Experimental study of the modulus of elasticity of concrete at different ambient temperature

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Abstract. The structural performance of concrete construction and bridges is directly influenced by the strength and the modulus of elasticity of concrete. The modulus of elasticity is an input parameter to the creep compliance important especially in design calculation of large concrete bridges. The development of strength and modulus of elasticity at the early ages depends also on the temperature of the environment during casting and curing of concrete. The effect of ambient temperature on modulus of elasticity is however not assessed by the EN 1992-1-1 [1]. The experimental program was focused on determination of static modulus of elasticity and compressive strength cast and cured at ambient temperature +20°C and temperature -5°C at different time. The paper also formulates preliminary design recommendations applicable in practice.

1. Introduction
The proper execution of concrete is controlled by using adequate recipes and technology process specified by relevant material standards when casting concrete on site [4-6]. The mechanical properties of concrete strength class can achieve different values depending on the concrete composition such as the type of aggregate, type of cement, the w/c ratio and admixtures [10-12]. The various results are obtained by using different testing methods (quasistatic, ultrasonic and resonant frequency) especially at early ages [13, 14]. Ultrasonic measurements provide values of modulus of elasticity that are higher than the values provided by the quasi-static test [12], [15]. The test procedure is not universal in several country [3], [7, 8]. Current knowledge [18-20] indicates that besides the above-mentioned factors, the development of strength and elasticity modulus during the first 28 days depends also on the temperature of the environment during casting and curing of concrete [9], [21]. It is usual that concrete structures and bridges are cast at temperatures below zero degrees Celsius. The hydration of cement requires water to be in liquid state. With low temperatures (or temperatures below zero), hydration might slow down or be stopped completely. This might directly impact the development of concrete properties during the first 28 days. The experimental studies [22, 23] observed that the mechanical properties of concrete are affected by hydration even before the setting time. The available references show [16, 17], [20] that the effect of low temperatures on the development of concrete strength is relatively small, but if the concrete temperature reaches freezing before a certain strength, the concrete will have reduced overall strength. Also the low temperature will affect the modulus of elasticity of concrete. The possible negative effect might be critical especially for structures where the design is governed by SLS criterions (e.g. large span bridges),...
especially given that EN 1992-1-1 might overestimate the modulus of elasticity of concrete even when concrete is cast in ambient temperatures [24, 25].

2. Experimental program
A series of laboratory tests focused on demonstrating the static modulus of elasticity of concrete cast at different temperatures has been performed at the testing laboratory of the University of Žilina in Slovakia. A concrete with a recipe corresponding to concrete class C 30/37 was used.

The test procedure for determination of the static modulus of elasticity in compression has been defined in the Slovak standard STN EN 12390-13 [2] since 2014. The standard code STN ISO 6784 (1993) [3] is valid simultaneously (replaced the STN 73 1319, from 1968). The test of modulus of elasticity according to this standard is recommended for the structures with large expected deflection. This procedure was used for the determination of static modulus of elasticity for cylindrical concrete samples. A series of compressive stress cycles loaded up to approximately 1/3 of the concrete compressive strength measured immediately before the tests of modulus of elasticity. Than the modulus of elasticity is calculated as follows:

$$E_c = \frac{\Delta \sigma}{\Delta \varepsilon} = \frac{\sigma_a - \sigma_b}{\varepsilon_a - \varepsilon_b}$$

where:

$\sigma_a$ – the upper stress at loading [N/mm$^2$],

$\sigma_b$ – the basic stress [N/mm$^2$],

$\varepsilon_a$ – the average strain at loading [-],

$\varepsilon_b$ – the average basic strain [-].

