Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 57/1/57/2 (1989)

Artikel: Thermal incompatibility of concrete components and durability of structures

Autor: Veneanin, Srdjan D.

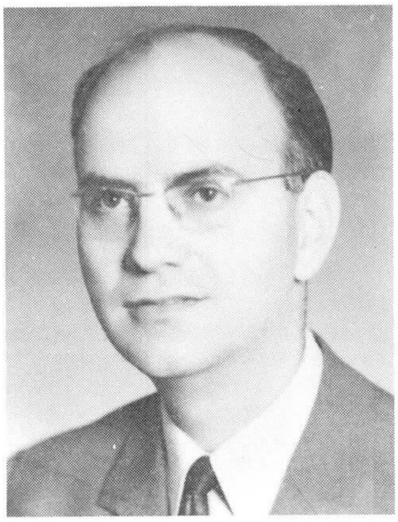
DOI: https://doi.org/10.5169/seals-44206

Thermal Incompatibility of Concrete Components and Durability of Structures

Incompatibilité thermique des composants du béton et durabilité des structures

Thermische Unverträglichkeit der Betonkomponenten und Dauerfestigkeit der Konstruktionen

Srdjan D. VENEČANIN
Docent
University of Beograd
Beograd, Yugoslavia



Srdjan Venečanin, born 1930, received his civil engineering degree at the University of Beograd, Beograd, Yugoslavia. He has designed reinforced and prestressed concrete structures. Now he lectures on Concrete Bridges at the Dep. of Civil Eng. of the University of Beograd. His research work is associated with durability of concrete structures.

SUMMARY

Unequal thermal expansions of aggregate and hardened cement paste reduce durability of concrete if it is exposed to temperature changes. Properties of aggregate which affect this phenomenon, and types of structures in which this phenomenon can appear are discussed.

RÉSUMÉ

Les dilatations thermiques différentes des granulats et de la pâte de ciment durcie réduisent la durabilité du béton s'il est exposé à des variations de température. Les propriétés des agrégats influençant ce phénomène ainsi que les types de structures concernés, sont décrits dans l'article.

ZUSAMMENFASSUNG

Die ungleichen Volumenänderungen der Zuschlagstoffe und der Zementkörner infolge von Temperaturänderungen verkleinern die Dauerfestigkeit des Betons. In der vorliegenden Arbeit wird über die Eigenschaften der Zuschlagstoffe, welche diese Phänomene beeinflussen, sowie über die Art der Konstruktionen, bei welchen sich derartige Fragen stellen, diskutiert.

1. INTRODUCTION

Unequal temperature volume changes of concrete components - aggregates and hardened cement paste - cause tensile stresses and cracks in concrete. This does not reduce much compressive strength, but cracks enable penetration of moisture and chlorides into concrete, and durability of such concrete is reduced.

This phenomenon is often called thermal incompatibility of concrete components (TICC). It appears if difference of coefficients of thermal expansion (CTE) of concrete components is sufficiently large, and if such concrete is exposed to sufficiently large temperature changes.

2. SHORT BACKGROUND

One of the first papers on TICC /1/ describes rapid failure of some cast stone steps in the winter 1938-39. An aggregate of unusually low CTE was used. The published discussion /2/ by ten writers was approximately five times as large as the original paper, and it shows the great interest for the theme.

In the last five decades the problem was discussed in journals, but "investigations in the literature and authoritative textbooks on the subject do not present a clear-cut picture of the effects that might be expected and some aspects of the problem are somewhat controversial" /3/. In fact some experiments confirmed theories on TICC, but some did not.

In the last ten years or so, analytical solutions supported the theories on TICC phenomenon /4, 5, 6/, and recent laboratory tests /7, 8/ and tests with concrete drilled from bridges /9/ absolutely confirm detrimental effects of TICC. Doubts that in specimens of young concrete, when exposed to temperature changes, are exposed to the effects of autogeneous healing and faster hydration during "hot" part of temperature cycles, which also were discussed in the literature /10/, have been taken into account: in specimens of young concrete, when exposed to large number of temperature cycles, and in old concrete drilled from bridges, there is no interference of autogeneous healing or faster hydration of cement.

