Investigations on the Modulus of Elasticity of young RCC

M. Conrad
Institute of Hydraulic & Water Resources Engineering, Technische Universitaet Muenchen, Germany

M. Aufleger
Laboratory of Hydraulic & Water Resources Engineering, Technische Universitaet Muenchen, Germany

A.I. Husein Malkawi
Civil Engineering Department, Jordan University of Science & Technology, Irbid, Jordan

ABSTRACT: The paper deals with the investigations on the modulus of elasticity (Young's Modulus) and the stress-strain-behavior of one Roller Compacted Concrete (RCC) mixture from the age of 6 hours to 365 days. Focus is on the characteristic of very young RCC as its behavior in respect of stress-strain-relations differs considerably from that of aged RCC. The results of the investigations are processed with regard to the accessibility of the data for numerical temperature stress analysis, for which a detailed knowledge of the evolution of stiffness has to be gained especially in the initial phases of the hydration process.

1 INTRODUCTION

1.1 *Significance of early-age considerations*

During the exothermic hydration process, the clinker minerals as the cementitious compounds of the cement powder form the hardened cement paste in the presence of water. With proceeding hydration, the formerly free water is chemically bonded while the cement compounds are commuted to C-S-H gel and Calcium Hydroxide, going along with an increase of strength and stiffness of the cement paste and so of the concrete.

The temporal growth of stiffness and the initial release of the hydration heat in conjunction with the temperature rise of the cement or concrete mass and present restraint (internal and external) result in moderate compressive temperature stresses, also due to high relaxation of stresses and creep effects in the early age. However, when the hydration process nearly finalizes and the rate of heat release retards, the temperature of the mass begins to drop. In this phase, the concrete mass has gained a much higher stiffness, so, only a small drop of temperature may compensate the initially built up compressive stresses. Further cooling effects tensile stresses, which may exceed the tensile strength, which in turn leads to thermal cracking.

For the prediction of thermal cracking in RCC the restrained thermal stresses resulting from the released hydration heat have to be well known from the hydration's very beginning. This may be realized by a better understanding of the temporal development of the Young's Modulus of RCC especially in the very early state of curing, where an erroneous determination of the initial compressive stresses may also lead to a defective estimation of the later tensile stresses and so of the thermal cracking risk.

1.2 *Objectives of own investigations*

Generally, only very little information on the temporal evolution of the Young's Modulus of very young RCC can be found in literature. In most publications RCC properties and their temporal evolution are considered to be equal to these of Conventional Mass Concrete (CMC) (USACE 2000, USACE 1997). A common approach for the temporal development of the static modulus of elasticity in compression of normal-weight concrete is (Eierle 1999 acc. to CEB-FIP 1993)

$$E_c(t) = E_{c,28} \cdot \left(\frac{t}{17.6 + 0.37t} \right)^{\frac{1}{7.35}} \quad (1)$$

where $E_c(t)$ time dependent modulus [GPa]
$E_{c,28}$ modulus at age of 28 d [GPa]
t concrete age [d],

or in general:

$$E_c(t) = E_{c,t} \cdot \left(\frac{t}{a + b \cdot t} \right)^{\frac{1}{c}} \quad (2)$$

where $E_{c,t}$ reference modulus at age t [GPa]
a, b, c constant model parameters [-].

Equation 1 along with other formulations found in literature is only suitable for rough estimations as the model parameters are just valid for a standard concrete (Eierle 1999), which does not apply to low cementitious content RCC due to much lower cement contents.

With the focus on an accurate numerical simulation of thermal restraint stresses of one RCC dam consisting of low cementitious RCC, it was necessary to find an appropriate model for the time dependent Young's Modulus, which is capable to reflect the moduli at a very early age.

As in the initial phase of the hydration process the restrained volume expansion of the concrete caused by the heat release is resulting in compressive stresses, the formulation of the temporal development of the modulus of elasticity has to be based on the static modulus of elasticity in compression. Later, when the net stresses in the concrete mass become tensile, which is usually happening in an advanced state of cement hydration, the modulus of elasticity in tension principally has to be considered. However, in this case the commonly made assumption of equal moduli of elasticity of concrete in compression and tension is consulted (USACE 2000). So, the envisaged formulation of the time dependent Young's Modulus will be consistent for the stress simulation in compression as well as in tension.

