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## Development of the Elastic Modulus of Concrete under Different Curing Conditions

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### Abstract

The modulus of elasticity is a property of concrete, which is known for its high variability of values. A high enough value of the modulus of elasticity is a critical requirement in complicated concrete structures and in order to attain it, a number of factors must be taken into account, as it is subject to many. Curing is one of the most important influences. It can be described as an effort to maintain the temperature of concrete within the correct limits, prevent loss of water and the shrinkage connected with this. This paper describes an experiment focused on the observation of the development of the dynamic and static modulus of elasticity in dependence on the method of curing. The experiment worked with air-entrained as well as non-air-entrained concrete of the C 30/37 strength class. The results show that the curing method strongly affects not only the development, but also the final values of the concrete modulus of elasticity.

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*Keywords:* Concrete; curing conditions; dynamic modulus of elasticity; static modulus of elasticity

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### 1. Introduction

The design of slender or pre-stressed concrete structures, or their structural assessment, considers the modulus of elasticity as one of the most important input values, especially in strain calculations. This explains why scientists

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and construction engineers have been showing increased interest in the modulus of elasticity in recent years [1,2,3]. The modulus of elasticity is a property of concrete, which is directly dependent on its formula. A specific compressive strength can thus correspond to a variety of elastic modulus values, which can be seen e.g. in Fig. 13 presented in [4]. Apart from concrete composition, the development and final value of the modulus of elasticity is also affected by curing, especially during the first few hours and days after casting. An important component of concrete curing is maintaining its correct temperature, since both too low and too high a temperature can have a negative impact on the concrete [5,6,7]. Another important factor is the moisture content of the concrete, especially during the first stage of its setting and hardening. If concrete is cast at high ambient temperatures, it is necessary to administer appropriate curing [8,9]. If the concrete surface is not protected from water evaporation, there can be a massive risk of microcracks forming not only on the surface but inside the concrete member as well. A rapid loss of water from the concrete, especially during the first few hours, has a critical influence on cement hydration. This can result in a great magnitude of shrinkage, which is usually the first cause of microcracks that form in the internal structure of the concrete [10,11]. If these microscopic defects should occur, the development of the concrete's mechanical properties will be irreversibly affected throughout the whole time of its aging. A worsening of mechanical properties combined with extensive occurrence of microcracks can then result in an overall reduction of the whole structure's durability. It was also found that, apart from the method and quality of curing, the curing time impacts the final values of the concrete's material properties as well, including the modulus of elasticity [12,13].

The modulus of elasticity can be determined by means of two basic groups of test methods. The first group comprises dynamic methods, see [14,15], and the second group includes static methods, see [3,16]. The initial tangent modulus of elasticity, which reaches the highest values, is a result of the dynamic test methods, while the secant modulus of elasticity, the values of which are lower, can be obtained by means of the static tests [17]. It is therefore necessary to distinguish between the static and the dynamic modulus of elasticity.

## 2. Experiment

The goal of the experiment described here was to determine the development of the dynamic as well as static modulus of elasticity in dependence on the method of curing. Two sets of concrete prism specimens with the nominal dimensions of  $100 \times 100 \times 400$  mm were made for the purposes of testing; one of the sets was stored under water and the other one in standard laboratory conditions. The influence of curing on the modulus of elasticity was determined on concretes belonging to the C 30/37 strength class, both air-entrained and non-air-entrained.