A rewiew of the problem of TICC is given in the literature /11/.

3. MAIN THERMAL PROPERTIES OF COMPONENTS THAT AFFECT TICC

CTE of hardened cement paste varies between 9 and 25.4×10^{-6}/K, which is not large interval /12/. CTE of rocks which are usually used as aggregate in concrete, varies between negative values - contracting when heated - and 16×10^{-6}/K - see /12/.

However, carbonate rocks, which have very low values of CTE, sometime have nonelinear relationship between strains and temperature; they are often nonhomogeneous to a high degree; after cyclic temperature changes they may have residual strains; and often they are more or less thermally anisotropic. All of these properties are important for the phenomenon of TICC, and it is obvious that they have to be studied, and that they make CTE very poor tool to describe thermal volume changes of carbonate (and some other) rocks.

Nonelinear relationship means that inside a temperature range of, say, 100 K, CTE can be lower and higher, for some subintervals, than the average value for the whole range. Usually for the lower temperatures CTE of limestones is lower - which means that damaging effects of TICC could be bigger at lower temperatures.

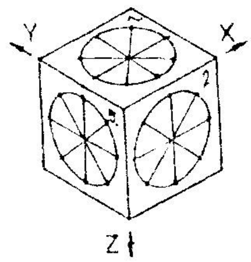
Nonhomogeneity means that average value of CTE should be measured with as much as possible readings. Special technique has been devised: cube rock specimens have been used to measure temperature strains on each cube face in four directions - 24 readings at each temperature level per specimen (see e.g. /9/).

Residual strains after cyclic temperature changes mean different coefficients of thermal contraction. Since after each temperature cycle new residual strains can appear, this means different CTEs after each cycle - up to a point when these residual strains between two subsequent cycles reduce to zero!

Thermal anisotropy mostly depends on orientation of calcite minerals - since calcite crystals are thermally anisotropic: they expand in the direction of one crystallografic axis, and contract in the directions of other crystallografic axes. If calcite crystals in the rock are oriented in the same direction, they transfer this anisotropy to the rock. This parallel orientation is often present to some degree, and degree of thermal anisotropy of the rock depends on the degree of parallel orientation of calcite crystals in it. The higher the thermal anisotropy of aggregate rock, the higher are the damaging effects of phenomenon of TICC. It is quite possible that the average value of CTE of a rock is rather near to that of hardened cement paste, but that damaging effects of TICC are high because thermal anisotropy of aggregate rock is high.

4. MECHANISM OF DETERIORATION OF CONCRETE DUE TO THE TICC

Generally TICC do not have to reduce much compressive strength of concrete. However it causes cracks in the concrete, mostly bond between aggregate and hardened cement paste is broken, and then moisture or chlorides penetrate concrete and damage it. So it is quite possible that TICC alone is not able to damage concrete significantly, and that frost action or chloride action is not able to damage concrete alone, but when TICC is combined with one of these two actions, concrete can be damaged. Combination of two or more adverse actions exponentially raises possibilities of damages of concrete.



Cube rock specimens measuring temperature strains parallel to the cube edges and in the directions of diagonals

5. TYPES OF CONCRETE STRUCTURES IN WHICH TICC CAN BE DANGEROUS

It is necessary that components of concrete change their volumes differently when exposed to temperature changes. So the structure must be exposed to temperature changes beside having components of different thermal properties. Such types of structures are bridge decks, concrete roadways, concrete airport runways, taxiways and aprons, industrial chimneys, prestressed concrete pressure vessels, cryogenic concretes, roof tiles, and other concretes exposed to temperature changes.

