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STRENGTH CHARACTERISTICS OF CONCRETE IN THE TEMPERATURE RANGE OF 20° TO 200°C

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Summary

In an experimental study concretes made of quartz aggregates and of limestone aggregates, respectively, have been exposed to elevated temperatures in the range of 20°C to 200°C under drying or under sealed conditions. Under sealed conditions the limestone concrete showed a loss of strength and of modulus of elasticity of up to 40% of the initial values. Drying limestone concrete and quartz concrete under sealed or under drying conditions showed either no change in strength or a slight strength increase. The strength loss of the limestone concrete is caused by changes in microstructure of the hydrated cement paste when exposed to hydrothermal conditions. In the quartz aggregate this strength loss is counteracted by a reaction between the silicates of the fine aggregate particles and the $Ca(OH)_2$ of the hydrated cement paste. On the basis of these findings it is hypothesized that for concretes with optimum characteristics i.e. sufficient resistance to hydrothermal exposure and a low coefficient of thermal expansion, fine quartzitic aggregates and coarse limestone aggregates should be combined.

1. Problem statement and scope of investigation

In prestressed concrete reactor vessels or in biological shields concrete is exposed to elevated temperatures. Because of the large dimensions of such structures drying of the concrete is hindered. Consequently, the moisture conditions for mass concrete prevail. Both temperature exposure and moisture state may affect concrete properties. Therefore, in the investigation described in the following the strength characteristics of concrete in the temperature range 20°C to 200°C have been investigated. The moisture states sealed or drying have been included as an additional parameter to simulate the conditions in mass concrete. Furthermore, microstructural changes in the concrete have been investigated to explain the observed behavior.

2. Strength properties of the concrete

2.1 Types of concrete

Because of their low thermal expansion limestone aggregates are used frequently in the construction of massive concrete structures. Therefore, in this study concretes made with limestone aggregate have been used. For comparison, also concretes with quartz aggregates have been included. All concretes contained 300 kg/m^3 of portland cement PZ 45F with a w/c-ratio of 0,5.

2.2 Specimens, curing and exposure conditions

Cylindrical specimens Ø 150 mm, 150 mm high have been used. The specimens were cured in water for 90 days prior to exposure at temperatures of 60°, 105° and 180°C, respectively. During temperature exposure some specimens have been allowed to dry. Additional specimens have been placed in sealed pressure vessels in order to simulate sealed or hydrothermal conditions. After 7, 21 and 40 days of temperature exposure compressive strength and stress-strain relationships of the concrete have been determined at the elevated temperature.

2.3 Strength results

Fig. 1 shows the relative compressive strength of the concrete as a function of duration of temperature exposure both for drying limestone concrete and quartz concrete. For all temperatures investigated the quartz concrete exhibits a slight strength increase whereas the compressive strength of the limestone concrete deviates little from its initial values.

The relative compressive strength of the sealed concretes are shown in fig. 2. Again, the quartz concrete exhibits a slight strength increase, whereas the compressive strength of the sealed limestone concrete decreases with increasing temperature. Exposure at 180°C over a period of 40 days reduces the compressive strength of the concrete to 40% of its initial value.

2.4 Stress-strain diagrams

As shown in fig. 3, in addition to the strength loss the sealed limestone concretes also exhibit a pronounced decrease of the modulus of elasticity and an increase in failure strain.

The modulus of elasticity of the drying limestone concrete as well as of the sealed and the drying quartz concrete decreases only slightly with increasing temperature. For these concretes also a slight increase of failure strain with increasing temperature has been observed (fig. 4).

2.5 Effect of cyclic temperature exposure

Some specimens were exposed to various programs of cyclic temperatures. Such exposure had no significant effect upon the strength of the quartz concrete as well as of the drying limestone concrete. For the sealed limestone concrete pronounced strength losses have been observed. The governing parameter for this strength loss is the duration of exposure at the maximum temperature.

3. Investigations of microstructure

3.1 Objectives

A study of microstructural changes in the two types of concrete has been conducted in order to investigate the causes of differences in behavior of quartz concrete and of limestone concrete in a drying or in a sealed state. It was hoped, that on the basis of such studies criteria could be established for the composition of concretes with a high resistance to temperature exposure in a drying or in a sealed state.

3.2 Sealed concrete at elevated temperatures

The differences in behavior of limestone and of quartz concrete when subjected to hydrothermal exposure conditions may be traced back either to microstructural changes in the aggregate or in the hydrated cement paste. In addition, reactions between aggregates and cement paste may take place. Therefore, the properties of the concrete components as well as reactions between those components have been investigated.

