Fédération Internationale du Béton
Proceedings of the 2nd International Congress
June 5-8, 2006 – Naples, Italy

ID 17-26 Session 17 – Monitoring, maintenance, repair, residual life and failures

Monitoring of Early and Very Early Age Deformation of Concrete Using Fiber Optic Sensors

Glišić, B., Inaudi, D.
SMARTEC SA, Via Pobbiette 11, 6928 Manno, Switzerland

INTRODUCTION

Concrete is the most used construction material and the percentage of concrete structures is over 50% in Switzerland [1]. Durability of concrete structures strongly depends on early age behaviour of the structure [2]. Hydration is a complex physico-chemical exothermal process. During hydration, the water-cement suspension transforms to hardened cement paste; strength and stiffness of concrete increase; a considerable amount of heat is discharged; and early age deformation occurs. The deformation due to hydration is caused by hydration heating and cooling and by material transition to hardened cement paste (autogenous deformation). Early age deformation is often restrained by previously poured parts of structure, or by other structural elements (steel or old concrete in case of hybrid structures, walls, foundations etc.). Therefore at early age, residual tensile and compressive stresses are generated. Residual tensile stresses, generated before the tensil strength of concrete is fully developed, cause early age cracking.

Studies and research [3, 4, 5] have shown that early age cracking of concrete can significantly increase the vulnerability of structures to noxious environmental influences. The cracks form "open doors" to the infiltration and penetration of noxious substances such as chlorides [6] and sulphate water [7]. These substances attack the concrete and rebars, and damage the structure, thereby reducing its long-term capacity and durability.

Figure 1 [8] shows the influence of early age cracking on durability for a hybrid old concrete-new concrete structure. Even small gains in concrete performance during very early age, have a consequence of extending considerably the life span of the structure. How does one evaluate the risk of the early age cracking? Generally there are two approaches, numerical simulation and monitoring. Numerical simulations are very complicated because of the problem complexity. They may be successful [8], only after calibration provided by measurements (notably of concrete parameters as elastic module, strength, creeping ratio etc.). Data collected by early age monitoring represent a unique source of information for understanding the real concrete behaviour.

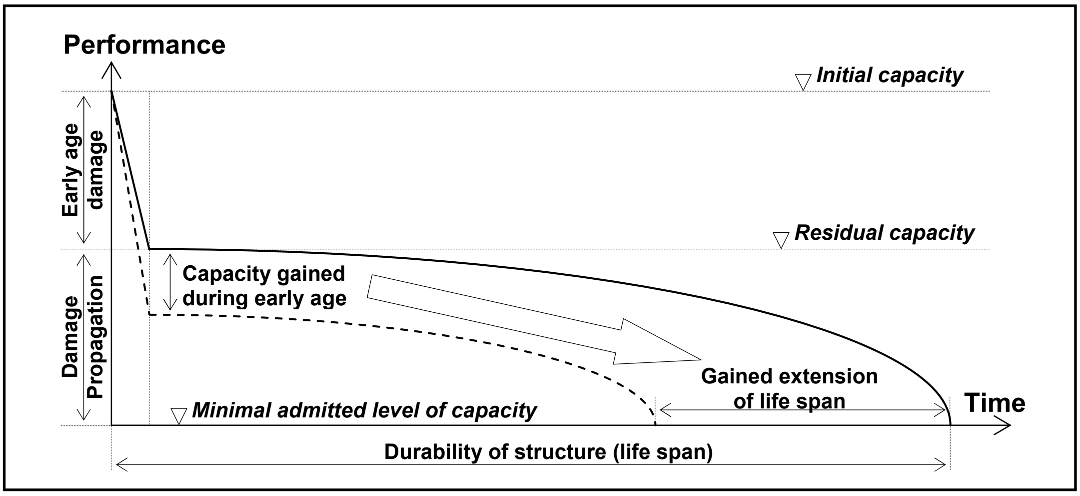


Fig. 1. Influence of the early age damage on the durability of an old-concrete – new-concrete hybrid structure [8].

It is recommended to start deformation monitoring of concrete structures from the moment of concrete pouring. In this way, the whole history of deformation is collected. This includes the very early age deformation which is generated while the concrete is still not hardened. For this purpose, it is necessary to provide the monitoring system with sensors that are capable of such measurements.

Keywords: monitoing, concrete, early age, very early age, fibre optic sensors

EARLY AND VERY EARLY AGE OF CONCRETE

The period which begins with pouring and finishes when all thermal processes in concrete are calmed is considered here as the early age of concrete [9]. It consists of the dormant period and the period of intense heat release, until concrete temperature is balanced with the environment temperature. The duration of the early age varies from a couple of days to several weeks depending on the thermal properties of the concrete components, the heat production potential of cement, the additives, the environmental conditions (temperature and relative humidity), the cure (thermoisolation) and geometry of the concrete element (massive and thick elements need more time to cool than thin elements).

The early age of concrete is an important period in the life of a concrete structure. Therefore during this period it is very important to take care of concrete, since a significant part of the hydration process and the mechanical properties (strength and stiffness) are developing at this stage. Due to the hydration process and the external influences, different types of deformation can appear. Residual and non-desirable stresses may also be generated. Since the strength of concrete at this stage is still low, the stresses can provoke cracking which affects the concrete resistance against unfavourable environmental conditions and decreases the durability of structure.

The period included in the early age, during which the concrete is still not hardened, is conventionally called the very early age [9]. The measurements show that during this period concrete owns a certain initial stiffness and strength [10, 11, 12]. The duration of the very early age is between several hours and one day depending mainly on the rate of hydration, concrete composition (notably the water-cement ratio) and curing conditions.

DEFORMATION OF CONCRETE AT THE EARLY AND VERY EARLY AGE

The early age deformation of concrete is provoked by internal and external causes that have mechanical, thermal or hydraulic origins [14, 15, 16, 17]. The early age deformation sources are presented in Table 1.

Tab. 1. Origins of the early age deformation.

