Optical Fiber Distributed Sensing System Applied in Cement Concrete Commixture Research

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Abstract. *DTS are unique optical-fiber distributed systems for measuring of temperature or mechanical tension. These systems use non-linear properties of optical fibers. Optical fiber can therefore be used not only for telecommunication purposes, as is currently the case, but also as a sensor. Optical fiber used by the DTS system can be therefore imagine as thousands of sensors placed along the route, taking all advantages of optical fiber, such as resistance to electromagnetic radiation, safe use in flammable and explosive environments, resistance to aggressive environments, small sizes, easy installation and maintenance-free operation. The properties of DTS system mentioned above seem to be ideal for detailed mapping of the hydration heat of concrete mix in the transition to a rigid structure. Values based on measurements will be used to better understanding of the processes inside the concrete mixture (individual samples) and will serve to develop better and more durable mixture.*

Keywords

Optical-fiber distributed sensing systems, nonlinear effects, temperature-profile measurements, cement concrete commixture, hydration heat.

1. Introduction

DTS (Distributed Temperature Sensing Systems) are unique systems able to measure temperature profile and mechanical tension profile along the optical fiber. Optical fiber, which is commonly used as data transmission medium, serves as a distributed sensor for sensing non-electrical quantities. Optical fiber, in the meaning of DTS systems, could be understood as a lot of thousands of sensors placed in a series, taking advantage of all prosperous properties of optical fibers, which are, for example:

- Immunity to electromagnetic disturbance.
- Safe in flammable and explosive areas.
- Could be immune to aggressive environments (in case of use of special types of cables).
- It is possible to measure in thousands of points in the same time..
- Easy installation and almost no need to maintenance.
- Non-stop monitoring of temperature, pressure or tension changes with localization of disturbance.
- Length of sensing fiber up to 10 km in case of DTS based on the stimulated Raman scattering and up to 30 km in case of use DTS based on stimulated Brillouin scattering.
- Long term monitoring based on long optical fiber time life.

2. Principle of DTS Systems

The principle of DTS systems is based on the principle of optical time domain reflectometry (in Fig. 1). It means that very short optical impulse of width about 10 ns in time is launched into the fiber and the system measures the amount of power returned back depending up to scattering and reflections. The wavelength of the pulse launched into the fiber is 975 nm, 1064 nm or 1550 nm depending on the DTS system construction. Some part of the optical power returns back with the same wavelength (the elastic (Rayleigh) scattering and reflections) and some power returns with different wavelength (the nonelastic scattering). The nonelastic effects causing the change of wavelength are named Raman and Brillouin stimulated scattering [2] [4].

The DTS systems are divided into two groups depending up those two principles – Raman and Brillouin scattering. The DTS systems based on the Raman scattering detection use multimode optical fibers with core diameter of 50 μm with large value of the numerical aperture (NA) as a sensor. This requirement is implied by the need of good guidance of the scattered light which has very

small power. The spectral-attenuation characteristic of the multimode optical fiber limits the range where those systems could be used to 8 - 10 km in length.

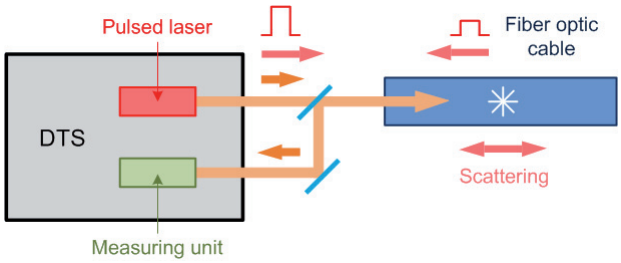

Fig. 1. The basic principle of a DTS system.

On the other hand the DTS systems based on stimulated Brillouin scattered light detection use single mode optical fiber with the core diameter of 9 μm. It enables measurements more than 30 km in length.

The resolution in length of those DTS systems is usually 1 m if the resolution 0.01 °C is used. In the most precise DTS systems based on the stimulated Brillouin scattering the longitudinal resolution is 0.5 m with resolution 0.05 °C in temperature. It implies that those systems must be very precisely manufactured [3], [4].