If climatic conditions are severe, like in the Middle East desert regions where daily temperature changes can be large, or in Alaska or Siberia where seasonal temperature changes are large, all concretes exposed to the sun rays could be damaged by TICC. In some cases direct sun rays cause concrete surface to have nearly 30 K higher temperature than the air temperature is.

5.1 Bridge decks

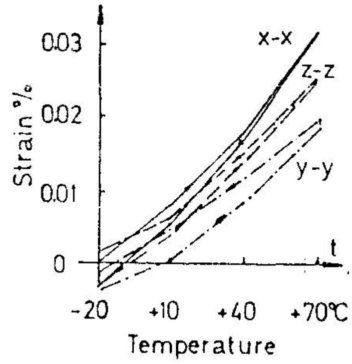
Great surface of bridge slabs is exposed to direct sun rays, and temperature measurments show great differences of slab temperature and temperature of other parts of concrete bridge. This means that concrete of a bridge slab is exposed to rather large temperature changes - larger than the changes of the surounding air's temperature.

Cores drilled from the slab of a ten years old bridge were exposed to the temperature changes between -20°C and +60°C for 28 days - two complete thermal cycles per day. Then four of these cores, and four of reference ones, drilled from the slab of the same bridge - but kept at room temperature, were exposed to water pressure for a week: each day water pressure has been raised for one atmospehere, and kept seven hours per day under pressure. In the first four cores penetrated 72% more water than in the reference ones. It was obvious that new cracks developed in the specimens which have been heated and cooled in the thermal chamber.

CTE of limestone that has been used as coarse aggregate for this bridge has been measured for the temperature range between -20°C and +65°C, and was found to be about $3x10^{-6}$/K. Such a low CTE of coarse aggregate, and developement of new cracks in the bridge cores, show that TICC considerably contributed to the degradation of the bridge concrete /9/.

5.2 Concrete pavements

Concrete exposed to the direct sun rays reaches considerably higher temperatures than the surounding air. This means that range in which temperature of this concrete changes during one day is higher than diurnal temperature changes of the air. For concrete pavements this is very important because these concretes are exposed to the sun with great area, and TICC effects are to be expected /13/.



Strains vs temperature for three orthogonal directions shows thermal anisotropy

Contractors prefer to use limestones for concrete pavements because this kind of aggregate usually gives excellent compressive strength, even excellent tensile strength of concrete - and owner of the works require mostly control of compressive strength after 28 days. However limestones are the rock type which can have extremely low CTE - and combination of low CTE of aggregate and large range of temperature changes are essential conditions for detrimental effects of TICC.

Large milage of concrete pavement in Missouri, where it was noted that desintegration characterized initially by a typical map-cracking, occurred only when a specific kind of coarse aggregate has been used in concrete - has been reported by Reagel and Willis in their discussion /2/ of the paper /1/. Detrimental effects of TICC have been suspected, but Reagel and Willis note that it was found that most serious desintegration was always associated with the use of an aggregate having a large CTE. But they also note that this could be explained by more factors and phenomena whose effects overshadow any effect of thermal expansion.

Difficulties in separating effects of TICC and, for example, autogeneous healing, higher rates of hydration during "hot" part of temperature cycle (in experiments with young concrete), or "rim reaction", resulted in contradictory results of tests, and authoritative textbooks on the subject show some reserve when discussing this problem.

In the case of the Missouri pavements, thermal anisotropy of aggregate could also be the reason of desintegration of concrete.

5.2 Prestressed concrete pressure vessels (PCPV)

Since the first nuclear reactor with PCPV came into operation in France in 1959, the normal operating pressures and temperatures for this kind of structure have been gradually rising. Today operating pressures are of the order of 10 MPa, and operating temperatures of concrete reach 100°C - the steel liners reaching 300°C or even more.

Thermal gradient in PCPV requires high amount of prestressing steel around the vessel, but the lower CTE of the concrete, the lower amount of prestressing steel is needed. So often limestone of low CTE is used as crushed aggregate for concrete of PCPV - and problem of TICC is neglected. The same reasons apply for nuclear containment vessels.