	Mechanical	Thermal actions	Hydraulic actions
Internal	-	Hydration heat	Hydration hydraulic processes
External	Load	Ambient temperature variation, natural or artificial	Ambient humidity variation, natural or artificial

Six following forms of the early age deformation are distinguished [16, 17]: plastic shrinkage, autogenous shrinkage, drying shrinkage and swelling, carbonatation shrinkage, thermal deformation (expansion and contraction), load and creep deformation.

Some of them could appear simultaneously or sequentially. In this case, their sum represents the total deformation. Each deformation appearance, its origin and consequences, are briefly described as follows.

The plastic shrinkage can appear before solidification, while the concrete still retains its plastic properties. It is caused by premature lose of water due to evaporation or absorption of water by dry porous material (soil or existing concrete) which is in contact with the observed concrete. Plastic shrinkage affects only superficial parts of the concrete and is avoided by using appropriate cure techniques (protection by napes or regular moisten).

Autogenous shrinkage is a direct consequence of the chemical and physical processes provoked by hydration. The volume of the hydrated cement paste is approximately 8 to 12% smaller than the initial volume of utilised water and cement. This diminution of volume does not change the apparent dimension of the hardened paste but rather increases its porosity. The volume of hydrated cement paste is capillary porous. The water utilised for hydration is consumed from the pores. The consumption of water increases the capillary pressure and as consequence, the apparent volume additionally decreases. This diminution of volume is called self-drying shrinkage. Thus autogenous shrinkage is a consequence of chemical shrinkage and self-drying shrinkage. The apparent autogenous linear shrinkage of concrete is less then that of cement paste, due to the relatively small content of the cement paste in the volume of concrete, and it achieves approximately 100 - 300 $\mu\varepsilon$ ($100 - 300\cdot10^{-6}$) [17]. The consequences of autogenous shrinkage are identified at macro and micro level. At macro level, the external dimensions of concrete are changed and if the deformation is restrained (hyperstatic structures) parasite self-stresses are generated. In the case of isostatic structures the concrete structure changes its dimensions without self-stressing. At micro level, due to the diminution volume of the cement paste which is restrained by the aggregates, additional micro-cracks are generated. The autogenous shrinkage is an entirely intrinsic phenomena which occurs quasi-uniformly in the whole volume of the cement paste. It can not be avoided because it is in the nature of hydration.

The best-known types of deformations are certainly the drying shrinkage and the swelling. They develop in solidified concrete as a result of the free pore water exchange with the environment (evaporation or absorption, natural or artificial i.e. industrial). The drying shrinkage and the swelling arise from the faces which are in contact with dry or humid air. Hence the phenomenon is not uniform in the whole volume of concrete and consequently, it provokes internal stressing of concrete even in isostatic structures. Due to those internal stresses, cracks could appear on the contact surfaces. During the early age, the drying shrinkage can be avoided if the concrete is cured (e.g. protected by napes). However, it is inevitable after the cure is ended, during the exploitation of the structure.

The carbonatation shrinkage develops only in the layers of concrete exposed to air with relative humidity limits of 30 to 70%. Carbonatation shrinkage is caused by the chemical reaction of hydration products with carbon gas from the air. Under the actions of drying and moistening the carbonatation shrinkage is coupled with drying shrinkage and provokes very fine cracks. Effects of carbonatation shrinkage are superficial and can be avoided during the early age using the same manner of cure as in case of drying shrinkage.

A concrete structure is exposed, during the whole life, to external thermal influences caused by ambience temperature variations, Sun radiance, or artificially by industrial heating. The result of these influences is thermal deformation of the structure. It causes self-stressing in the case of hypersatatic structures. Rapid thermal variation (heating or cooling) could cause self-stressing in massive elements of isostatic structures too. It may also provoke cracks, but since it is usually predictable, serious damage can be avoided.

Thermal processes due to hydration affect the structures at the early age. In ideal adiabatic conditions, the heat develops uniformly in the whole volume of the concrete. Nevertheless, in real structures, thermal exchanges with the environment cause a thermal gradient. The warmth of the concrete layers close to surface is lower than in the layers far in the middle of the concrete. This temperature difference in the concrete volume causes not only uneven advancement of the hydration, but also dangerous self-stressing in the very important phase of concrete life, when the full strength has not been yet developed. Recent research shows that the early age thermal cracking is the origin of several phenomena that imperil durability and shorten the lifespan of the structure.

The deformation generated by loads is mainly composed of elastic and viscous (creep) part. The elastic deformation is predictable (can be calculated), while the creep is difficult to determine notably during the early age because it is still evolving. At the early age it is usually possible to avoid external load deformation.

The total deformation of concrete is the sum of all the different deformations which appear simultaneously. It is always composed of at least two different types of deformation. In Figure 2 periods of apparition of different types of deformation are represented.

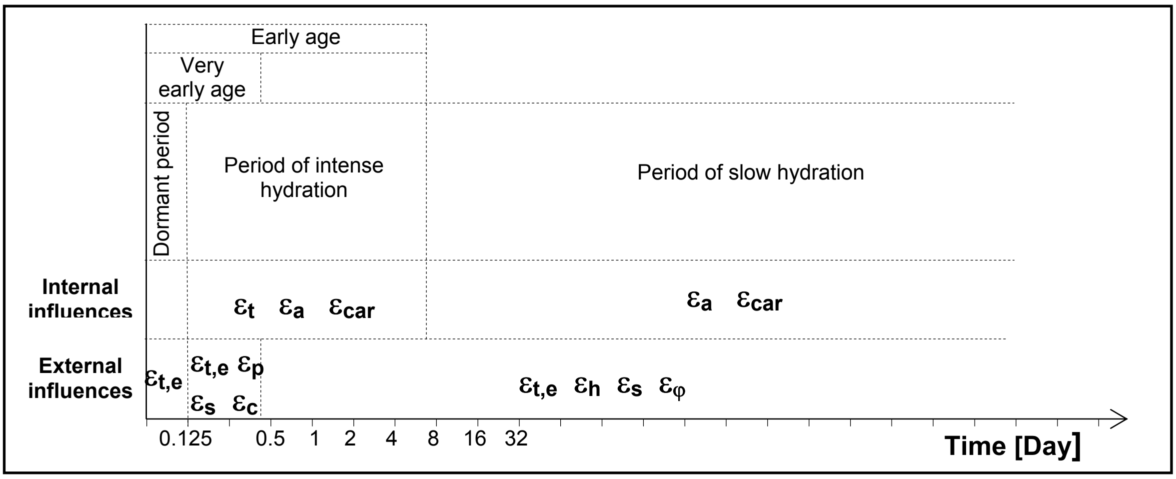


Fig. 2. Periods of apparition of different types of deformations in concrete.