3.2.1 Properties of limestone at elevated temperatures

Limestone is decomposed at a pressure of 1 atm and a temperature of 880°C. The presence of water vapor accelerates the decomposition of limestone. However, this acceleration is not sufficient to cause thermal decomposition of limestone at temperatures below 300°C.

3.2.2 Behavior of hydrated cement paste under hydrothermal conditions

Fig. 5 shows the relationship between relative compressive strength and modulus of elasticity of hydrated cement pastes made of portland cement PZ 35F and a w/c = 0,4 after exposure to hydrothermal conditions at an age of 90 days. The strength properties of the hydrated cement pastes are similar to those observed for the limestone concrete shown in fig. 2. Scanning electron micrographs (fig. 6) show clearly, that due to hydrothermal exposure the structure of the paste has been changed resulting in a significant increase of porosity.

On the basis of X-ray diffraction analysis of hydrated cement pastes prior to and after exposure to hydrothermal conditions it has been found that the change of microstructure and increasing porosity can be traced back to the formation of new cristalline hydration poducts. Furthermore, a reduction of the specific surface of the hydrated cement paste up to 20% of its initial value has been measured. It is this increase of porosity and decrease of specific surface which is considered to be responsible for the strength loss of the hydrated cement paste |1| and of the limestone concrete respectively.

3.2.3 Behavior of quartzitic aggregates in concrete exposed to hydrothermal conditions

Since a strength loss had been observed only for hydrated cement pastes and for limestone concrete when exposed to hydrothermal conditions a study was carried out to investigate if and under what conditions the addition of quartzitic aggregates may compensate this strength loss.

The strength of quartz concrete may be affected by a reaction between calcium hydroxide ($Ca(OH)_2$) and silicates (SiO_2) under hydrothermal conditions |2|. The solubility of SiO_2 in water increases with increasing temperature and increasing pH-value. Therefore, a significant reaction between SiO_2 and $Ca(OH)_2$ can be observed only at temperatures above 100°C. The reaction between $Ca(OH)_2$ and SiO_2 is described schematically in fig. 7.

In the surface regions of a quartz particle SiO_2 is dissolved in water thus generating silicic acids. These silicic acids react with Ca-ions resulting in the formation of calcium-silicate-hydrates (CSH-phases) and a subsequent strength increase of the paste. This reaction continues as long as there is free $Ca(OH)_2$ in the cement paste.

Fig. 8 shows a scanning electron micrograph of a quartz particle in concrete after hydrothermal exposure. Plate-like CSH cristals growing into the hydrated cement paste can be seen easily. The reaction of $Ca(OH)_2$ with SiO_2 has been substantiated also by X-ray diffraction analysis of hydrated cement pates. After hydrothermal treatment the free $Ca(OH)_2$ has disappeared. With increasing dispersion of the aggregate particles the rate of reaction increases. Consequently, the reaction described above is of particular significance for quartzitic aggregates with a size < 4 mm.

3.2.4 Composition of concrete with a high resistance to hydrothermal exposure

The strength loss of some concretes when exposed to moisture and elevated temperatures above 105°C is caused by changes in the microstructure of the hydrated cement paste. These changes occur both in pastes made of portland cement and of blast furnace slag cement. In concretes made with limestone aggregates the changes in microstructure of the hydrated cement paste cause a severe strength loss. In concretes made with quartz aggregates the strength loss is counteracted by a strength increasing reaction between the quartz and the free $Ca(OH)_2$ of the hydrated cement paste.

Fine, quartzitic aggregates, therefore, should be recommended for concretes with a high resistance to hydrothermal exposure. On the other hand limestone aggregate is preferred when concrete is exposed to high temperatures since such aggregates will result in a concrete with a low coefficient of thermal expansion. Therefore, at the present time concretes are investigated which should satisfy both conditions. For these concretes fine quartzitic sand is combined with limestone for the coarse aggregate fractions. The results will be available at the time of the conference.

3.3 Drying concrete at elevated temperatures

Previous results from various investigators indicate that in the temperature range between 20°C and 300°C the compressive strength of the concrete may either increase or may be markedly reduced |3-5|. Generally, it is assumed that the extent of the strength loss depends on the type of aggregate used for the concrete. Different types of aggregate exhibit different coefficients of thermal expansion and thus generate internal stresses of different magnitude at elevated temperatures. These internal stresses are supposed to be responsible for the strength loss. However, this hypothesis is in contrast to the results presented in section 2.3 where dry concretes containing quartz aggregates or limestone aggregates with portland cement have shown similar strength characteristics at elevated temperatures though both aggregates differ significantly in their thermal characteristics. Furthermore, recent tests conducted at our institute indicate, that dry concrete made with quartzitic aggregates or with limestone aggregates and blast furnace slag cement also show a significant strength loss when exposed to a substained temperature of 200°C. This may indicate that the strength properties of the concrete at elevated temperatures also depends on the type of cement. An explanation for this particular behavior of concrete made with blast furnace slag cement may be the decomposition of various phases in the hydrated cement paste which are nor anymore stable in the temperature range of 150° - 250°C.