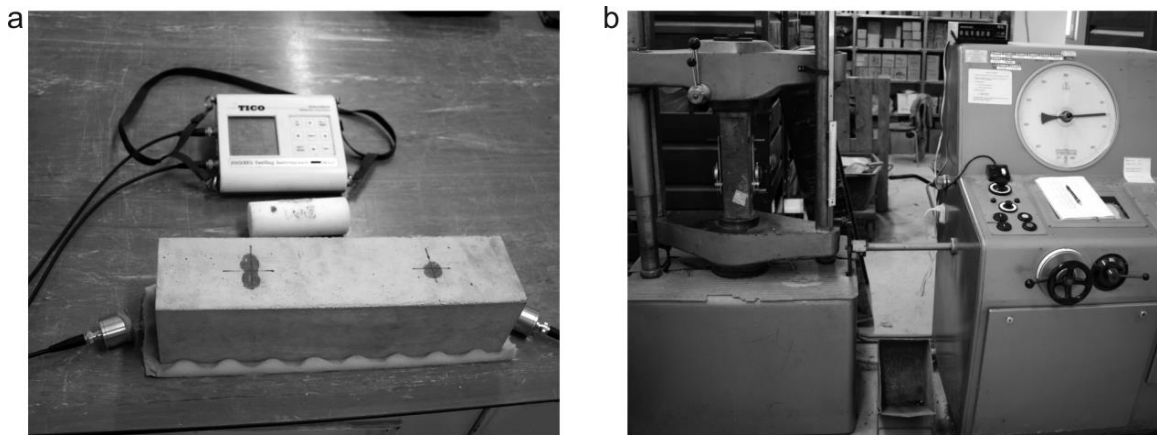


Fig. 1. (a) Determination of the dynamic modulus of elasticity  $E_{cu}$  using the ultrasonic pulse velocity test; (b) determination of the static modulus of elasticity  $E_c$  by cyclic loading in a press.

The dynamic modulus of elasticity was determined by means of the ultrasonic pulse velocity test. The principle of the method is the repeated sending of ultrasonic pulses into the specimen with the goal of measuring the time it takes for them to travel through. This was done using the instrument TICO with 82 kHz probes. The time of ultrasonic pulse travel, which was measured three times along the longitudinal axis of the specimens, see Fig. 1 (a), was then used in the calculation of the velocity of ultrasonic wave propagation through the concrete. Next, the dynamic modulus of elasticity  $E_{cu}$  was determined according to ČSN 73 1371 [18]. The static modulus of elasticity was determined by means of the compressive test. The specimens were subjected to cyclic loading within stress limits of  $0.5 \text{ N/mm}^2$  and  $1/3$  of the expected compressive strength of the specimen according to ČSN ISO 6784 [19], see Fig. 1 (b), and relative strain of the specimens was measured along the longitudinal axis, after which the static modulus of elasticity  $E_c$  was calculated.

The specimens were made of concrete, which was taken from agitator trucks present at a site of bridge construction. The first set of specimens was made from an air-entrained concrete identified as **A**, the composition of which is in Tab. 1. This concrete was used in the construction of the bridge abutment. The second set of specimens was made from non-air-entrained concrete identified as **B**; its composition is also shown in Tab. 1. It was used for the construction of the bridge deck (Fig. 2). The bulk density of fresh concrete was  $2\,250 \text{ kg/m}^3$  for set **A** and  $2\,330 \text{ kg/m}^3$  for set **B**. Average cube compressive strength of concrete **A** after 28 days of ageing was  $41.3 \text{ N/mm}^2$  with variation coefficient 3.0 % and for concrete **B**  $49.9 \text{ N/mm}^2$  with variation coefficient 4.6 %.

Table 1. Concrete formulae – amount per  $1 \text{ m}^3$  of fresh concrete.

| Concrete component       | Concrete <b>A</b> [kg] | Concrete <b>B</b> [kg] |
|--------------------------|------------------------|------------------------|
| Cement CEM I 42.5 R      | 400                    | 400                    |
| Sand 0-4 mm              | 700                    | 700                    |
| Aggregate 8-16 mm        | 669                    | 669                    |
| Aggregate 11-22 mm       | 284                    | 284                    |
| Water                    | 172                    | 172                    |
| Air-entraining admixture | 0.60                   | 0.00                   |
| Plasticizing admixture   | 2.40                   | 2.40                   |



Fig. 2. Bridge deck construction, during which a sample of concrete **B** was taken to make test specimens.