The tests were carried out on 44 cylinders with a diameter of 150 mm and a height of 300 mm, Fig. 1. The specimens were cast from the same concrete composition corresponding to the concrete class C 30/37 used commonly in bridge superstructures. After casting, the specimens were stored in a mold and curing in a room with ambient conditions at (20.0±2) °C during 24 hours. After 24 hours, all specimens were removed from the moulds and stored in freezing and climate chamber, Fig. 2. The 24 concrete cylinder specimens were stored in freezing chamber with a temperature of -5.0 °C. The others 20 specimens were stored in climate chamber with temperature at +20.0 °C.
Thereafter, the four cylinder specimens were tested for each series. The one reference specimen was used for determination of compressive strength and three specimens were tested for secant modulus of elasticity and cylindrical compressive strength.

![Figure 2. Storage of specimens in a) climate chamber and b) freezing chamber.](image)

The specimens were measured at the temperature of +20.0 °C after 3, 7, 14, 21, 28, 90 days and at the temperature of -5.0 °C after 7, 14, 21, 28, 90 days. Total 11 series have been tested.

The top of the specimen has been ground before testing to achieve a parallel surface of both compressive ends. Before the test, the cylindrical compressive strength \( f_{c,cyl} \) was determined for each series. The upper stress level at loading was obtained as approximately 1/3 of cylindrical compressive strength \( (\sigma_a = f_{c,cyl} / 3) \). The basic stress was defined with the value of 0.5 N/mm\(^2\) \( (\sigma_b) \). The special devices-extensometers were used for measuring the changes of the length. The two strain gauges were installed circumferentially at opposite points at the height of the specimen to measure transverse deformation, Fig.3. The modulus of elasticity of the concrete corresponds to the average slope of stress-strain responses captured during cyclic loading.

In the first loading cycle, the specimen was loaded up to \( \sigma_b = 0.50 \) N/mm\(^2\) and recorded the longitudinal strain \( \varepsilon_a \) on both extensometers. Than load was applied at a continuous rate of movement corresponding to a stress 0.60 N/mm\(^2\) per second until a stress level reached the 1/3 of measured compressive strength. The load was kept at this level for 60 seconds and the strain \( \varepsilon_a \) was read. The two additional loading cycle was repeated. The load was kept constant for 60 seconds again and the linear-elastic response of the specimen \( \varepsilon_a \) and \( \varepsilon_b \) was recorded. Then the specimens were loaded to failure and the static modulus of elasticity was calculated, Fig. 3.

![Figure 3. Testing arrangement of a) modulus of elasticity and b) cylindrical compressive strength.](image)
3. Results and discussion
The first tests were performed at 3 days after casting of specimens at temperature +20°C. The results of the static modulus of elasticity and compressive strength are listed in Table 1. The results of tests carried out on specimens at temperature (-5°C) are shown in Table 2. The average compressive strength of specimen tested cast low temperature was about 27 percent lower that the strength of specimen cast at ambient temperature while the modulus of elasticity was only about 17 percent lower. The negative effect of an ambient temperature (below zero) is more visible in the cylinder compressive strength. Development of the compressive strength of concrete over the first 90 days at different ambient temperature is shown in Fig. 4. The comparison of the development of the modulus of elasticity of concrete over the first 90 days at different ambient temperature is shown in Fig. 5.

Table 1. Mechanical properties of concrete cylinders at the temperature -5°C.