In Figure 2 the notation is as follows:

- ε_t – Deformation due to hydration heat (expansion and contraction);
- ε_a – Autogenous shrinkage;
- ε_{car} – Carbonatation deformation;
- $\varepsilon_{t,e}$ – Deformation due to external thermal influences (expansion and contraction);
- ε_p – Plastic shrinkage;
- ε_h – Deformation due to external hydraulic influences (swelling and drying shrinkage);
- ε_s – Elastic deformation due to loads;
- ε_φ – Deformation of creep.

Figure 2 shows the possible combination of deformation at the different stages of concrete life. It is not possible to have all types of deformation during the whole life of the structure. Furthermore, some of them can be avoided as previously explained.

MONITORING SYSTEM FOR THE EARLY AND VERY EARLY AGE MONITORING

An appropriate way to evaluate influence of the early and very early deformation is to monitor it. In order to perform the monitoring, in laboratory or on-site, it is necessary to use an appropriate set-up. The most important is the selection of the sensors and the monitoring system. The sensors must be embeddable in concrete in order to make possible measurements immediately after the pouring. The second obligatory condition is a good transfer of deformation from concrete to the sensor, which is guaranteed by the sensors low stiffness. Finally, to avoid local material defects, such as crack openings or air pockets, the sensor must have a long gage length.

Traditional sensors do not fulfil these conditions. They have certain stiffness and it is difficult to estimate what is really measured during the very early age: the real deformation of concrete or the sensor deformation. In addition the short measurement basis makes them sensitive to local influences that are particularly important during the very early age, when the concrete is not hardend yet. That is why the solution is found in innovative optical fiber sensors.

The deformation monitoring system named SOFO (French acronym of "Surveillance d'Ouvrage par Fibres Optiques" - "Monitoring of Structures by Optical Fibers") has been developed at the Stress Analysis Laboratory of the Swiss Federal Institute of Technology (IMAC-EPFL) [18] and by SMARTEC SA. It is based on low coherence interferomtery in optical fibre and is capable of monitoring micrometer deformations over long measurement bases (gage length up to 10 meters and more). It is particularly adapted to measure civil structures built with conventional civil engineering materials (concrete, steel and timber). Since 1993 it has been successfully applied to different types of structures such as bridges, tunnels, piles, buildings etc. [9]. The system is fully automated and shows a high long-term stability since insensitive to electro-magnetic fields, humidity corrosion and temperature.

The SOFO standard sensors can be externally installed attached to the surface of the structure, but also, internally, embedded in fresh concrete. Installation of sensors before the pouring of concrete is a mandatory condition for deformation monitoring at very early age. The second condition is a good transfer of deformation from the concrete to the sensor. It has been proven through numerical simulations and experiments that the standard sensor responds well to both requirements even if attached (but not fixed) to rebars [9].

All deformation measurements presented in this paper are performed using SOFO standard sensors. The performance of the SOFO system with standard sensors is presented in Table 2 and a view to the sensor attached to rebar undergoing the pouring of concrete in Figure 3.

Tab. 2. Performance of the SOFO system.

Parameter	SOFO characteristics
Gage length	25cm to 10m for standard sensors
Resolution	2μm, independently from gage length
Dynamic range of the sensors	1% elongation, 0.5% shortening
Dynamic range of the reading unit	Up to 60mm in elongation and shortening
Precision	Better than 0.1% of the measured deformation
Measurement speed	Less than 7 seconds
Stability	Drift not expected and not observable since 1996

Fig. 3. SOFO sensor attached to rebar undergoing the pouring of concrete.

TYPICAL DEFORMATION OF CONCRETE AT EARLY AND VERY EARLY AGE

Typical total early and very early age deformation of a concrete element measured by standard sensor is presented in Figure 4 [9]. During monitoring, the concrete element has been thermally and hydrologically isolated. Therefore two components of the total deformation are dominant: thermal and autogenous deformation. The total deformation was restrained by the formwork and the friction with the base. The first twelve hours from Figure 4 (encircled area) are presented in Figure 5.

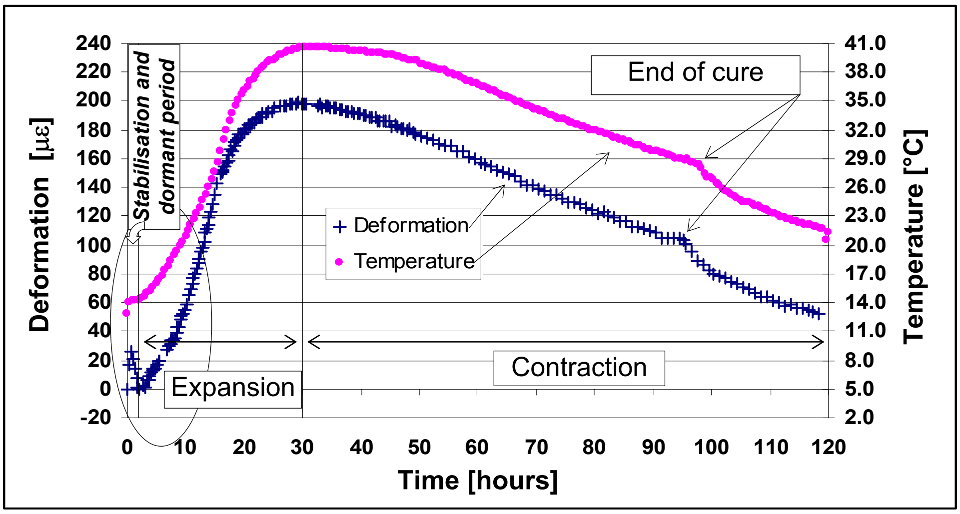


Fig. 4. Typical ordinary concrete deformation and temperature evolution curves at early and very early age.