2INVESTIGATIONS ON THE YOUNG'S MODULUS AT EARLY AGES

2.1*RCC samples and test execution*

RCC cylinders, 300 mm in height and 150 mm in diameter, were cast according to prevailing standards. After molding, the specimens were stored in water tanks, which were kept at a temperature of approximately 23 °C. At the testing age, the samples were removed from the wet curing and set into a surface dry state for testing and determining the Young's Modulus. In addition to tests performed at ages of 3 d to 365 d (Schrader et al. 2002), also samples at ages of 3 h to 48 h were tested in a construction site laboratory. Table 1 shows the composition of the investigated RCC and its testing ages.

Table 1. RCC composition (Malkawi 2001) and testing ages.

OPC Content (Cement Type I)	85 kg/m³
Puzzolan Content	0 kg/m³
Free Water Content	137 kg/m³
Water-Cement-Ratio	1.61
Basalt Content	2060 kg/m³
Sand Content	154 kg/m³
Max. Size Aggregate	37.5 mm
Testing Ages	3 h, 6 h, 12 h, 24 h, 36 h, 48 h, 3 d, 7 d, 14 d, 28 d, 56 d, 91 d, 182 d, 365 d

In the frame of the presented investigations, the cylidrical specimens were set up in a compressive strength testing machine for testing the static modulus of elasticity in compression (Fig. 1). The stress-strain-curve was recorded from a force controlled uniaxial compressive strength test for which ASTM C 39-86 suggests a constant loading rate of 0.15 to 0.34 MPa/s (Neville & Brooks 1990).

Evaluation of the stress-strain-curves in respect of the elastic modulus has been done according to the EC 2 standard (Eurocode 2 1992). The static elastic modulus of concrete is defined as a secant modulus between $\sigma = 0$ and $\sigma = 0.4f_c$.

$$E_c = \frac{0.4 \cdot f_c}{\varepsilon(0.4 \cdot f_c)} \tag{3}$$

where E_c static elastic modulus [MPa]
f_c ultimate compressive strength [MPa]
ε axial strain [mm/mm].

The effects of cracks on the first portion of the stress-strain-curve and their consideration in the evaluation of the elastic modulus according to ASTM C 469 (Oluokun et al. 1991) have been neglected for the presented investigations. To eliminate these effects of cracks, ASTM C 469 introduces the evaluation of a chord modulus from the stress-strain-curve with a first point at 0.00005 mm/mm of strain.

$$E_c = \frac{0.4 \cdot f_c - \sigma_1}{\varepsilon(0.4 \cdot f_c) - \varepsilon_1} \tag{4}$$

where E_c static elastic modulus [MPa]
f_c ultimate compressive strength [MPa]
ε axial strain [mm/mm]
ε_1 0.00005 [mm/mm]
σ_1 stress corresponding to ε_1 [MPa].

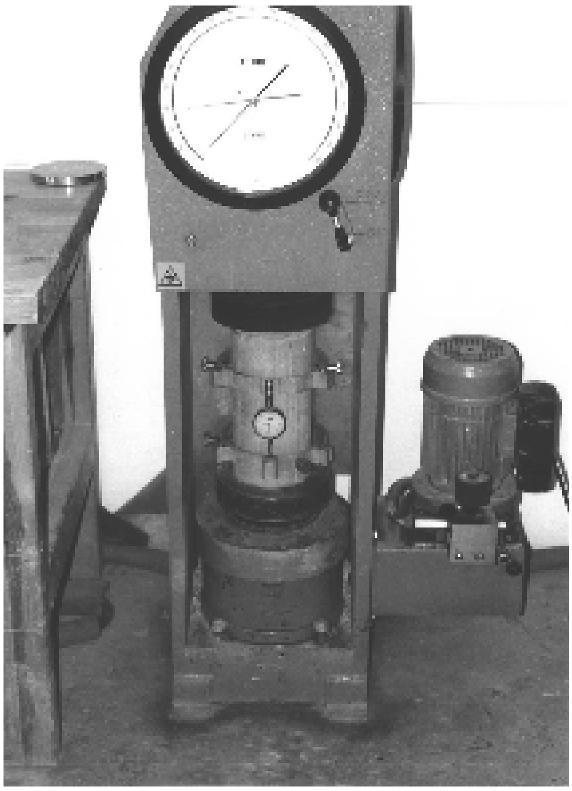

Figure 1. Setup of static elastic modulus test.

