53.4    | 98.3    | 83.2    |
|          |        |         |         |         | 62.4   | 56.5    |
|          |        |         |         |         | 64.6   | 57.2    |
|          |        |         |         |         | 106.5  | 87.4    |
The results of the secant modulus of elasticity in compression testing are presented in Table 5 and Figure 4. The "A" method was used (according to PN-EN 12390-13:2014), so the initial \((E_{C0})\) and stabilised modulus of elasticity \((E_{CS})\) were calculated. Test results show that in case of concrete containing basalt aggregate (C1 and C3), the values of \(E_{C0}\) are equal to 96% of \(E_{CS}\) values, while in C2 concrete it is 93%.

Table 5. The secant elastic modulus of concrete specimens from the compression test (GPa).

| concrete | 7 days | 14 days | 28 days |
|----------|--------|---------|---------|
|          | \(E_{C0}\) | \(E_{CS}\) | \(E_{C0}\) | \(E_{CS}\) | \(E_{C0}\) | \(E_{CS}\) |
| C1       | 33.9   | 35.9    | 39.8    | 41.2    | 42.9    | 43.7    |
| C2       | 29.3   | 31.9    | 31.4    | 34.0    | 35.4    | 37.3    |
| C3       | 53.1   | 55.0    | 56.6    | 59.3    | 57.8    | 59.5    |

Figure 5 presents the relationships between compressive strength and Young's modulus of concrete proposed by Kakizaki and others (Eq. 1) and according to ACI 318-89 and ACI363R-92 - respectively for the compressive strength of concrete below 83 MPa (Eq. 2) and over 83 MPa (Eq. 3).
where: \( E \) - Young's modulus of concrete, \( f_c \) - compressive strength, \( \rho \) - density. The test results were presented in Figure 5. In the case of concrete containing basalt aggregate (C1 and C3), significant differences were observed between in research results in comparison of these relationships, especially in the case of HPC concrete (C3). The differences between our testing results and the values calculated using relationships proposed by ASTM 318-95 (Eq. 4) are lower. It should be noted that this relationship takes into account not only compressive strength but also concrete density. Values calculated using relationship as proposed by the ASTM 318-95 (for the densities of the concretes C1, C2 and C3), were compared with own testing results and presented in Figure 6. Although Eq. 4 is considered correct in the range of concrete density between 2320 kg/m\(^3\) and 2480 kg/m\(^3\), Figure 6 shows that it can also be successfully used for higher density concrete.

### Table 6. Dynamic Young’s modulus testing results \( E_D \) (GPa).

| concrete | 7   | 14   | 28   |
|----------|-----|------|------|
| C1       | 40.8| 44.3 | 46.7 |
| C2       | 37.6| 39.7 | 42.1 |
| C3       | 56.9| 59.3 | 60.5 |

The dynamic Young's modulus testing results are presented in Table 6. The achieved values (\( E_D \)) were compared with values of the initial elastic modulus (\( E_{C,0} \)) and presented in Figure 7. Taking into account that the dynamic testing was conducted without applied significant stress to the specimens, it is more appropriate to compare dynamic Young's modulus with initial elastic modulus (\( E_{C,0} \)) than with the stabilised (\( E_{CS} \)). As found in other investigations the values of Young's modulus obtained in the dynamic way have proven to be higher (e.g. [6,15]). It was found, that the difference between compared values (\( E_{C0} \) and \( E_D \)) were the smallest for HPC concrete - C3 (about 5%), greater in the case of SCC with basalt aggregate - C1 (about 12 %) and the biggest for SCC concrete with natural aggregate - C2 (about 20%).

![Fig.7. Static and dynamic Young's modulus of concretes C1, C2 and C3.](image-url)
5. Conclusions

- The investigation of SCC concrete mixes demonstrated that concrete with natural aggregates needs significantly less water to achieve the required flowability of concrete mix than concrete with crushed basalt aggregate.
- Young's modulus of concretes testing demonstrated that values obtained with dynamic testing are clearly higher than those obtained with the static testing method.
- The Young's modulus of concrete value (both static and dynamic) for SCC concrete with basalt aggregate is higher than in case of concrete with natural aggregate, although both concretes are characterised by similar compressive strength.
- The results of concretes testing (SCC and HPC) shows, that differences between static and dynamic Young's modulus are lower with an increased volume content of coarse aggregate.

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