In Figure 4 four periods are distinguished. The first is the dormant period, the second is the period of stabilisation of the concrete, the third is the expansion period and the fourth is the contraction period.

During approximately the first two hours the temperature of concrete is constant, with exception of the first measurement, which corresponds to the initial temperature of concrete. The hydration process is practically paused; therefore this period corresponds to the dormant period. During approximately the same period, the Standard Sensor has registered important variations of the deformation. Since there are no other sources of deformation (temperature is constant and autogenous deformation is practically equal to zero) this variation is certainly the consequence of the segregation and the stabilisation of concrete.

The end of the stabilisation period corresponds to the attenuation of the deformation variations. The end of the stabilisation period cannot be strictly defined, since the stabilisation is a continuous process (e.g. in

Figure 4, an earlier point could be also chosen to define the end of the stabilisation period). Moreover it is not uniform in the whole volume of the concrete element. However, the standard sensor can give good information related to the end of stabilisation.

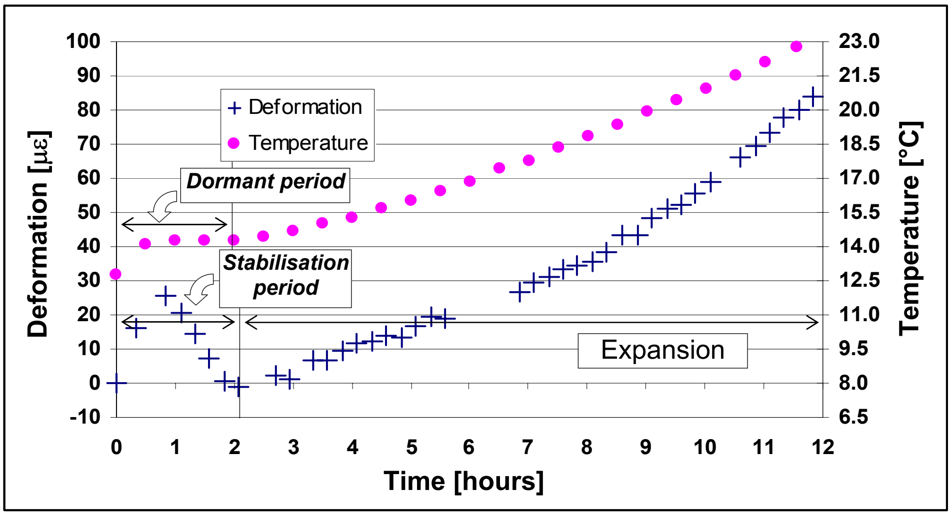


Fig. 5. Encircled area from Figure 4 - Deformation and temperature evolution during the first twelve hours in the concrete life.

In Figure 5 the dormant and stabilisation period nearly coincide, but this is not a general rule. They could be different, depending on concrete composition, method of pouring and sensor position in the concrete.
The expansion period corresponds to the period of intense release of hydration heat. The concrete expands due to an increase of temperature. During this period, cement sets and the concrete rapidly hardens. If the concrete is restrained, stresses start to be generated, especially after hardening.
When the period of intense discharge of hydration heat is finished, concrete cools and as a result it contracts. Since already hardened, during this period important tensile stresses are generated, and these stresses are often the origin of premature cracking.
The standard sensor allows the magnitude of the early age deformation to be accurately determined. The examples from the practice presented in the next section illustrate importance of the early age deformation and its influence to the structural condition.

EXAMPLES OF MONITORING OF CONCRETE ELEMENTS AT EARLY AGE

Monitoring of hybrid old-concrete – new-concrete specimen

Monitoring was carried out on a hybrid old-concrete – new-concrete specimen. The old concrete layer was poured two months before the new concrete. Its initial thickness was 17cm. In order to increase the interaction between the two concrete layers, its upper surface was treated by hydroblasting two days before the pouring of new concrete. This operation reduced the thickness of the old concrete to 15cm. The geometry of the specimen is represented in Figure 6.

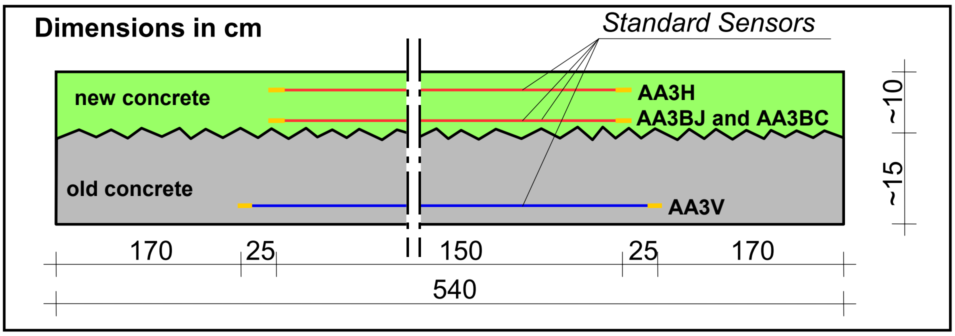


Fig. 6. Geometry and sensor emplacement in hybrid old concrete-new concrete specimen AA3.

The new concrete consists of 300kg/m^3 of cement, type CEM I 52.5R, cement water ratio of 0.5 and aggregate from lake of Neuchâtel (Switzerland) with maximum diameter of 16 mm. The new concrete is reinforced with bars 6ϕ14. Two hours after the pouring the new concrete layer was covered for 105 hours with an isolating mat.

The specimen is equipped with thermocouples and Standard Sensors as shown in Figure 6. The sensors AA3BJ and AA3BC are placed at same level, but they are differently attached: the AA3BJ is free while the sensor AA3BC is fixed on the surface of the old concrete by means of iron corners. The deformation and the temperature of both layers were monitored during the whole life of the specimen. The first four days are represented in Figure 7.

