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Wider perspective of testing early shrinkage of concrete modified with admixtures in changeable W/C ratio as innovative solution in civil engineering

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Abstract

The problems of concrete shrinkage have been debated by a number of authors, including those specializing in concrete chemistry. The development of concrete technologies, introducing chemical admixtures and mineral additives and high resistance concretes has contributed to creating a wider perspective on shrinkage in recent years and charting a new area of research. This article is the result of author's work in creating innovative solution for concrete shrinkage testing taking into consideration the following stages: initial shrinkage comprising: swelling, chemical (contraction), and plastic shrinkage, followed by expansion and then a second shrinkage (during drying).
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Keywords: Innovative concrete testing; Concrete; Rheology; Shrinkage; Cement

1. Introduction

Chemical reaction between water and cement brings about a general reduction of the volume of the resulting mix. Volume changes, called "chemical" shrinkage or contraction, are directly related to smaller quantities of water in hydrated stages, compared to its volume in the liquid stage. Shrinkage occurs both before and during bondage, and is

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usually referred to, as the so-called first shrinkage and then expansion follows. During the initial reaction of grout with water, the “plastic shrinkage”, as it is often pointed at, is related to evaporation of water from the surface layers of concrete. This process may lead to surface cracking. Another (the second) shrinkage takes place in the period of hardening, and is classified as hardening shrinkage or self-drying. The reason is, that this process is related to the formation of pores filled with air, which leads to the decrease in particle pressure in vapor and, therefore, to self-drying. The value of shrinkage in dehydrated grout is directly influenced by the w/c ratio, as it defines the amount of water vaporized in the grout, and the rate at which water will move towards the surface of the sample [1]. Concrete shrinkage is more intensive if the value of w/c is higher, because it is the rate that defines the amount of vaporized water from the grout and the rate at which water moves towards the surface of the sample. In ordinary cement with, for example, w/c ratio being higher than 0.50, there is more water than necessary to complete the hydration of cement particles. There is a large amount of water in well connected, big capillaries, so that meniscuses resulting from self-drying can only evoke minor tensions. Therefore, the hardened cement grout shrinks alongside with self-drying. In case of concrete characterized by the w/c ratio of 0.30, the network of pores consists basically of small capillaries. When the process of self-drying begins, as soon as hydration starts, meniscuses are rapidly transformed into small capillaries if water is not supplied internally [2]. The w/c ratio not only influences the course of shrinkage in the cement grout or concrete itself. It is clear from experiments that it greatly influences the microscopic structure of the hydrated cement grout and concrete, especially in the transition period, that is, in the hydrated cement grout which surrounds thick grains of aggregate. It has been observed that, in the cement grout or in high w/c concrete, the transition area is highly porous and is filled with large crystals of lime and etryngite. With a constant w/c ratio, alongside with the increase of the amount of grout in the volume unit of concrete, the shrinkage intensifies. It is both connected with larger amounts of water in concrete, and with less aggregate, whose presence limits the shrinkage. There is always less concrete shrinkage compared to cement grout shrinkage, even with the same w/c ratio. Concrete, exposed to dry air or wind dries, losing certain amount of water and its weight reduces. A sample, dried for the first time, shows irreversible shrinkage. The magnitude of the irreversible shrinkage depends on the porosity of the grout, while the magnitude of irreversible does not depend on porosity. The relationship between irreversible shrinkage and the phenomenon of water content reduction in concrete is also quite definitely influenced by drying shrinkage, namely the drying shrinkage intensifies alongside with the reduction of the water content. The concrete begins to swell if, prior to being dried in the open air at certain relative humidity, it is placed in water or in a room where humidity is relatively high. Nonetheless, even after a long time in under water, the whole initial shrinkage will not be reversed. In case of ordinary concrete, the irreversible part of the shrinkage consists 0.3 to 0.6 of the value of drying shrinkage, while it is the lower value that occurs more often. Defining a strict relationship between evaporation and curing time of concrete is quite complex. Evaporation begins from a wet surface of concrete, and continues at a constant rate, and then the rate slows down until the time when moisture concentration on the surface equalizes with ambient air humidity. In the final stage, there is a diffusive movement of water from the inner parts to the surface of the concrete. Volume changes in the hardened cement grout, in the range of low relative ambient humidity values, are related to the increase in surface tension of the dispersed fine particles of cement gel deprived of adsorption water. Changes in surface tension increase normal pressure on their curved surfaces, as well as changes in volume. In the range of higher humidity values, when changes in surface energy of gel are not that significant, shrinkage strain results from lower rate of increase of van der Waals forces, interaction of particles, in comparison with the opposite wedging force of adsorption water [3,4]. When concrete is kept under water, or cured at the humidity close to 100%, the phenomenon of swelling may be observed. Swelling of concrete with normalized chemical content cement occurs primarily due to the phenomenon of adsorption of water by the gel.