After the test prisms of both sets were cast, they were covered by moist geotextile and tightly wrapped in PE foil. They were left like this on a level surface at the construction for 3 days. After this time, the specimens were

transported to a laboratory at the Faculty of Civil Engineering of the Brno University of Technology, where they were demoulded and separated into two groups of 6. The first half of the specimens was designated **N** and was stored in water at the temperature of  $(20 \pm 3)^\circ\text{C}$ . The other half, identified as **S**, was stored in laboratory conditions at air temperature of  $(20 \pm 3)^\circ\text{C}$  and relative humidity of  $(50 \pm 10)\%$  with no extra addition of water. The test prisms **N** represented concrete, which had undergone quality curing for the whole time of its aging, while the test prisms **S** represented concrete, the curing of which ended after only 3 days of being in moulds with measures in place to prevent the escape of moisture.

The dynamic modulus of elasticity of all specimens was determined at the age of 3 days, i.e. immediately after demoulding, and again at the age of 7, 28, 90, 365, and 730 days. The static modulus of elasticity was determined after 28, 90, 365 and 730 days of aging.

### 3. Results and discussion

Fig. 3 shows the results of the development of the elastic modulus of concrete **A** in dependence on the method of curing. Fig. 4 shows the results for concrete **B**. At the age of 3 days, the dynamic modulus of elasticity  $E_{cu}$  was tested after demoulding, i.e. before the divisions of the prisms into cured **N** and uncured **S**. The 3-day values of  $E_{cu}$  are thus almost identical. However, after the specimens had been divided into **N** and **S**, the positive influence of curing, i.e. storage under water, was already apparent at the age of 7 days. The modulus of elasticity  $E_{cu}$  of specimens of the **N** group increased more steeply than that of group **S**. This trend can be well observed in the following day of testing, which was at the age of 28 days. The specimens of the **S** group were intentionally unprotected against drying. Significant water evaporation from the concrete had caused a drop in the relative moisture content in its structure and thus affected the development of cement hydration. This leads to changes in the mechanical properties of the concrete [9,20].

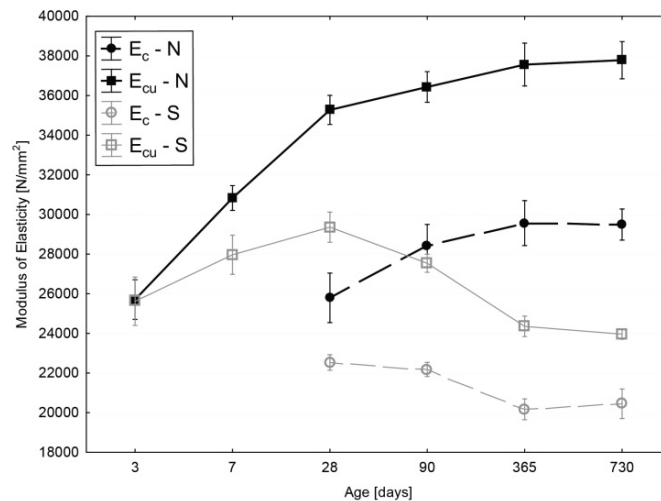


Fig. 3. Development of the dynamic modulus of elasticity  $E_{cu}$  and the static modulus of elasticity  $E_c$  of air-entrained concrete **A** in dependence on the method of curing – cured concrete is identified as **N** and uncured as **S**.

At the age of 28 days, both the dynamic  $E_{cu}$  and the static modulus of elasticity  $E_c$  were determined. The cured concrete **N** performed better than the uncured concrete **S**. The positive influence of curing was greater in the 28-day values of  $E_c$  in the air-entrained concrete **A**. The development of the modulus of elasticity between the ages of 28 and 90 days is rather interesting. While both the dynamic and static modulus of elasticity of the cured specimens **N** continues to increase in both concretes, the case of the uncured specimens **S** is different – the modulus of elasticity  $E_{cu}$  as well as  $E_c$  of the uncured concrete **B** stagnates during this period and in concrete **A** it is even

decreasing. A similar trend can be observed up to the age of 365 days; after this point the values appear stable, as the results for the age of 730 days are essentially no different from the results for the age of 365 days. The modulus of elasticity  $E_{cu}$  of the uncured specimens of the **S** group at the age of 365 and 730 days is comparable to the 3-day values (non-air-entrained concrete **B**) or even lower (air-entrained concrete **A**).