3. Stimulated Raman Scattering

If we take a look at the light returned back from the optical fiber we can see that almost every power is returned with the same wavelength which was launched into the fiber (the Rayleigh scattering). However a small amount of power returns with a changed wavelength. This effect has been predicted by the Austrian scientist Smekal in 1923 and has been studied theoretically in 1925 - 1927 by Heisenberg, Dirac, Kramers and Schrödinger. In 1928 this effect has been proved experimentally by the Indian scientist Chandrasekhara Venkata Raman after whom this effect took its name [1], [5].

The scattering effect could be observed at time of collision between photon and a molecule of the material of the optical fiber. Approximately one thousandth (10^{-3}) of the optical power contributes to the elastic collisions. During the elastic collision the energy of the molecule and the photon is not changed (in Fig. 2 denoted E) and the wavelength of the incident light does not change. This leads to the Rayleigh scattering. Rayleigh scattering behaves like a lot of point sources, because it emits the light into all angles. Considerably smaller part of the power (cca 10^{-8}) contributes to the nonelastic collisions. During the nonelastic collision the incident photon transmits some part of energy to the molecule of the material or receives some energy from the molecule. Regarding to the fact, that energy of the photon corresponds with its frequency, transmission or acceptance of energy leads to changes in frequency and wavelength of the light. This phenomenon is called Raman scattering [1], [2].

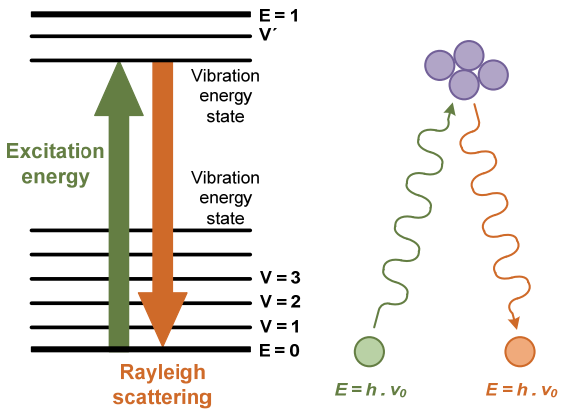

Fig. 2. The origin of the Rayleigh scattering.

During the nonelastic collision kinetic energy of the molecule remains the same, only the internal energy changes. Change of internal energy resulting in transition to higher or lower vibrating - rotation state. The difference between incident and emitted light is called Raman shift and corresponds with a frequency band in Raman spectrum (Fig. 3). To detect the Raman frequency shift the light source needs to be monochromatic.

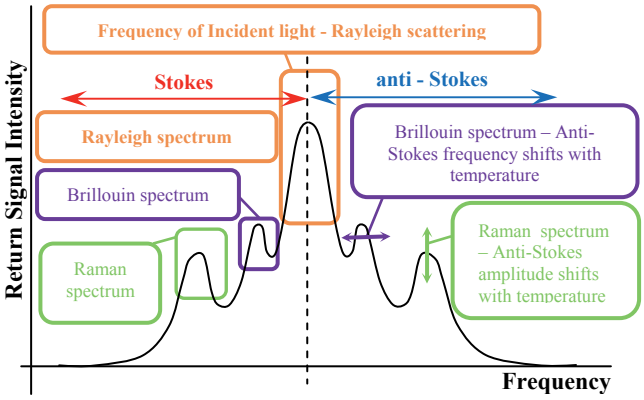

Fig. 3. Raman spectrum of scattering radiations.

There are two possibilities which could happen during the nonelastic collision. The energy of the photon could increase or decrease. If the energy of the photon decreases, the energy of the molecule increases and the molecule moves on higher energetic state. The energy of the photon has decreased so the frequency of the photon decreases. It corresponds with so called Stokes region in the Raman spectrum (see Fig. 4, *h* is the Planck's constant). It is the red shift to lower frequencies or higher wavelengths [1].

During the collision the molecule could accept the energy of the photon and move on higher energetic level. After that the molecule could move to lower energetic level, but higher than the original one. The molecule stays on higher vibrating state and the energy needed to stay on this level is taken from the photon. So the energy and frequency of that photon is lower that energy before collision.

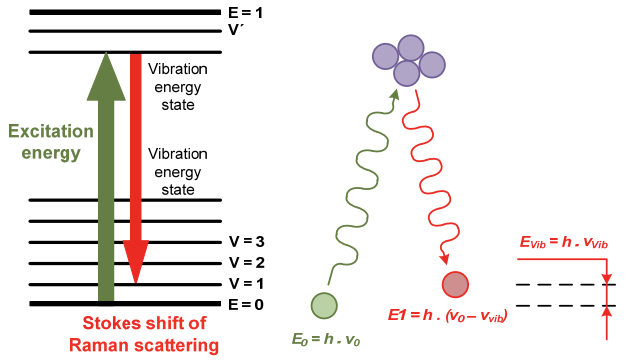

Fig. 4. The Stokes shift.