2.2 *General findings from the tests*

In general, the modulus of elasticity in compression is defined as the ratio of normal stress to its corresponding strain for compressive stresses below the proportional elastic limit of the material (Andriolo 1998). The elastic limit can be concluded from the different stress-strain-curves at the certain ages (Fig. 2). The elastic limit is exceeded where the portion of the stress-strain-curve cannot be approximated by a linear regression.

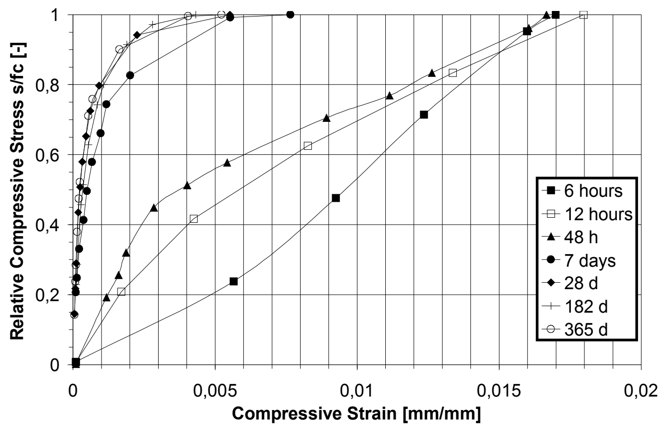

Figure 2. Comparison of typical stress-strain-curves at different RCC ages.

Figure 2 clearly shows, that the stress-strain-curves all can be characterized by a linear material behavior at least up to stresses of 40 % of the actual ultimate compressive strength. Also for conventional vibratable concrete, comparable results are presented in literature (Laube 1990). This underlines the chosen way of evaluation of the static elastic modulus of RCC according to Equation 3.

At the very early age of 6 h, the low cementitious RCC shows linear stress-strain properties for the complete loading path. With increasing age, the shape of the stress-strain-curves changes to the for concrete rather typical nonlinear shape. This tendency could be observed for samples older than 12 h.

Samples were also molded for tests at the age of 3 h. With the investigated RCC mixture it was not possible to reasonably perform Young's Modulus tests at this very young age. Further trials with samples to be tested after 4 and 5 h were not successful as well. It could be interpreted, that for the used equipment and for such kind of low cementitious content RCC minimum ages of 6 h have to be adopted for a suitable performance of Young's Modulus tests.

2.3 *Static modulus of elasticity in compression*

The following paragraph deals with the evaluation of the Young's Modulus data, resulting from the stress-strain-curves according to Equation 3. The presented results and relations are based on the average elastic moduli referring to one age, which reflects the concrete age at isothermal curing conditions (23 °C). So, the here stated concrete age corresponds to the effective concrete age. Table 2 gives an overview of the number of performed tests consulted for the evaluations.

In general, manufacturing of low cementitious RCC samples follows a completely different procedure than molding conventional vibratable concrete samples. Without going into detail, it is stated here, that various factors in the molding phase influence the later sample quality at testing age. So, as human accuracy is much more involved in the preparation of RCC samples, it is coherent, that test results especially of stress-strain investigations show higher variations compared to conventional concrete samples.

Table 2. Number of tests, average and standard deviation values for Young's Modulus.

Age [d]	No. Tests [-]	Average Modulus [GPa]	Stand.Deviation [GPa]
0.25	4	0.05	0.01
0.5	9	0.27	0.17
1	6	0.68	0.34
1.5	6	0.90	0.40
2	6	0.95	0.14
3	62	3.39	1.82
7	250	6.30	2.68
14	190	9.25	3.49
28	178	11.97	4.20
56	90	15.76	4.40
91	156	16.92	5.54
182	108	19.97	6.19
365	29	24.40	6.32

Figure 3 presents the temporal development of the static elastic modulus, the range of values in which 68.8 % of the measured values are to find and two types of regressions for comparison. The evolution of average moduli shows a S-shape, which is typical for the development of the Young's Modulus. This S-shape may be expressed by exponential type functions as also used for modeling the hydration heat evolution (Eierle 1999) and by functions typed in accordance with Equation 2.