However, additional studies of structure and strength properties of hydrated cement paste samples will be required in order to sufficiently explain the behavior of dry concrete in the temperature range of 100° - 300°C.

4. Conclusions

Moisture state, type of aggregate and probably type of cement may have a significant effect upon strength and deformation characteristics of concrete at elevated temperatures.

Thus possible strength losses can be avoided or minimized by a proper choice of concrete making materials. It is likely that the use of fine quartzitic aggregates combined with coarce limestone aggregates will result in a concrete with good strength and deformation properties at elevated temperatures.

5. References

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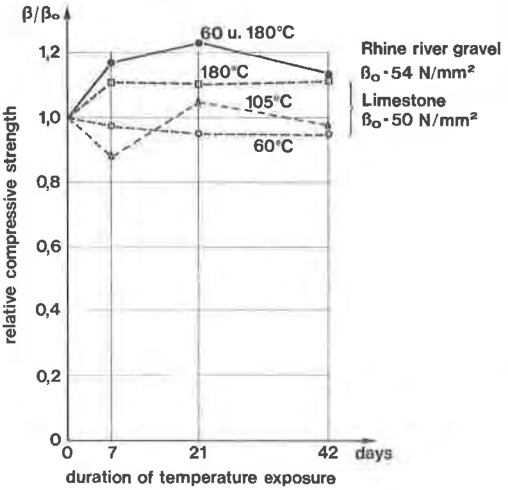

fig. 1: Relative strength development of unsealed concrete specimens exposed to elevated temperatures.

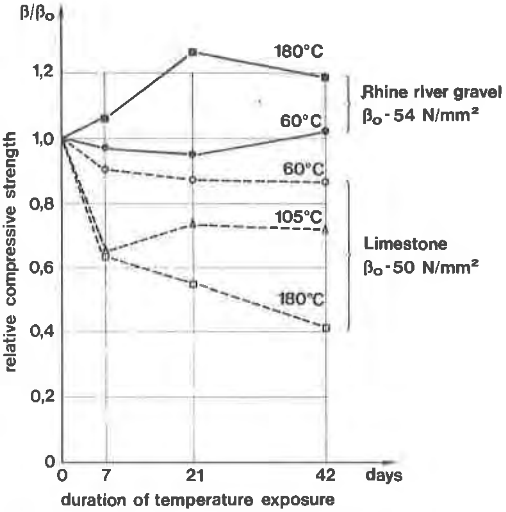

fig. 2: Relative strength development of sealed concrete specimens exposed to elevated temperatures.

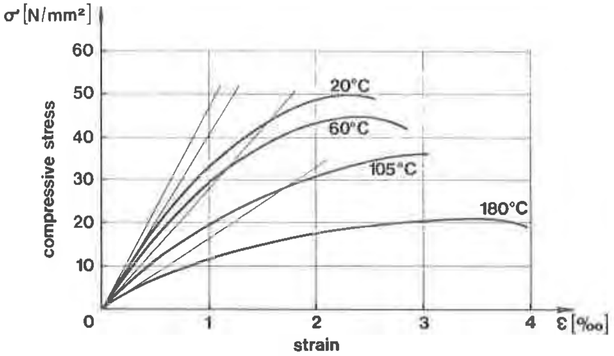

fig. 3: Stress-strain diagrams of sealed limestone concrete specimens.

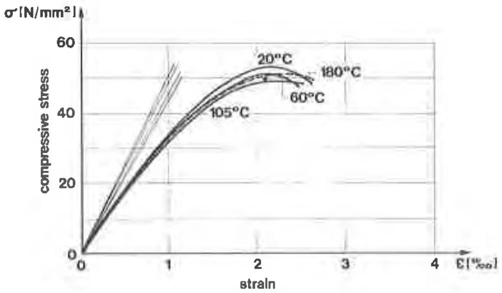

fig. 4: Stress-strain diagrams of unsealed limestone concrete specimens.

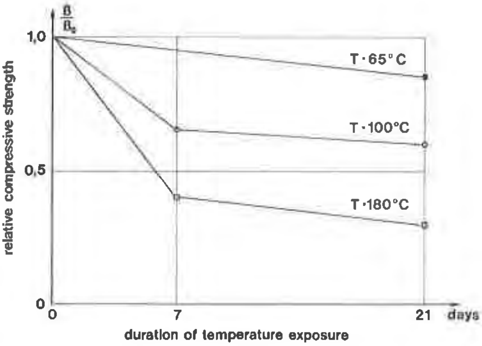

fig. 5: Relative strength development of sealed hydrated cement paste specimens (PZ 35, w/c = 0,4) exposed to elevated temperatures.