On the other hand the energy of the photon could increase after the collision. In that case the photon receives energy from the molecule if the molecule moves to the lower energetic level than the original one. This region of frequencies is called anti-Stokes region (see Fig. 5, h is the Planck's constant). That shift is a blue one because the energy and corresponding frequency is shifted to higher values.

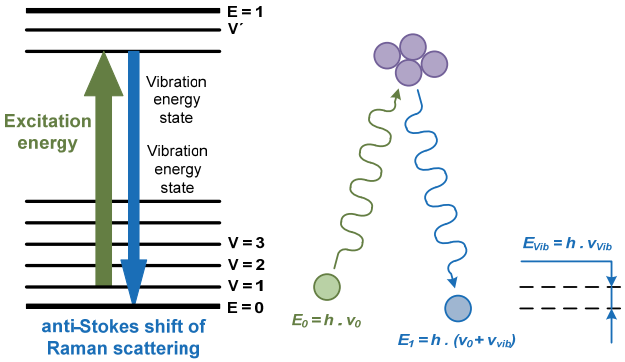

Fig. 5. The anti-Stokes shift.

The key property of molecules which enables the Raman scattering is their polarisability α. It represents the ability of electrical field $\boldsymbol{E}$ to cause creation of the dipole moment μ_0 in molecule [1] [5],

$$\mu_0 = \alpha \cdot E \,. \tag{1}$$

In case of molecule with stabile geometry the polarisability is denoted α_0. In some distance $\boldsymbol{\Delta r}$ from the stabile geometry of the molecule the immediate polarization is:

$$\alpha_{\rho\sigma} = \alpha_0 + \left(\frac{\partial \alpha}{\partial r}\right)\Delta r \,. \tag{2}$$

If the atom or molecule is in its sinusoidal vibrational or rotation mode, Δr could be written in form of sinusoidal function as a function of vibration frequency v_{vib} and time t:

$$\Delta r = r_{\max} \cos\left(2\pi v_{vib} t\right) \tag{3}$$

where $r_{\max}$ is the maximum vibration amplitude. The light radiation of specified frequency of v_0 is induced by the electrical field $\boldsymbol{E}$, which has sinusoidal shape also:

$$E = E_{\max} \cos\left(2\pi v_0 t\right) \tag{4}$$

where $E_{\max}$ represents the maximum of the electrical field induced. If we use (3) and (4) in (2), we have the final equation as follows

$$\begin{aligned} \mu_0 &= \alpha_0 E_{\max} \cos\left(2\pi v_0 t\right) + \\ &+ E_{\max} r_{\max} \left(\frac{\partial \alpha}{\partial r}\right) \cos\left(2\pi v_{\text{vib}} t\right) \cos\left(2\pi v_0 t\right) \end{aligned} \tag{5}$$

Using the formula for multiplication of two goniometric cosine functions:

$$\cos a \cdot \cos b = \frac{1}{2}\left[\cos\left(a+b\right) + \cos\left(a-b\right)\right] \tag{6}$$

we get the final equation determining the dipole momentum μ_0:

$$\begin{aligned} \mu_0 &= \alpha_0 E_{\max} \cos\left(2\pi v_0 t\right) + \\ &+ \frac{E_{\max} r_{\max}}{2} \left(\frac{\partial \alpha}{\partial r}\right) \left[\cos\left(2\pi t\left(v_0 + v_{vib}\right)\right) + \cos\left(2\pi t\left(v_0 - v_{vib}\right)\right)\right] \end{aligned} \tag{7}$$

The first part of this equation is the Rayleigh scattering (only the frequency of incident light v_0 is used). The second part of (7) represents the Raman scattering, its Stokes part $(v_0 - v_{vib})$ and anti-Stokes part $(v_0 + v_{vib})$ respectively – see Fig. 4 and 5. From the second part of (7) it is obvious that the existence of the Raman scattering depends on the change of the polarisability $\partial\alpha$ with change of the distance ∂r.