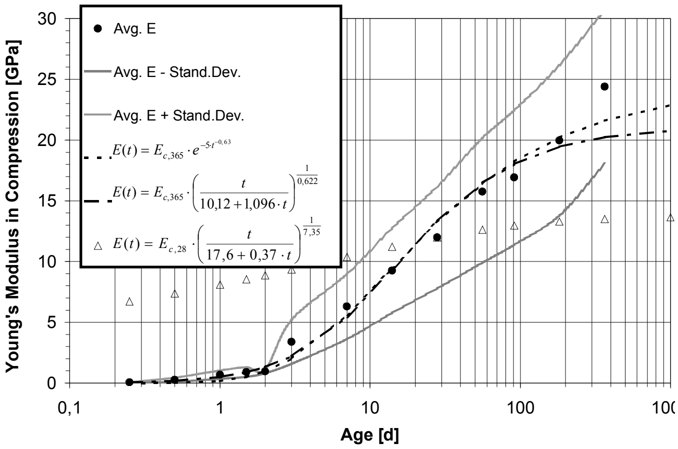

Figure 3. Temporal evolution of Young's Modulus and various regressions for modulus vs. time.

Form Figure 3 it is clearly visible, that with Equation 1 a reasonable approximation of the average moduli cannot be reached. Equation 1 reflects an empirical temporal elastic modulus evolution for standard conventional concrete, in which the early-age moduli are strongly overestimated and the elastic moduli of the aged concrete are highly underestimated. From the standpoint of the low cementitious RCC, stresses simulated by using a modulus prediction according to Equation 1 would not even get near to realistic conditions.

A much more acceptable approximation of the evaluated modulus data can be achieved using Equation 2 and the parameters $E_{c,t} = E_{c,365} = 24.4$ GPa, $a = 10.12$, $b = 1.096$ and $c = 0.622$. The early-age moduli can be perfectly modeled, whereas the aged concrete moduli of ages greater than 182 d are slightly underestimated. Thus, stresses calculated from thermal displacements, for instance, would also be underestimated. This might lead to misinterpretations in respect of thermal cracking potentials, when talking about tensile stresses.

Another convincing regression of the measurement data is realized by an exponential type function such as

$$E_c(t) = E_{c,\infty} \cdot \exp(a \cdot t^b) \tag{5}$$

where $E_c(t)$ time dependent modulus [GPa]
$E_{c,\infty}$ final modulus of elasticity [GPa]
t concrete age [d]
a, b model parameters [-].

The best data fitting of the test results could be reached, applying $E_{c,\infty} = E_{c,365} = 24.4$ GPa and the model parameters $a = -5.0$ and $b = -0.63$, by which the static elastic moduli can be reproduced in the early-age as well as for higher ages. In comparison with Equation 2 the exponential type function has the advantage of only two model parameters to vary for best approximation and might so be easier to use. As variations between the exponential regression and the evaluated average moduli are small for all testing ages, it is possible to apply the exponential law according to Equation 5 for a realistic simulation of stresses in a RCC structure.

3CONCLUSIONS AND SUMMARY

Only little information on the temporal evolution of the Young's Modulus of RCC, especially low cementitious RCC can be found in literature. Therefore, investigations on the static elastic modulus in compression of one lean mix RCC were performed. Available compressive stress-strain data of cylindrical RCC samples of ages between 3 d and 365 d were completed by results from very young RCC samples of ages between 6 h and 48 h. It has been found, that a testing age below 6 h is not suitable for Young's Modulus tests of a lean RCC mix.

Common approaches for the temporal evolution of the modulus of elasticity in compression of conventional concrete are not transferable to the low cementitious RCC investigated. By such approaches, moduli of early-age RCC would be highly overestimated, moduli of aged RCC would be underestimated considerably in comparison with the measurement results.

However, for approximation of the elastic modulus values over time, the hyperbolic type function, which most approaches for temporal behavior of concrete rely on, in general give appropriate results, especially for the early ages. With the available modulus data it could be seen, that the hyperbolic approximation underestimates the Young's Modulus for ages above 182 d.

A very satisfactory approximation of the temporal evolution of the Young's Modulus for the early ages as well as for aged low cementitious RCC can be achieved by an exponential type function, which is more advantageous compared to the above described hyperbolic one as only two model parameters have to be adopted for the best data fitting. As the presented exponential model is easy to handle and also gives agreeable results, it may be preferably used as implementation in finite element models used for the simulation of stresses particularly in young RCC.

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