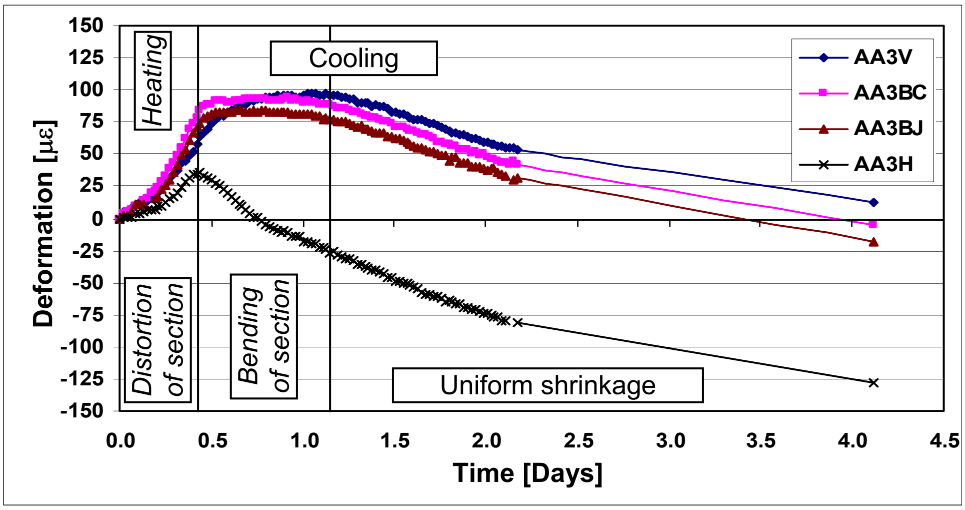
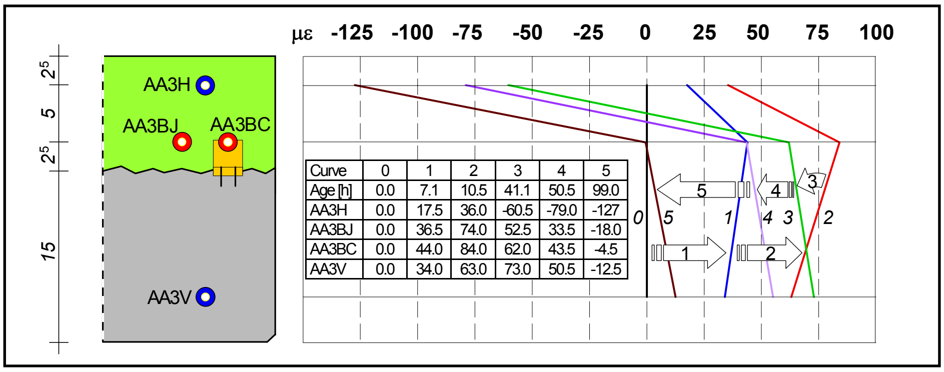


Fig. 7. Early and very early deformation of new concrete and deformation of old concrete.

Three types of curves are obtained. The first curve (AA3V) describes the behaviour of the lower surface of the old concrete support. The curves of second type (AA3BC and AA3BJ) are similar to the first type, but with some differences. They describe the behaviour of the interface where the temperature is the highest during the period of intensive thermal reaction of hydration. Therefore the deformation of the interface is greater than the deformation of the lower surface of the specimen. When the maximum temperature in the new concrete is reached, the deformation of the interface is initially constant because of the very slow cooling and finally the same as the deformation of lower surface of the support. The measurements of sensors AA3BC and AA3BJ are different in the beginning since the sensors measure deformations of the old and the new concrete, respectively. Ten hours after pouring both sensors measure the same change of deformation, which means that the new concrete is hardened and good interaction between the new and the old concrete is realised.

The third curve (AA3H) describes the deformation of the upper surface of the new concrete layer. This curve is remarkably different from the two previously described. The deformation of the upper surface achieves its maximum simultaneously with the maximum temperature of hydration, and after this maximum it decreases due to cooling and autogenous shrinkage. Since the old and the new concrete are coupled, the contraction of new concrete generates tensile stresses in the new concrete. This contraction also provokes a bending of the old concrete: the upper part of the cross section is compressed and the lower part is tensioned. Thus, the deformation measured by sensor AA3V continues to increase after the achievement of the maximum hydration temperature.

From the structural point of view, three periods are distinguished in Figure 7 and are more clearly presented in Figure 8: the first period is between curves 0 and 2, the second between curves 2 and 3 and the third period between curves 3 and 5.



Curve	0	1	2	3	4	5
Age [h]	0.0	7.1	10.5	41.1	50.5	99.0
AA3H	0.0	17.5	36.0	-60.5	-79.0	-127
AA3BJ	0.0	36.5	74.0	52.5	33.5	-18.0
AA3BC	0.0	44.0	84.0	62.0	43.5	-4.5
AA3V	0.0	34.0	63.0	73.0	50.5	-12.5

Fig. 8. Evolution of the cross-section of the specimen.

During the first period a distortion of the cross-section is observed, due to the plastic properties of concrete and due to the non-uniform heating of concrete with respect to the height of the section. The second period is characterised by non-uniform cooling. As a consequence, a bending of the cross-section appears. Finally during the third period a uniform contraction is registered as a consequence of the shrinkage of the new concrete and a very good interaction between the two concretes.

Monitoring hybrid steel - concrete specimens

In the previous paragraph we have shown how the early age monitoring helps to understand real behaviour of the structure. Here we compare concretes with different initial temperatures.

The hybrid steel-concrete specimens, called P6 and F2, are analysed. Both specimens are mixed with 350 kg/m^3 of the cement CEM I 52.5, the water cement ratio is of 0.48, granulate with maximal diameter of 32 mm, and 1.2% of plasticiser. These two concretes are different in two details: concrete for the specimen P6 is refrigerated to 5°C using the liquid nitrogen while 50 kg/m^3 of steel fibres DRAMIX is added to the concrete of specimen F2. The dimensions of the fibres are 35 mm of length and 0.35 mm of diameter. Both specimens are cured in the same conditions after the pouring. Each specimen has the same length of 8.4 m, and the identical dimensions of cross section, as shown in Figure 9.