4. DTS Systems that Use the Stimulated Raman Scattering

In the DTS system that uses the stimulated Raman scattering in optical fiber the anti-Stokes part of the spectrum is the most important part. This part of spectrum changes its intensity if temperature changes along the optical fiber – see Fig. 3. The Stokes part, on the other hand, is independent on temperature. DTS systems are based on the principle of intensity changes of the anti-Stokes part compared with the Stokes part:

$$R(T) = \frac{I_{a-S}}{I_S} = \left(\frac{\lambda_S}{\lambda_{a-S}}\right)^4 \exp\left(-\frac{hc\,v_{vib}}{kT}\right) \exp\left(-\Delta a z\right) \tag{8}$$

where $I_{a\text{-}S}$ is intensity of the anti-Stokes part of spectrum, I_S is the intensity of the Stokes part of spectrum, λ_S is the Stokes wavelength, $\lambda_{a\text{-}S}$ is the anti-Stokes wavelength, h is the Planck's constant, c is the speed of the light in vacuum, v_{vib} is the vibration frequency, k is the Boltzmann constant, T is the thermodynamic temperature, Δa is the optical attenuation between the Stokes and anti-Stokes part of the spectrum, z is the distance from the optical fiber face end [1], [2].

5. Research of Concrete Mixtures

While using DTS system in the civil engineering we are able to specify properties of new and existing construction materials, verify their function in various surrounding environments and prevent their failure. The subsequent identification of the caused degradation can be quite significant to extend their working life. Typical example of applying DTS systems in civil engineering can be a research of concrete mixtures.

Placement of optical fiber into the concrete mixture sample allows us to precise mapping of the temperature profile depending on time, i.e. the rate of heat release during hydration. A sample of simple concrete using slag Portland cement and aggregates of size fraction from 1 to 2 mm was created for measurement. The sample was placed in the wooden (spruce) test mould; dimensions of this mould were 400 mm × 400 mm × 350 mm (Fig. 6); in which a layered meander from multimode optical fiber of dimensions of 50/125 micrometers was previously created.

Fig. 6. Wooden test mould for concrete mixture research.

Layers of meander were 100 mm apart, respectively, in the test mould there were 4 layers with a total length of optical fiber of 15.5 m. The mould was filled and compacted by plain concrete sample and the end. DTS measurements showed clearly three known periods of concrete mixture aging (cement hydration) [6]:

- *Induction period*; 10 to 15 minutes - wetting of cement grains, the beginning of cement hardening. The temperature of the concrete mixture fluctuated around 15.5 °C at an ambient temperature of 18.5 °C (Fig. 7), 1 to 2 hours - creating of crystals nucleus, the temperature stagnation at 16 °C.
- *Transition to solid state*; 2 to 24 hours - noticeable increase of hydration heat, obvious rise in temperature toward the center of the preparation (Fig. 8).
- *Period of stable structure*, within 28 days - hydration heat is unified together with the ambient temperature, visible accumulating effect of concrete mixture (Fig. 9).

In Fig. 7 individual monitoring meanders placed inside of the preparation are shown, whereas layer No. 4 of meander was placed on the very bottom of test mould.

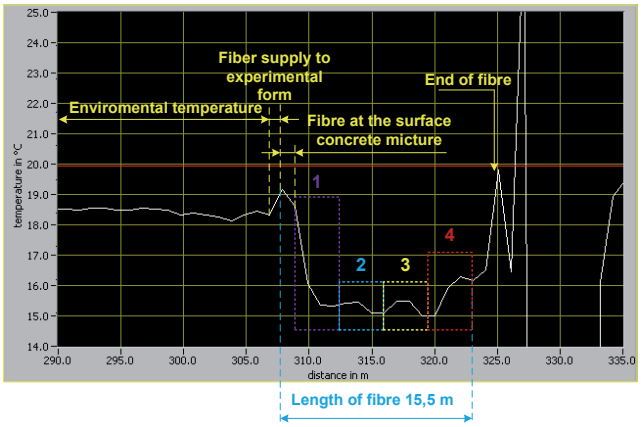

Fig. 7. Process of hydration heat after placement of concrete mixture into the test mould.

In the case of the situation after 5 hours, which is shown in Fig. 8, steady temperature around the value of 20 °C is apparent. The value of heat of hydration within the concrete remained stable throughout the test on the value of 17.5 °C. However, it is possible to monitor the increase (about 0.3 °C) toward the centre of each layer in the meander.