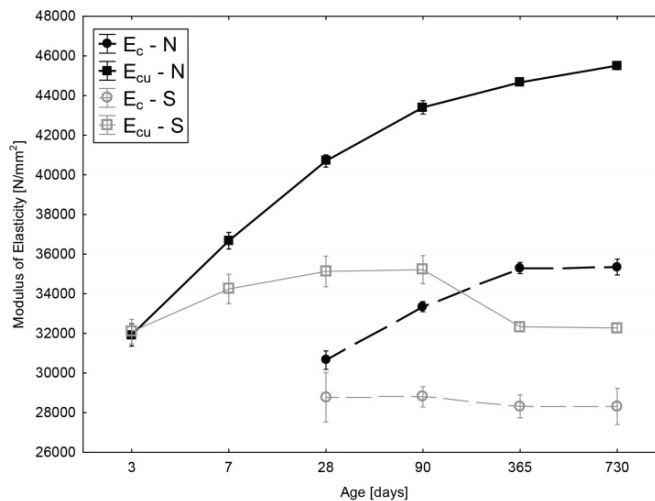


Fig. 4. Development of the dynamic modulus of elasticity  $E_{cu}$  and the static modulus of elasticity  $E_c$  of non-air-entrained concrete **B** in dependence on the method of curing – cured concrete is identified as **N** and uncured as **S**.

The development of the modulus of elasticity of the uncured concrete **S**, i.e. the decrease in the value of  $E_{cu}$  between the ages of 28 and 90 days, can be explained by a lack of water necessary for the cement to fully hydrate. Rapid water evaporation from the concrete surface accelerates its shrinkage [21]. The tension created in its internal structure due to volume changes then causes the formation of microcracks, which in turn negatively impact the development of physico-mechanical properties of the concrete, reduce its quality, durability and modulus of elasticity [22,23]. The effect of removing the concrete from contact with water resulting in its shrinkage is further documented in the papers [10,11,21,24]. The stagnation in the development of the material properties of uncured concrete has already been published in [12,13].

The influence of curing on the modulus of elasticity can be illustrated by a numerical evaluation of differences in its value at the age of 730 days. The dynamic modulus of elasticity  $E_{cu}$  of cured specimens **N** of air-entrained concrete **A** was determined to be 37.8 GPa, while in the uncured specimens **S** it was only 24.0 GPa, which is a difference of 36.5 %. The static modulus of elasticity  $E_c$  of cured specimens was 29.5 GPa and in uncured specimens it was 20.5 GPa, i.e. a difference 30.5 %. In the non-air-entrained concrete **B** the difference in  $E_{cu}$  amounted to 29.0 % (45.5 GPa in **N** specimens and 32.3 GPa in **S** specimens), the difference in  $E_c$  was 19.8 % (35.3 GPa vs. 28.3 GPa).

#### 4. Conclusions

The obtained results indicate the following.

- The positive influence of curing on the static and dynamic modulus of elasticity of concrete, which was used in the experiment described herein, was positively proved.
- The concrete cured under water showed a constant increase in the modulus of elasticity. During the first few days, this increase was fairly steep. On the other hand, the uncured concrete showed a less significant increase in the modulus of elasticity during the first few days. Between the age of 28 and 90 days, the uncured concrete saw

a gradual stagnation in the increase of the modulus of elasticity, which even began to decrease later. The 730-day dynamic modulus of elasticity was lower than at the age of 3 days. The static modulus of elasticity of the uncured concrete was lower at the age of 730 days than at 28 days. The degree of reduction in the modulus of elasticity in the uncured concrete was very significant compared to the cured concrete.

- A positive influence of concrete curing on the development of its modulus of elasticity was markedly more apparent in the air-entrained concrete.

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