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Durability of Concrete and Reinforced Concrete Structures Subjected to Temperature Cycles: Insight from Multiscale Thermomechanical Analysis

Bernhard L.A. Pichler

Institute for Mechanics of Materials and Structures, TU Wien (Vienna University of Technology), Karlsplatz 13/202, 1040 Vienna, Austria, bernhard.pichler@tuwien.ac.at

Abstract. *This document refers to thermal expansion of cementitious materials and to related thermal stresses activated in samples of concrete as well as in unreinforced and reinforced concrete structures. It provides an overview of multiscale research which was carried at the Institute for Mechanics of Materials and Structures, TU Wien, Vienna, Austria, in cooperation with Tongji University and Shanghai Jiao Tong University, China. The overview starts with the nanoscopic origin of the thermal expansion behavior of cement paste, which is triggered by the heating-induced release and the cooling-induced uptake of water by calcium-silicate-hydrates (C-S-H). Temperature changes lead to thermal strains. Thermal stresses are activated provided that the thermal strains are constrained. Such constraints prevail at microstructural scales of concrete as well as at cross-sectional and macrostructural scales of unreinforced and reinforced concrete structures such as beams, plates, and frames. Diurnal temperature changes result in daily cycles of self-equilibrated thermal stresses. They represent a considerable loading for interfacial transition zones (ITZs) separating the aggregates from the cement paste matrix. Extreme events such as sudden hail showers or moderate fires are very likely to result in thermal cracking, at least in the microscopic region of the ITZ, but frequently also at the larger scale of concrete.*

Keywords: *Thermal Expansion, Transient Heat Conduction, Interfacial Transition Zones, Tensile Cracking.*

1 Introduction

In academic courses it is usually taught that reinforced concrete structures are durable, because the coefficients of thermal expansion of both steel and concrete are virtually the same. As regards the microstructure of concrete, however, the coefficient of thermal expansion of cement paste differs very often significantly from the one of the aggregates. This mismatch gives rise to microscopic thermal stresses. Transient heat conduction through structural elements is another source of thermal stresses. Such time-dependent processes of heat ingress are characteristic for unsheltered concrete structures, including pavements, bridges, and reinforced concrete elements which are part of the envelope of buildings.

The present document provides an overview of multiscale research focused on thermal expansion of cementitious materials and on related thermal stresses activated in concrete as well as in unreinforced and reinforced concrete structures. Research was carried out at the Institute for Mechanics of Materials and Structures, TU Wien, Vienna, Austria, in cooperation Tongji University and Shanghai Jiao Tong University, China. The aims are two-fold:

1. Create awareness that the coefficients of thermal expansion of cement paste and aggregates are different, and that this gives rise to microscopic stresses induced by any change of temperature.
2. Create awareness that daily temperature cycles represent a considerable loading of

ITZs separating the aggregates from the cement paste matrix, and that extreme weather events such as hail showers hitting concrete structures after solar heating represent a significant threat to the microstructural integrity of concrete.

2 The Nanoscopic Origin of Thermal Expansion of Cement Paste

The coefficient of thermal expansion of mature cement paste is a non-linear function of the internal relative humidity [Emanuel and Hulsey, 1977]. Provided that the material is either saturated by water or completely dry, the coefficient of thermal expansion is very similar to that of steel, but it is almost twice as large at an internal relative humidity amounting to some 65%, see Fig. 1. This material behavior is virtually independent of the initial water-to-cement mass ratio [Wang et al., 2018].

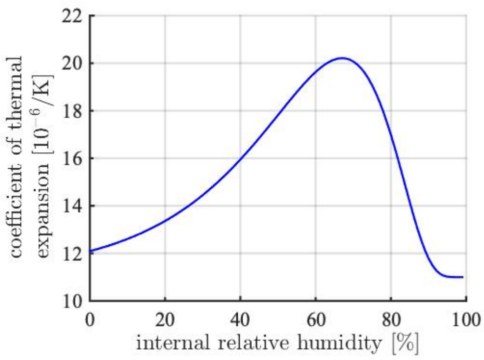

Figure 1. Coefficient of thermal expansion of mature cement paste as a function of the internal relative humidity of the material: evaluation of Eq. (3) of [Wang et al. 2018].