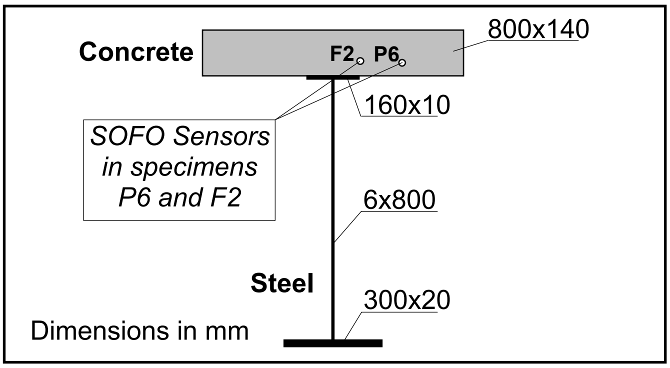


Fig. 9. Cross-section of the specimens P6 and F2.

The specimens are equipped with thermocouples and Standard Sensors. The sensor emplacement in the cross-section is presented in Figure 9. Both sensors are presented in the same figure in order to facilitate the comparison.

In the longitudinal direction the sensor are centred in the middle of the specimens' spans. During the first two days the measurements of the sensor P6 is registered every 15 minutes and of the sensor F2 every 30 minutes. Afterwards the rhythm of measurement of the sensor F2 is unchanged while the measurements of the sensor P6 are registered less regularly. The monitored deformations of both specimens are presented in Figure 10.

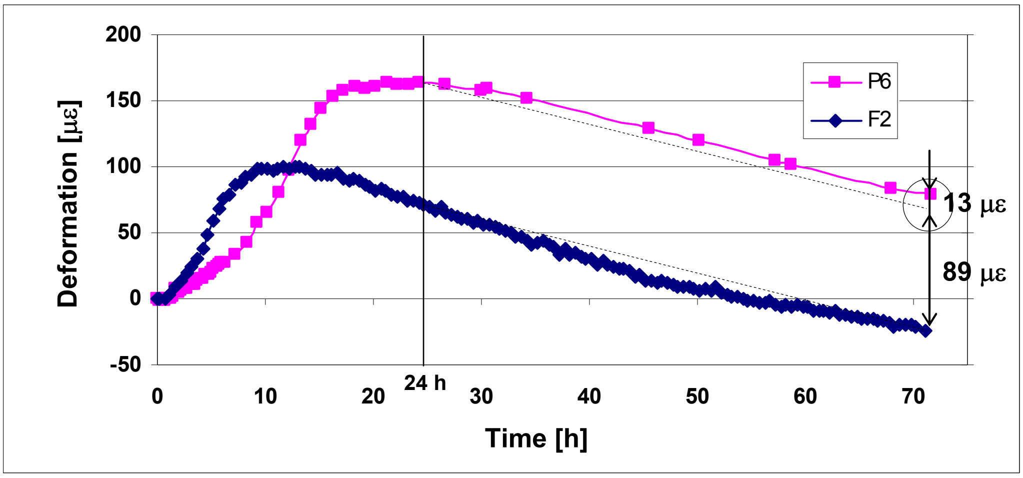


Fig. 10. Behaviour of two different concretes cured in the same conditions.

Initial, maximal and final (71 hour after the pouring) temperatures of specimens are presented in Table 3. The difference between very early age behaviour of specimens is noticeable in Figure 10. The difference between initial and final temperature is approximately equal for both specimens (29.5°C for specimen P6 and 26.2°C for specimen F2). However, thermal expansion of the specimen P6 is higher for 75%. Moreover the maximum in expansion of specimen P6 is achieved 8 hours later than for the specimen F2. This difference in behaviour of specimens is consequence of their different initial temperature: the hydration process of refrigerated concrete was slowed down due to low temperature, therefore the period of intense heating was long, and since in this period the TEC of concrete is elevated, the thermal expansion of concrete is higher than in case of non-refrigerated concrete.

Tab. 3. Initial, maximal and final temperatures of specimens P6 and F2.

Specimen	***Initial temperature***	***Maximal temperature***	***Final temperature****
P6	6.2	35.7	26.7
F2	26.1	52.3	33.1

* 71 hour after the pouring

If we suppose that a monitoring systems using external sensor was applied on the concrete 24 hours after the poring, then after 71 hours it would register a significantly smaller difference between specimen deformations (13 με instead 102 με, see encircled area in Figure 11). The error obtained using such way of monitoring is very high (89 με > 87%) and it does not allow understanding of the different behaviour between the specimens. More details related to the described test are found in [20] and [21].

Monitoring of cut-and-cover tunnel

The cut-and-cover tunnel of Champ Baly [22] is situated on the motorway A1, connecting Lausanne with Bern, in Switzerland. Construction work began in July 1998 and the end of the concrete pouring phase was in August 1999. The length of the tunnel is 230 m and the volume of concrete used is approximately 6000 m3. The concrete has been poured in twenty-one stages, i.e. nineteen 11.60 m long vaults and two 6 m long portals. The cross-section of the tunnel consists of two reinforced concrete vaults as shown in Figure 11 [23]. The cross-section of the tunnel has been equipped with nine, 4 metres long Standard Sensors and nine thermocouples prior to the pouring of concrete, as shown in Figure 11. Each thermocouple is placed side by side with one sensor, which allows the concrete temperature at each sensor location to be measured. In Figure 11, the thermocouples are represented by numbers (1 to 9) and the sensors by "S" followed by their respective serial number (S-740, S-741, etc.).

Sensors S-748, S-743 and S-741 are located in the foundations, which have been poured approximately three months prior to the vaults. The other sensors were mounted on the vault rebars a few days before the casting took place. The passive zones of the sensors are guided through plastic tubes to the connection box (see Figure 11). The reading unit is placed in a small portable chamber some twenty metres away from the tunnel. It is linked to the connection box by means of an optical cable.