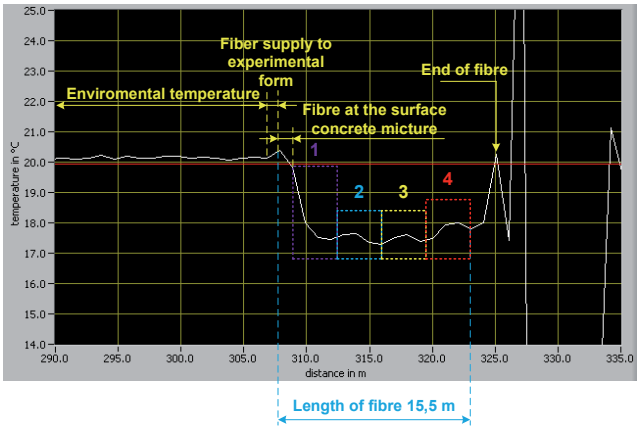

Fig. 8. Process of hydration heat after 5 hours after placement of concrete mixture into the test mould.

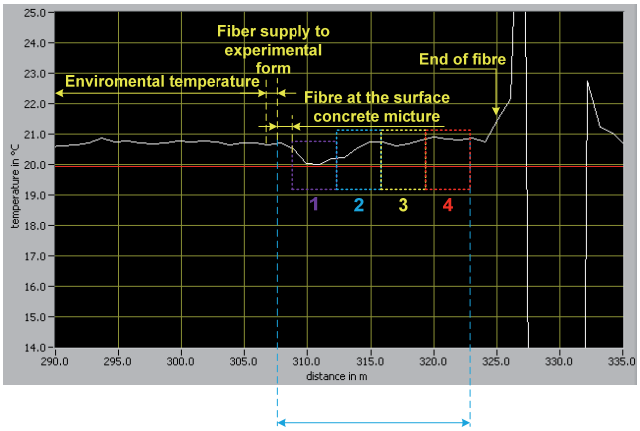

Fig. 9. Process of hydration heat after 26 hours after placement of concrete mixture into the test mould.

In the case of surveyed concrete mixture inside the test mould, the value of heat of hydration reached the temperature of the surroundings, concretely to the value of 20.8 °C, after 26 hours after placement of concrete mixture into the test mould. Only in the top layer of concrete mixture (layer 1 and a part of layer 2) the hydration heat reached the temperature about 0.8 °C lower than the surroundings.

The accumulate effect of concrete mixture can be substantially monitored after 36 hours from placement in a test mould (Fig. 10). Layer 1 has reached the level of ambient heat, respectively 20.5 °C; the temperature in the remaining layers was accumulated to levels close to the value of 21.8 °C.

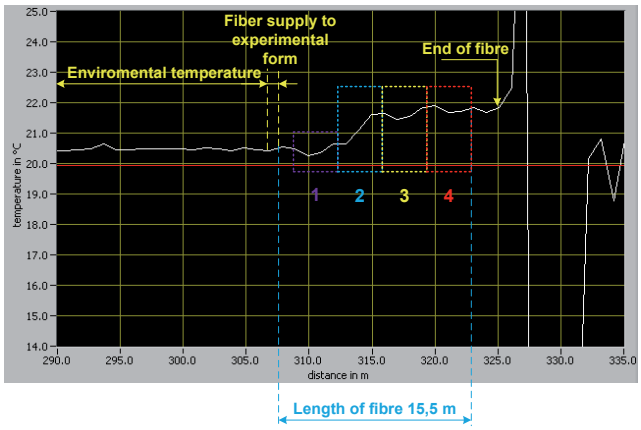

Fig. 10. Process of hydration heat after 36 hours after placement of concrete mixture into the test mould.

The overall course of the release of heat in the concrete mixture during the hydration of individual layers is shown in Fig. 11. There are noticeable differences in the values of heat of hydration, depending on the layer of concrete.

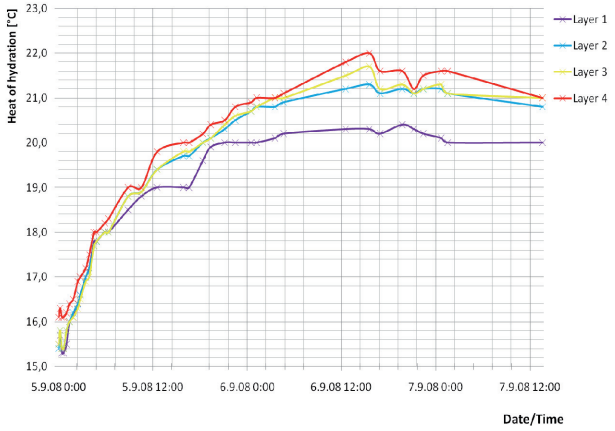

Fig. 11. Releasing of the heat during hydration process.