The thermal expansion behavior illustrated in Fig. 1 can be traced back to the release of water by nanoscopic C-S-H upon heating and to the uptake of water by nanoscopic C-S-H upon cooling [Wang et al., 2018]. These water migration processes are quasi-instantaneous and reversible, as demonstrated by means of proton nuclear magnetic resonance relaxometry [Wyrzykowski et al., 2017]. Nanoscopic water migration is linked to macroscopic thermal expansion (Fig. 1) as described next. For the sake of simplicity, the focus rests on *partially saturated* cement paste subjected to an *increase* of temperature. The solid skeleton of the material will expand according to its specific coefficient of thermal expansion, but this is only one part of the macroscopically measurable thermal expansion. In addition, the following processes will take place [Wang et al., 2018]:

- C-S-H will release water into the adjacent nanoscopic pore network consisting of gel pores and capillary pores.
- The radius of curvature of the menisci separating water-filled from air-filled domains of the microstructure will increase.
- The internal relative humidity will increase and the underpressure in the water-filled parts of the porosity will decrease.
- Subjected to smaller pore underpressure, the solid skeleton will expand.

The effective thermal expansion of mature cement paste is the sum of the classical thermal expansion of the solid skeleton described before the bulleted list, and the poromechanical expansion of the solid skeleton described in the bulleted list.

3 Thermal Stresses in Samples of Concrete Subjected to Uniform Temperature Changes

The present section is focused on samples of concrete subjected to a *spatially uniform* change of temperature. Notably, the coefficient of thermal expansion of cement paste is, particularly at intermediate relative humidities around 65%, significantly larger than that of the aggregates; compare Fig. 1 with the coefficients of thermal expansion of limestone, quartz, and granite, which amount to $4.75 \times 10^{-6}/\mathrm{K}$, $11.75 \times 10^{-6}/\mathrm{K}$, and $7.50 \times 10^{-6}/\mathrm{K}$, respectively. Upon heating, the cement paste matrix expands more than the aggregates. This activates tensile stresses acting on the ITZs covering the aggregates. These stresses can be computed analytically [Wang et al., 2019a; Königsberger et al., 2014a and 2014b]:

- Methods of continuum micromechanics allow for quantifying the average stresses experienced by the aggregates.
- Stresses experienced by the aggregates can be translated into corresponding stresses experienced by the ITZ based on (i) knowledge regarding the elastic stiffness of both the aggregates and the ITZ, and (ii) continuity conditions regarding both traction and displacement vectors across the two-dimensional interface between the aggregates and the thin but still three-dimensional ITZ.

4 Thermal Stresses in (Reinforced) Concrete Structures Subjected to Transient Heat Ingress

The present section is focused on concrete structures subjected to *transient heat ingress* from a surface exposed to solar heating. Corresponding temperature fields inside the structure are spatially nonlinear. The reference configuration, which is free of thermal stresses, is usually isothermal. Thus, temperature changes relative to the reference configuration are also spatially nonlinear. Multiplying the temperature changes with the coefficient of thermal expansion of concrete yields spatially nonlinear distributions of thermal strains. Provided that they are free to develop, they will not activate thermal stresses, but in case the thermal strains are constrained, thermal stresses will be activated. Such constrains are to be considered at two different scales: the cross-sectional scale (this is the smaller scale) and the macrostructural scale (this is the larger scale). Because two different scales are involved, the spatially nonlinear field of thermal strains is to be decomposed, in every cross-section, into three parts: (i) its average value, referred to as the thermal stretch of the structural element, (ii) its first moment, referred to as thermal curvature of the structural element, and (iii) the nonlinear rest. The latter has a vanishing mean value and a vanishing first moment. If this nonlinear part of the thermal strain field were free to develop, the cross-sections would undergo a warping deformation, i.e. they would not stay plane. However, it is well-known in structural mechanics that cross-sections of beams stay virtually plane (this is referred to as the Bernoulli-Euler hypothesis), even when the beam is subjected to thermomechanical loading. The nonlinear part of the thermal strain field is completely suppresses at the cross-sectional scale. Consequently, the nonlinear part of the thermal strain field is nullified by mechanical strains which have the same cross-sectional distribution and size as the nonlinear thermal strains, but the opposite mathematical sign. These mechanical strains are proportional to thermal stresses. They are self-equilibrated, i.e. they neither contribute to the normal force (because they have a vanishing mean value) nor to the bending moment (because they have a vanishing first moment), see [Wang et al., 2022].

