## SUMMARY

This thesis deals with the properties of concrete at early ages, their investigation in laboratory tests and constitutive modelling. The detailed knowledge of the properties of the early age concrete and their modelling is indispensable for the calculation of the temperature and the stresses in hardening concrete structures.

At first the important factors of thermal cracking are identified and the common ways for the assessment of the thermal cracking risk are described. Furthermore, a survey on the recent knowledge about the mechanical properties of the concrete at early ages is presented (Chapter 2). In Chapter 3 the laboratory tests and the different test equipment are described. Comprehensive tests were carried out for the determination of the

- **adiabatic heat release** and the **degree of hydration**,
- development of the **mechanical short-term properties** namely the **axial tensile strength**, the **compressive strength** and the **modulus of elasticity** under tensile stress,
- short-term **stress-strain line under tension** and micro-cracking,
- **viscoelasticity**, namely **creep and relaxation under tension** and variable temperature conditions,
- **autogenous shrinkage** and **thermal dilatation**.

The tests were primarily performed with two different concrete compositions: "PZ-Beton" with CEM I 32.5 and fly-ash (w/b = 0.61) and "HOZ-Beton" with CEM III/B 32.5 (w/c = 0.47). For the "PZ-Beton" the influence of the cement content and of a retarding admixture on the thermal and mechanical properties were additionally studied.

The **degree of hydration** is in this report described via the heat release of the concrete. Therefore, the heat release of the different concretes was measured in adiabatic calorimetry. For the modelling the temperature effect on the heat release, the degree of hydration is expressed in terms of the equivalent time, on basis of the Arrhenius-equation. Based on the test results, it was shown that the Jonasson-equation is appropiate for the modelling of the degree of hydration (Chapter 4).

The **mechanical properties** (axial tensile strength, compressive strength and the modulus of elasticity) of concrete at early concrete age were tested in the equivalent time range of 7 hours up to 365 days (Chapter 4). The results showed a linear relationship between the degree of hydration and the axial tensile strength, a more rapid development of the elastic

modulus and a slower development of the compressive strength. On the basis of the test results, models for the mechanical short-term properties dependent on the degree of hydration were developed and verified. The tests revealed that the transition from the dormant phase to the on-set of hardening of young concrete is not yet sufficiently clarified. Further investigations are necessary.

In the future, the calculation of temperature and stresses in concrete structures at early age will have to be performed under the aspect of reliability in order to quantify the uncertainties. For this purpose the results of the laboratory tests, the models of the degree of hydration and of the mechanical short-term properties were studied under the statistical point of view to quantify the scatter (Chapter 4.6). It was found, that the measured values of the degree of the hydration, the tensile strength and of the compressive strength are distributed Normal-Gaussian for different ages. The variability of the measured values was quantified.

For the calculation of stresses in a structure, the **stress-strain line under tension** must be known to determine the instantaneous and the inelastic strain. Therefore, the stress-strain line under tension was studied for different ages at loading (Chapter 5). From these tests, the fracture energy, the characteristic length and the ultimate strain at tensile strength were deduced. In addition, models for the fracture energy and for the ultimate strain dependent on the degree of the hydration were established. A model for the stress-strain line under tension for different ages at loading was presented and its correspondence with the test results was shown.

The main topic of the research work was the investigation of the viscoelastic behaviour of concrete at early ages (Chapter 7). Creep and relaxation tests under tension were performed with initial stresses in the ascending branch of the stress-strain line (pre-peak) in the range of $0.5 \leq \sigma/f_{ct} \leq 0.9$. The specimen were always sealed.

The age of first loading varried between t = 16 h and 7 d to study the effect of the age at on-set of loading. The tests were performed under isothermal conditions at T = 20 °C and 40 °C and under anisothermal conditions (always sealed) as well. It was the aim of the tests to study the effect of the age at loading and the effect of the temperature before loading and also during the creep and relaxation period.

For all concretes, the viscoelasticity was very pronounced, if the load was applied at early concrete age. Creep and relaxation increase with a decreasing equivalent age at first loading and the degree of hydration at first loading, respectively. The initial stress-strength ratio seems to have less influence on the creep and relaxation. The creep strain after a certain time under load is linearily related to the applied stress, if the spontaneous cracking strain at loading is taken into account. On the basis of these results, linear and aging viscoelasticity was assumed to be valid for the modelling of creep and relaxation under tension. The models based on the degree of the hydration were calibrated with the test results.

As creep and relaxation tests were performed simultaneously with the same concrete mix and under equal loading and ambient conditions, the relationship between creep and relaxation could be studied. Based on the test results, a relationship between the creep and the relaxation function was deduced and the relaxation coefficient was quantified dependent on the degree of the hydration.

In the structure, the stresses and strains vary in time and location. As the principle of superpostion has the be applied for the calculation of stresses and strains in the structures, creep and relaxation tests with several load steps in the ascending branch of the stress strain line were performed to study whether the application of the principle of superpostion is valid. The comparison showed a rather good correlation between the measured and the calculated stress or strain histories. It can be concluded that the principle of superposition is valid for the stress calculation of early age concrete structures.

An elevated temperature ($T > 20$ °C) has an ambivalent effect on creep and relaxation of concrete at early ages. A high temperature before the first loading yields a higher equivalent age and degree of hydration, respectively. This leads to a decrease of creep and relaxation. On the other hand, viscoelasticity of hardened concrete is more pronounced at high temperatures.

The tests performed, showed a more pronounced creep and relaxation for curing under $T =$ 40 °C (isothermal) than under $T = 20$ °C (isothermal), even at the same equivalent age at first loading, respectively degree of hydration. For modelling the temperature effect on the viscoelastic behaviour of concrete at early ages the time intervall $t - t_1$ in the creep and relaxation functions was replaced by the equivalent time under load $t_e - t_{e1}$. The equivalent time under load was determind with the Arrhenius-equation, and the activation energy was deduced from the creep and relaxation tests to $E_v = 50.000$ J/mol.

Creep and relaxation tests were also performed in the descending branch of the stress strain line (post peak). It was found that creep tests are usually terminated by creep failure after a certain time under load. On the other hand, relaxation in the descending branch of the stress strain line occours, if the initial strain in applied in an early equivalent age ($t_e = 18$ h to 24 h) and at a low degree of hydration, respectively. The relaxation tests in the descending branch also showed that the tensile stress increases due to the on-going of hydration although the tensile strength had been reached before. This indicates the healing of the early microcracks in course of the hydration process.

The **autogenous shrinkage** was measured under isothermal conditions at T = 20 °C and 40 °C. It was found, that the autogenous shrinkage under T = 40 °C is about twice than under T = 20 °C (Chapter 8). For the modelling of the autogenous shrinkage a model is presented that takes the temperature effect into account, using the equivalent age based on the Arrhenius-equation.

**Thermal dilatation** at different ages was measured only for one concrete mix (Chapter 8). The results showed an slight increase of the thermal dilatation in the age between 1 d and 28 d and greater values during cooling that in the heating circle.