| Series | No. of specimen | Density [kg/m³] | Compressive strength f_{ci} [N/mm²] | Compressive strength f_{cmi} [N/mm²] | Modulus of elasticity E_{ci} [N/mm²] | Modulus of elasticity E_{cmi} [N/mm²] |
|--------|----------------|----------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| B-7    | 5*             | 2345           | 31.0                             |                                  |                                  |                                  |
|        | 6*             | 2348           | 30.6                             | 30.7                             | 24 100                           | 23 600                           |
|        | 7*             | 2371           | 31.3                             |                                  | 24 100                           |                                  |
|        | 8*             | 2330           | 29.8                             |                                  | 22 700                           |                                  |
|        | 13*            | 2328           | 33.6                             |                                  |                                  |                                  |
| D-14   | 14*            | 2357           | 29.8                             | 32.5                             | 25 100                           | 25 100                           |
|        | 15*            | 2351           | 31.6                             |                                  | 24 800                           |                                  |
|        | 16*            | 2350           | 35.0                             |                                  | 25 500                           |                                  |
|        | 21*            | 2321           | 34.2                             |                                  |                                  |                                  |
| F-21   | 22*            | 2385           | 35.6                             | 34.6                             | 25 600                           | 25 600                           |
|        | 23*            | 2332           | 34.0                             |                                  | 26 500                           |                                  |
|        | 24*            | 2325           | 34.8                             |                                  | 24 800                           |                                  |
|        | 29*            | 2365           | 33.9                             |                                  |                                  |                                  |
| H-28   | 30*            | 2342           | 38.0                             | 37.0                             | 26 800                           | 26 000                           |
|        | 31*            | 2320           | 37.2                             |                                  | 24 800                           |                                  |
|        | 32*            | 2363           | 38.8                             |                                  | 26 300                           |                                  |
|        | 37*            | 2405           | 37.9                             |                                  |                                  |                                  |
| J-90   | 38*            | 2339           | 40.9                             | 39.2                             | 27 100                           | 26 600                           |
|        | 39*            | 2340           | 40.7                             |                                  | 26 000                           |                                  |
|        | 40*            | 2305           | 37.1                             |                                  | 26 700                           |                                  |

Figure 4. Measured compressive strength of concrete.
Table 2. Mechanical properties of concrete cylinders at the temperature +20 °C.

| Series | No. of specimen | Density $\rho$ [kg/m$^3$] | Compressive strength $f_{ci}$ [N/mm$^2$] | Compressive strength $f_{cm,i}$ [N/mm$^2$] | Modulus of elasticity $E_{ci}$ [N/mm$^2$] | Modulus of elasticity $E_{cm,i}$ [N/mm$^2$] |
|--------|----------------|---------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| A-3    | 1              | 2312                      | 35.7                                | 36.4                                | 25 400                              | 25 600                              |
|        | 2              | 2349                      | 35.4                                | 36.4                                | 25 400                              | 25 600                              |
|        | 3              | 2348                      | 37.3                                | 42.2                                | 28 500                              | 28 500                              |
|        | 4              | 2344                      | 37.4                                | 42.2                                | 28 500                              | 28 500                              |
|        | 9              | 2345                      | 41.6                                | 44.6                                | 29 600                              | 29 900                              |
| C-7    | 10             | 2343                      | 43.5                                | 47.6                                | 29 300                              | 31 000                              |
|        | 11             | 2325                      | 42.1                                | 47.6                                | 33 400                              | 33 400                              |
|        | 12             | 2354                      | 41.7                                | 47.6                                | 30 100                              | 30 100                              |
|        | 17             | 2336                      | 36.9                                | 44.6                                | 30 100                              | 30 100                              |
| E-14   | 18             | 2355                      | 46.1                                | 47.6                                | 29 600                              | 29 900                              |
|        | 19             | 2321                      | 46.3                                | 47.6                                | 30 100                              | 30 100                              |
|        | 20             | 2335                      | 49.0                                | 47.6                                | 30 100                              | 30 100                              |
|        | 25             | 2322                      | 47.4                                | 47.6                                | 30 100                              | 30 100                              |
| G-21   | 26             | 2339                      | 48.9                                | 51.9                                | 29 300                              | 31 000                              |
|        | 27             | 2309                      | 45.4                                | 51.9                                | 33 400                              | 33 400                              |
|        | 28             | 2346                      | 48.6                                | 51.9                                | 30 400                              | 30 400                              |
| I-28   | 33             | 2327                      | 51.4                                | 54.1                                | 31 500                              | 32 100                              |
|        | 34             | 2335                      | 53.5                                | 54.1                                | 30 900                              | 32 100                              |
|        | 35             | 2332                      | 52.6                                | 54.1                                | 30 900                              | 32 100                              |
|        | 36             | 2321                      | 50.2                                | 54.1                                | 30 300                              | 31 100                              |
| K-90   | 41             | 2310                      | 55.4                                | 54.1                                | 32 000                              | 32 100                              |
|        | 42             | 2318                      | 56.1                                | 54.1                                | 33 300                              | 33 300                              |
|        | 43             | 2336                      | 48.9                                | 54.1                                | 33 300                              | 33 300                              |
|        | 44             | 2323                      | 56.1                                | 54.1                                | 31 100                              | 31 100                              |