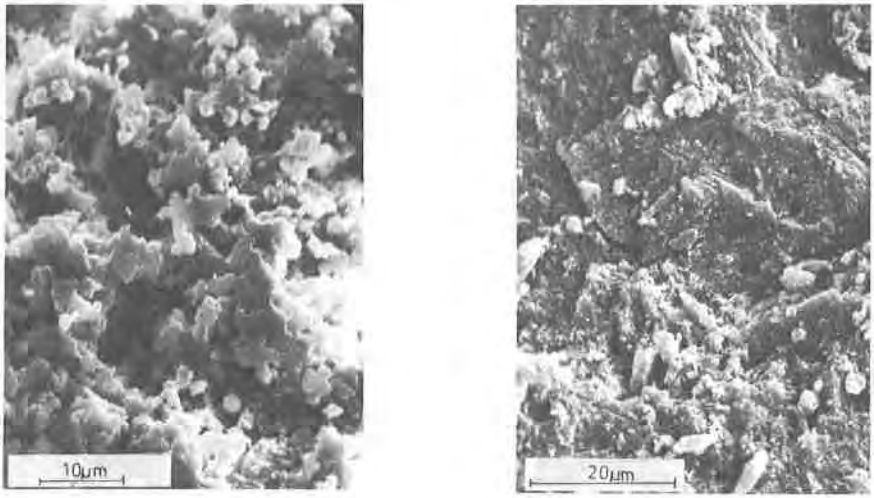

fig. 6: temperature exposed sealed specimens (T = 180°C, 7 days)

untreated specimens (T = 20°C)

Scanning electrone microscope (SEM) micrographs of hydrated cement paste specimens.

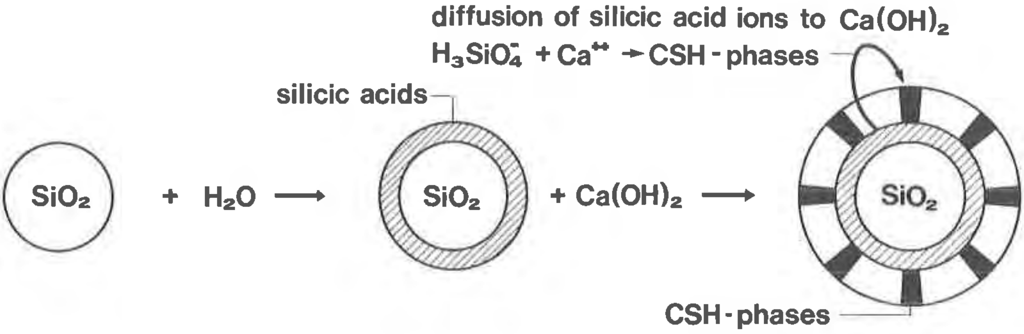

fig. 7: Schematic presentation of hydrated cement paste-silicious aggregate reactions.

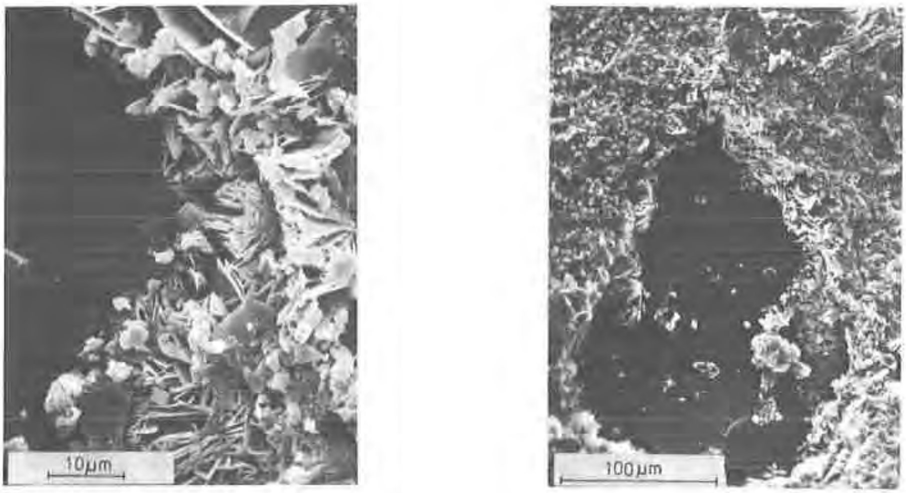

fig. 8: SEM-micrographs of quartz particles in sealed Rhine river gravel concrete after temperature exposure (T = 180°C, 40 days).