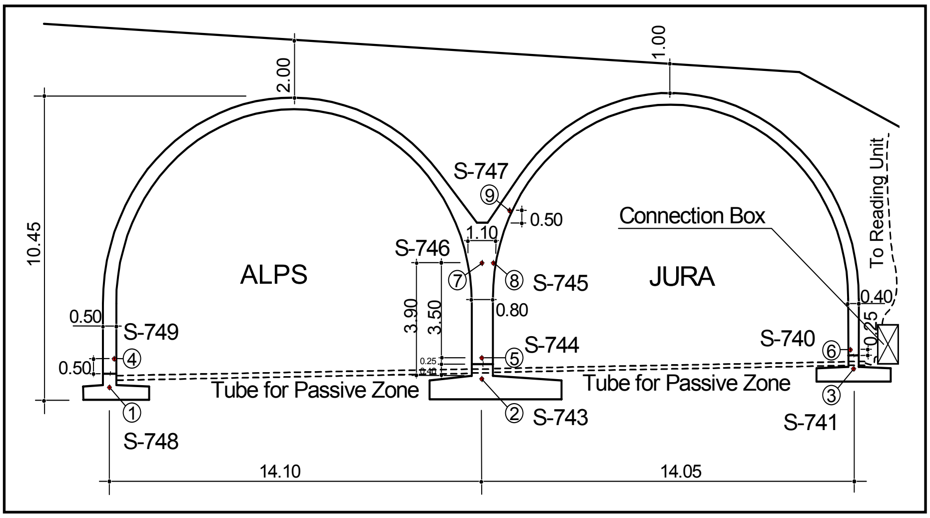


Fig. 11. Cross section and sensor equipment of the cut-and cover tunnel Champ Baly [23].

The vaults early and very early age deformation was monitored during seven days following concrete pouring. Measurements were recorded automatically every 30 minutes. They are presented in Figure 12. Three different periods during the early age deformation are distinguished and separated by lines in Figure

8. The first period corresponds to the pouring period. During this period the concrete is cast with the sensors measuring the corresponding deformation. A relatively small deformation due to the additional load of the fresh vault concrete is noticed with the sensors that measure the deformation of the foundation (S-748 and S-743). The deformation of the foundation is significantly smaller than the deformation measured with the sensors located in the lower part of the vaults (sensors S-749, S-744 and S-740). This is a consequence of the plasticity and rheology of fresh concrete. Finally the sensors that are higher in the vaults (S-746, S-745 and S-747) measured very small deformation due to the reduced load at their locations. Since the setting time is retarded, the new concrete is in a "dormant period" during the pouring period. This fact is also confirmed by the temperature measurements.

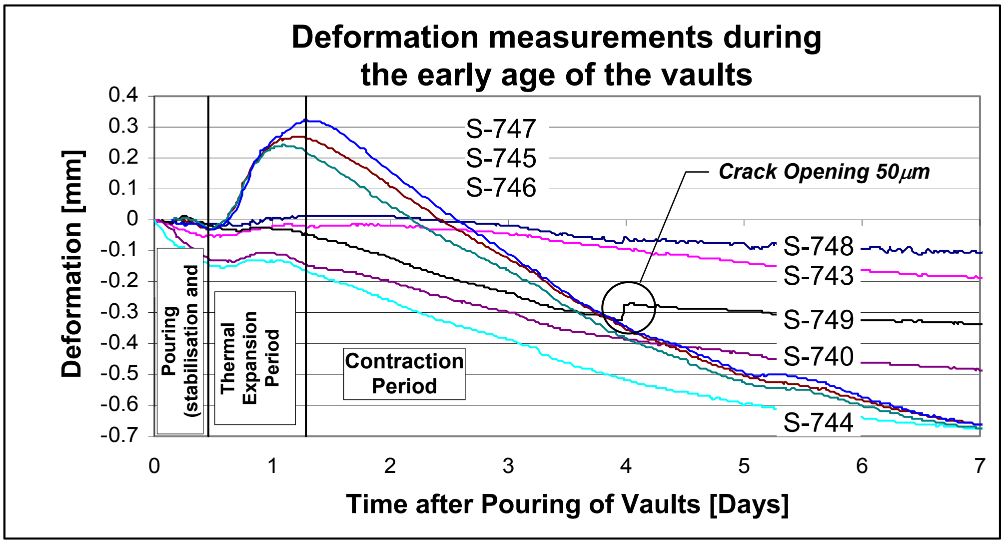


Fig. 12. Early and very early age deformation of the tunnel cross-section.

The second period in Figure 12 is the thermal expansion period. During this period the hydration process is activated, the temperature increases and induces deformations too. While the deformation of the foundation is very small, the deformation of the lower parts of the vaults is larger and the deformation of the upper parts is very large. The smaller deformation of the lower parts of the vaults can be explained by their restraint from the foundations. The upper parts of the vaults are not confined and the concrete in these zones swells significantly. During this period the concrete sets and stresses are generated in the vaults.

During the contraction period the deformation generally decreases due mostly to the thermal contraction of concrete. During this period, a 50 μm wide crack opening was recorded by sensor S-749 and confirmed after visual inspection of the structure. The crack is a consequence of the vault-foundation interaction and the early age deformation induced by thermal stress.

Different behaviours of the tunnel's different parts can be identified and described by the three different types of curves shown in Figure 12. The first type concerns the foundation, the second type the lower parts of the vaults, and the third type the upper parts of the vaults. The deformation curves of the foundation and the lower parts of the vaults after the cooling are parallel and point to a monolithic behaviour of the foundations and the vaults. The deformation curve of the upper parts of the vaults is not parallel to the other curves and this indicates that the cross-section does not remain plane during early age deformations. Since the bonding between the vaults and the foundation can be assumed to be good, stresses are therefore introduced into the vaults. As a consequence, cracking of concrete may appear.

CONCLUSIONS AND RECOMMENDATIONS

The period, which begins with pouring and finishes when all thermal processes in concrete are calmed is considered in this paper as the early age of concrete. The period included in the early age, during which the concrete is still not hardened, is conventionally called the very early age. Determination of the end of very early age exceeds the scope of this paper, but more details can be found in [9, 24, 25].

Diagrams that present real early and very early age deformation of concrete are presented in this paper. Tests are carried out in the laboratory and in-situ. Four characteristic periods are distinguished in diagrams: the dormant period, the stabilisation period, the thermal expansion period and the contraction period.

Thermal expansion and contraction is measured in laboratory and in-situ. Distortion of the cross section of structures as well as real mean strain distribution in structural elements are identified and quantified.

The influence of elevated TEC during the very early age is confirmed in tests. Different behaviour of two equal concretes with different initial temperatures has proven this important characteristic of concrete at very early age.