Figure 5. Measured static modulus of elasticity of concrete.

The characteristic value of compressive strength of concrete is estimated in accordance with Table 3.12 of EN 1992-1-1 as:

$$f_{cm} = f_{ck} + 8$$

(2)
The modulus of elasticity is estimated as:

\[ E_{cm} = 22 \cdot \left[ (f_{cm})/10 \right]^{0.3} \]  

(3)

Then the values of modulus of elasticity of the tested concrete specimens calculated in accordance with STN EN 1992-1-1 [1] are plotted in Table 3.

Table 3. Compression test and elastic modulus test results.

| days | \( f_{cm,20} \) [MPa] | \( f_{cm,5} \) [MPa] | \( f_{ck,20} \) [MPa] | \( f_{ck,5} \) [MPa] | \( E_{cm,20} \) [GPa] | \( E_{cm,5} \) [GPa] |
|------|-------------------|------------------|------------------|------------------|-------------------|-------------------|
| 7    | 42.2              | 30.7             | 34.2             | 22.7             | 31.81             | 28.13             |
| 14   | 44.6              | 32.5             | 36.6             | 24.5             | 32.47             | 28.79             |
| 21   | 47.6              | 34.6             | 39.6             | 26.6             | 33.25             | 29.50             |
| **28** | **51.9**         | **37.0**         | **43.9**         | **29.0**         | **34.29**         | **30.28**         |
| 90   | 54.1              | 39.2             | 46.1             | 31.2             | 34.80             | 30.95             |

The measured values were compared with values of modulus of elasticity specified in EN 1992-1-1 [1]. The concrete strength class specified to the manufacturer was C 30/37. While the compressive strength of concrete measured at ambient temperature by tests at 28 days is largely sufficient to classify the concrete in that class \((f_{ck}= 43.9 \text{ MPa})\), the measured modulus \((30.9 \text{ GPa})\) is slightly inferior to the value specified for C 30/37 in Table 3.12 of EN 1992-1-1 (32 GPa). The value \(E_{cm}\) determined using Eq. (3) overestimates the elasticity modulus in comparison to the tested value. This is an observation that confirms findings available in earlier references [8]. The elasticity modulus of specimen cast at -5 degrees determined by tests (26 GPa) is 20 percent lower than the elasticity modulus specified for class C 30/37 in Table 3.12 of EN 1992-1-1 [1]. The value calculated using the characteristic compressive strength \(f_{ck,5}\) in Eq. (2) provides the non-conservative estimate of the modulus of elasticity.

4. Conclusions

The experimental research allowed to demonstrate the influence of the low temperature at casting and curing on the elasticity modulus of concrete. While the modulus of elasticity determined by tests is relatively close to the value of the modulus specified by EN 1992-1-1 for concrete C 30/37 for the concrete cast and cured at ambient temperature, the modulus of specimen cast and cured at -5 degrees is significantly lower. In absence of more accurate design recommendations, the authors recommend to design structures expected to be constructed at low temperatures assuming a reduced value 0.8.\(E_{cm}\). The design recommendations will be further developed following the completion of a research program. Currently, the testes of dynamic modulus of elasticity are verified. Based on the experimental results, the numerical model will be created for analysis of segmentally cast cantilever bridges considering additional mechanical properties (creep, shrinkage).

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