Strength of concrete can be expressed as a function of time. The speed of hydration is corresponding to increasing in the strength of concrete mixtures. Acquisition of strength is associated with the speed of filling the space between the hydrating cement grains neoplasms. Empirical relation (Weber) (9) expresses the growth of the strength of concrete R_B

$$R_B[\mathrm{MPa}] = A.R_C.w.\exp(B.w).\exp\left(\frac{C.w}{t^{0,55}}\right) \qquad (9)$$

where A, B and C are empirical constants depending on the type of used cement, w is the water factor, R_C is compressive strength of cement [MPa] and t is the time period from mixing of concrete in days [6].

The advantage of applying of DTS system is the accurate determination of the temperatures in all periods. Perfect environment to achieve the required handling strength of the material can be formed. Such a situation may arise during warming of concrete mixture for reasons of reducing the hardening time of concrete in regulating the temperature versus time. During the warming of concrete mixture negative forming of structure mostly occurs due to the accelerating hydration.

Heat exchange of concrete mixture with the surroundings was found during sample exposure to the direct sunlight at air temperature of 22.2 °C. The sun rays caused increasing temperature of the internal environment by 5°C. Duration of temperature exchange between the surroundings and sample lasted 4 hours. Creating a solid structure at higher temperatures was observed at evolution of hydration heat. The extreme was found in used concrete mixture placed in direct sunlight during the measurement. When the ambient air temperature was 22.2 °C after 12 hours extreme of 10 kJ/kg occurred (see Fig. 12.).

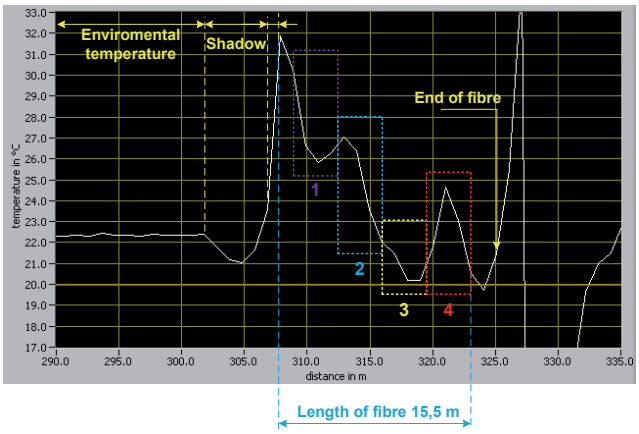

Fig. 12. Process of hydration heat of concrete mixture after test mould placing to the direct sunlight. (after four days of process).

The remarkable changes in the distribution of heat of hydration within the concrete mixture are shown in Fig. 12. The orientation of the test mould caused changes in the distribution of hydration heat, when one side of the test mould was oriented directly to the south. Fig. 12 shows us that the distribution of hydration heat in laboratory conditions is quite different from real situations.

6. The Future of Application of DTS Systems to the Research of Concrete Mixtures

Optical fiber distributed systems represent a new way to research concrete mixtures, which can cause a new perspective on the issue. These systems can be applied to explore new concrete mixtures, in which durability in the longer term is not verified. Another application can be offering directly for real conditions in the civil engineering industry. During the initial monitoring it will be possible to determine whether the material went through all stages of setting and obtained the resulting tensile strength and pressure, eventually the absence of negative formations due to accelerating the process of hydration.

Generally warming cannot exceed recommended value of 30°C after 3 hours and the like, or for example in the cooling stage exceed the optimal speed of decline of temperature, thereby avoiding exceeding strength of concrete mixtures in tensile (depending on internal and external stress) as well as cracks. It is obvious that the processes and distribution of hydration heat inside the concrete mixtures are significantly different for the laboratory measured values and the real situation**.**

Application of DTS systems into the civil engineering industry could therefore bring both, the new concrete mixtures, new methods and ways of concreting in real terms and also monitoring, which is necessary for reasons of compliance with the boundary conditions for ripening.

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