The moment of opening of cracks as well as the measurement of their width is recorded in-situ. Thus the early age cracking is detected and quantified.

The permanent monitoring of deformations using optical fibre based system SOFO and the standard sensor, starting immediately after pouring provides accurate measurements that help to understand the real behaviour of concrete at early and very early age.

The importance of very early age monitoring has been confirmed by laboratory experiments and in-situ. It provides rich information, and helps to understand real structural behaviour. The authors recommend the following points to taken into account when monitoring the concrete at early and very early age:

- It is important to monitor both, deformation and temperature;
- The sensors (both deformation and temperature) must be embeddable in the concrete;
- The sensors to be used for early and very early age monitoring must not perturbe strain field of non hardened concrete (they have to have very low stiffness);
- The design of the sensors to be used for early and very early age monitoring must guarantee full transfer of the strain from the non-hardened concrete to the sensor;
- It is recommended to use long-gage sensors in order to minimise the influence of different types of material discontinuities (air pockets, inclusions, cracks) to measurement;
- The position of the sensors within the structure must be well planed and selected in a manner to provide relevant data concerning the structural behaviour;
- Monitoring should start as soon as the pouring of concrete is completed;
- All the border conditions (type of workform, existence of interaction with previously poured parts of structures, humidity exchage with environment, temperature exchange with environment, etc.) must be known (at least qualitatively) for correct interpretation of data obtained from monitoring;
- Finaly, the properties of concrete mixture (notably the ciment type, w/c ratio and the presence of retarders) must be known for correct interpretation of data obtained from monitoring.

REFERENCES

1. Walther R., Miehlbradt M., Dimensionnent des structures en béton, *Traité de génie civil*, Vol.7 pp. 3, Presses polytechniques et universitaires Romandes, Lausanne, 1990.
2. Baron J., Ollivier J.-P., (sous la direction de), *La durabilité des bétons*, Presses de LCPC, Paris, France,1992.
3. Tazawa E., Iida K., Mechanism of thermal stress generation due to hydration heat of concrete, *Transactions of the Japan Concrete Institute*, 1983, vol. 5, p.p. 119-126.
4. Thermal Cracking in Concrete at Early Age, *RILEM International Symposium,* Munich, Germany, 1994.
5. *Limitation de la fissuration au jeune age du béton dans des structures hybrides*, research report, MCS, IMAC et ICOM, EPFL, Lausanne, Switzerland, 2000.
6. Nagesh M., Bhattacharjee B., Modelling of Chloride Diffusion in Concrete and Determination of Diffusion Coefficients, *ACI Materials Journal*, Vol. 95, N°2, April 1998.
7. Hammerschlag J.-G., Mécanismes des réactions alcalis-granulats et leurs effets sur la structure du béton, *Service de recherches et conseils techniques de l'industrie suisse du ciment*, 1999.
8. Bernard O., *Comportement à long terme des éléments de structures formés de bétonsd'âges différents*, Ph.D. Thesis N° 2283, EPFL, Lausanne, Switzerland, 2000.
9. Glisic B., *Fibre Optic Sensors and Behaviour in Concrete at Early Age*, Ph.D. Thesis N° 2186, Swiss Federal Institute of Technology Lausanne, EPFL, Switzerland, 2000
10. Nonat A., Mutin J. C., From hydration to setting, Thermal Cracking in Concrete at Early Age, *RILEM International Symposium*, p.p. 171-191, Munich, Germany1994.
11. Legrand C., Wirquin E., First developments of strength in a microconcrete, Thermal Cracking in Concrete at Early Age, *RILEM International Symposium*, p.p. 89-100 Munich, 1994.
12. Paulini P., Gratl N., Stiffness formation of early age concrete, Thermal Cracking in Concrete at Early Age, *RILEM International Symposium*, p.p. 63-70, Munich, 1994.
13. ASTM 04.02, US Norms.
14. Schöppel K., Springenschmid R.,The Effect of Thermal Deformation, Chemical Shrinkage and Swelling on Restraint Stresses in Concrete at Early Age, Thermal Cracking in Concrete at Early Age, *RILEM International Symposium*, p.p. 215-220, Munich, 1994.

15. Acker P., *Les retraits du Béton, Origines physiques et paramètres influets*, Analyse par type d'ouvrage et mode de mise en oeuvre, Rilem GMC, LCPC, Paris, Avril 1995.
16. Acker P., Les retraits du béton: Origines Physiques, Rôle des paramètres de Composition, Formulation de Bétons a Faible Retrait, *Pontes mixtes, Annexe 1*, p.p. 71-84, SETRA, Bagneux - France, Septembre 1995.
17. Aïtcin P.-C., Neville A., Acker P., Les différents types de retrait du béton, *Bulletin des laboratoires des Ponts et Chaussées*, Vol. 215, p.p. 41-51, LCPC, Paris, Mai - Juin 1998.
18. Inaudi D., *Fiber Optic Sensor Network for the Monitoring of Civil Structures*, Ph.D. Thesis N°1612, EPFL, Lausanne, Switzerland,1997.
19. www.smartec.ch.
20. Blanc A., Gómez Navarro M., *Poutres mixtes à âme mince avec béton de fibres métalliques*, Rapport d'essai N°394, ICOM-EPFL, Juillet 1999.
21. Monney C., Ducret J.-M.., *Essais de poutres mixtes à âme mince*, Rapport d'essai N°357, ICOM-EPFL, Septembre 1999.
22. Glisic B., Badoux M., Jaccoud J.-P., Inaudi D., Monitoring A Subterranean Structure with the SOFO System, *1st International Conference Long Road and Rail Tunnels*, November 29 - December 1, 1999, Basel, Switzerland.
23. Badoux M., Jaccoud J.-P., Fleury B., Simon N., La tranchée couverte de Champ Baly - Projet pilote d'application de BHP, *Publication SIA D0160*, 1999.
24. Glišić B., Simon N., Monitoring of Concrete at Very Early Age Using Stiff SOFO Sensor, *Cement and Concrete Composites,* Elsevier, Vol. 22, Issue 2, Pages 115-119, 1 April 2000
25. Viviani M., *Monitoring and modeling of construction materials during hardening*, Ph.D. Thesis No.3168, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland 2005