The question whether the thermal stretches and curvatures are free to develop, constrained, or completely suppressed is to be answered on the macrostructural scale. In this context, the support conditions play an essential role. Provided that a structure is supported in a *statically determinate* fashion (this implies that support reactions and internal forces can be computed based on equilibrium considerations only), thermal stretches and curvatures are *free* to develop, i.e. no additional thermal stresses are activated. Provided that a structure is supported in a *statically indeterminate* fashion (this implies that support reactions and internal forces cannot be computed based on equilibrium considerations only, but additional deformation compatibility conditions are necessary), thermal stretches and curvatures are *at least constrained*, and this yields additional thermal stresses [Wang et al., 2022].

As regards concrete plates, the described decomposition of the thermal strain field is performed along directors of the plates (directors are the sum of all points which are on a normal to the midplane of the undeformed plate). The nonlinear part of the thermal strain field is prevented at the scale of the directors. This gives rise to self-equilibrated thermal stresses. Thermal stretches are typically considered to be free to develop in pavement slabs made of concrete, because of the joints between neighboring slabs. Thermal curvatures, in turn, are constrained by the subgrade on which the plate rests. Daily temperature cycles of pavement slabs made of concrete result in considerable tensile stresses experienced by the material [Schmid et al., 2022]. Extreme weather events, such as hail showers hitting a concrete pavement after several hours of intense solar heating, in turn, will almost inevitably lead to at least partial microcracking in the region of the ITZs [Wang et al., 2019b]. These cracks provide additional pathways for the ingress of aggressive species, threatening the long-term durability of the structure.

The same type of structural analysis regarding quantification of thermal stresses was applied to a reinforced concrete frame subjected to a moderate fire [Sorgner et al., 2023]. The analyzed structure is a part of a metro station. It consists to a top slab and a bottom slab, a right wall and a left wall, as well as two columns. Because of the spatially nonlinear part of the thermal strains, tensile stresses were activated in the core regions of the columns, i.e. in domains surrounding the axis if the columns. Tensile cracking affected more than 50% of the cross-sections, only some 11 minutes after the start of the fire. At that time, the temperature had increased, at the surfaces of the columns, to some 170 degrees centigrade only. It is concluded that even if fire brigades are capable to quickly extinguish a fire in the immediate vicinity of a reinforced concrete member, a detailed thermomechanical analysis appears indispensable, because significant thermal cracking might have occurred unnoticed *inside* the structural member.

6 Conclusions

- A process as seemingly simple as a change of temperature of concrete induces a nanoscopic water migration process: calcium-silicate-hydrates release water upon heating and take up water upon cooling. Through a poromechanical chain of processes, the described water migration effect manifests itself in a coefficient of thermal expansion of cement paste, which is a nonlinear function of the internal relative humidity, see Fig. 1.

- The coefficient of thermal expansion of cement paste is, particularly at intermediate internal relative humidities around 65%, significantly larger than that of the aggregates. Thus, temperature changes activate microscopic thermal stresses. Heating of concrete goes along with tensile stresses activated in the region of the interfacial transition zones. This is a threat to the long-term durability of concrete, as microcracking in the region of the interfacial transition zones provides undesired pathways for aggressive species to enter a concrete structure.
- Unreinforced and reinforced concrete structures exposed to the ambient environment are subjected to daily temperature cycles. Transient heat conduction goes along with spatially nonlinear temperature fields, and this inevitably activates self-equilibrated thermal stresses within cross-sections of structures. Additional thermal stresses are activated at the full scale of (reinforced) concrete structures which are supported in a statically indeterminate fashion. Daily temperature cycles represent a threat to long-term durability. Exposure to extreme weather events such as hail showers or fires will almost certainly damage (reinforced) concrete structures.

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ORCID

Bernhard Pichler: https://orcid.org/0000-0002-6468-1840

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