To save on prestressing steel in such a way is a dangerous thing because low CTE of concrete is obtained by using aggregate of low CTE, making difference of CTEs of aggregate and hardened cement paste bigger - and enhancing detrimental effects of TICC. When TICC starts cracking in such concrete, then "gas in cracks" loading problem, arising from leaks in the steel liner, exponentially raises possibilities of leakage of radioactive gasses outside the vessels.

The point is that TICC problem can be solved only by using concrete components of approximately the same CTE, and problem of stresses due to the thermal gradient can be solved by adding more prestressing steel - and not only by using concrete of low CTE. Conclusion should be that using thermally compatible concrete components means more prestressing steel, but it means less trouble during operation of reactor: less shutdowns during operation due to the leakage of radioactive gasses, and less consequent damages to the environment, etc.

5.4 Industrial chimneys

Though modern industrial chimneys have more than one flue in the exterior reinforced concrete shell, and the flue gasses are too hot and need liners, concrete shell still has higher temperature than the surrounding air. The temperature of exterior concrete shell is often changing, especially in higher parts of the chimneys, where constantly changing winds change concrete temperature. If concrete of such a chimney shell is made of thermally incompatible components, the cracks will appear soon.

The problem is rather similar as in PCPV: temperature gradient requires more reinforcement if CTE of concrete is higher - and vice versa. So it happens that some designers and contractors prefer limestone of low CTE for concrete aggregate, because this relults in concrete of low CTE, and save on reinforcing steel. However, this means trouble during operation of the plant - and, possibly, shutdowns and repairs of concrete.

5.5 Roof tiles

Measurements of temperature of roof covers which are exposed to sun rays show sometimes 40 - 50 K higher temperatures than the air. Cloudy weather affect temperature changes: some measurements have shown changes of 17 K in 7.5 minutes. The rain could be the reason of fast temperature changes of surfaces exposed to sun rays: some measurements have shown 8.3 K changes in only one minute, and 37 K in 30 minutes, of the surface hot due to the sun rays, when it was exposed to the rain.

Such severe conditions must destroy composite material if it consists of components with different CTE. If roof tiles are made of sand and cement, the sand should be quartzitic - with high CTE, which is near to the CTE of hardened cement paste.

Replacement of asbestos fibres by polymer fibres should cause trouble, because polymers usually have very high CTE, much higher than the CTE of hardened cement paste.

5.6 Concrete structures at cryogenic temperatures

Concretes exposed to cryogenic temperatures exhibit irregular volume changes when cooled: usually roughly between -20^{o}C and -70^{o}C concrete expands when cooled! Namely hardened cement paste expands when cooled, while nothing similar happens to the aggregate. This means great influence of TICC - and independently of the type of agregate, large tensile stresses and corresponding cracks appear. This is probably one of the main reasons why compressive strength of concrete decreases very much after only few temperature cycles in this range. Type of cement, moisture content, and pore structure are the factors affecting this phenomenon.

6. SOME CONSLUDING REMARKS

The problem is that nobody measures CTE of aggregate which will be used for a concrete. So there is no possibility at all to suspect TICC effects when concrete cracks. And everybody can see moisture or salts, and ascribe cracking to frost or chloride actions, or to something else.

Concrete structures described in Section 5 of this paper could be affected by TICC, but all kinds of concrete structures exposed to temperature changes could be affected by TICC - e. g. industrial floors.

If limestone aggregate is to be used for a structure which will be exposed to temperature changes, CTE of this rock should be measured for the temperature range in question. Also other properties discussed in Section 3 of this paper should be checked.

Practically all climatic conditions similar to the ones prevailing in the desert regions of the Middle East require cautiosness with respect to TICC.

Rocks containing silica minerals should be good with respect to TICC because they have high CTE - near to the CTE of hardened cement paste.

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