The influence of chemical admixtures on concrete shrinkage has been described by a number of authors, though none of them has been able to clarify the observed phenomenon in a satisfactory manner. Two extreme views are usually presented. A.M. Neville [2] suggested that adding superplasticizers to the concrete mix results in the intensification of shrinkage by 10% to 30%, but simultaneously made a reservation that changes within such a small range were too minimal to be given credibility. Jens Engstrand (Sweden) presented his view in 1997, to the effect that shrinkage, reducing admixture (SRA) group superplasticizers could reduce shrinkage even by 40%. In the quoted research results, the SRA concrete shrinkage was, nonetheless at 0.5 to 0.6 mm/m (values recognized as the upper limit of cement shrinkage), whereas ordinary shrinkage as much as 0.95 mm/m. Such shrinkage is exhibited by concrete with $w/c > 0.7$, while at present, the main focus is on concrete with $w/c = 0.3 \div 0.5$. It may be hard, therefore, to interpret those results as representative for contemporary types of concrete [5]. Cement concrete, modified with mineral and chemical admixtures doubtless undergoes shrinkage. Introducing additional ingredients to concrete will complicate the process which is complex enough anyway. This is common knowledge among manufacturers of contemporary construction materials and subcontractors; therefore the list of frequently asked questions in this regard becomes longer every day[6,7].

2. Research station description

Shrinkage research is diverse, it takes into account changing ambient conditions: from low to high relative air humidity levels to changing contents and proportions of concrete mix; from ordinary concrete, modified by chemical admixtures, with changing w/c ratios, to SCC concrete. Concrete shrinkage research to date have not looked in a wider perspective at the phase of adding water to the concrete mix, the shrinkage values have not been measured with appropriate precision and frequency as it is done now. S. Miyazawa and E. Tazawa research is the only exception [8,9,10]. The process started from gathering modern measurement equipment. Metric gauges have been replaced by potentiometers which measure precisely the electric current which flows through the sensors placed in the concrete. The research station consists of the following: Megalb measurement equipment, climatic chamber, clamp bar, the assisting device – a computer and software, emergency power generator, manual calibrating device with a micrometric sensor, potentiometer sensors to measure the shrinkage, temperature and humidity measurement devices.

The set ensures long time measurement using relocation sensors, and has the potential of advanced processing of the measurement data collected in the computer. A change in the length of the sample results in a change of electrical parameters which, after the calibration, are automatically processed and changed into units of length. Measurement using such complex sensors has many advantages. First of all, it is possible to measure chemical shrinkage right after concrete mix components have been mixed with water. It is, therefore, possible to measure chemical shrinkage, plastic shrinkage, and the shrinkage of hydrated grout. The shrinkage readings can be taken every 2 seconds, and the results are numerically recorded. The disadvantage of this measurement set is an utmost sensitivity to changes in ambient temperature and relative humidity of air, therefore, the results need to be corrected by means of introducing a coefficient taking into consideration the eternal parameters. Concrete samples are placed in a climatic chamber which makes it possible to retain the introduced humidity and temperature parameters at a constant and unchanged level. Such conditions can be retained even over the length of a few months and modified at any time. The size of shrinkage test samples is 250x100x20 mm (length, width, height). Measured length l=190mm is defined by the type of fixing of shrinkage sensors. Potentiometer sensors have been used here which provide precise measurements of electric current flowing through the sensor placed in the concrete [11].

2.1. Shrinkage measurement methodology

Concrete shrinkage tests by means of the above presented measurement technology, were preceded by equipment calibration and testing, and setting appropriate initial parameters.

2.2. Setting the magnitude of current supplied to the potentiometric sensors

Basing on tests and calculations, it had been assumed that the sensors would be supplied with 200mA direct current, which gives output voltage of 3,7V per sensor.

2.3. Calibrating the potentiometric sensors

Potentiometric slide sensors, as a result of movement, measure voltage drops or resistance, depending on the settings on the electrical current supply control panel. Strain - shrinkage – is defined in metric values. It is necessary to calibrate and scale the sensors, so that the measured current units can be translated into metric units. In order to do this, a manual calibration device has been designed, with an affixed micrometric sensor. The characteristics of individual sensors differ, therefore each sensor is scaled separately. The procedure of scaling is performed by means of a metric screw. Each sensor has been firmly associated with an appropriate channel of the measurement equipment. Table 1 presents the results of scaling procedures regarding strain sensors and figure 1 shows operating characteristics of shrinkage sensors.

Table 1. Results of strain sensor scaling

Channel (sensors)	Changes in mm per 1[V], [mm/V]
11	2,55
13	2,57
14	2,53
15	2,54
11	2,52
13	2,52
14	-2,56
15	2,49

Owing to the procedure of calibration, it was possible to define the range of linear strains in metric units, depending on the changes in voltage measurements in mV taken on the potentiometric sensor.

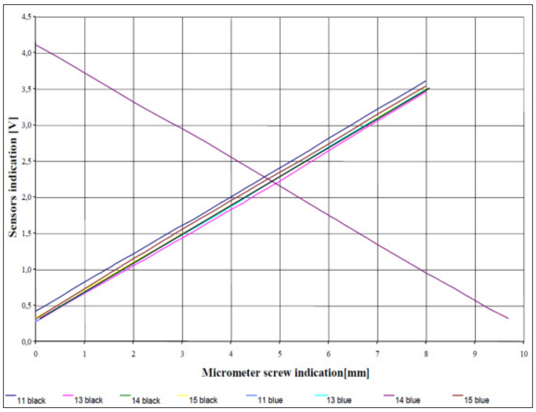

Fig. 1. Concrete shrinkage sensors operational characteristics.

2.4. Scaling temperature sensors

Inductive temperature sensors have been scaled with 5V current. Assuming certain operational characteristics of the sensors, the relationships between the measured voltage drops on the sensors and real temperature changes in °C have been worked out. Basing on those relationships, the authors arrived at the conclusion that the measured change of voltage on the sensors at the level of 10mV corresponds with ambient temperature increase or decrease by 1°C, with respect to temperature of sensor environment

2.5. Assessment of the influence of external conditions on magnitude of measurements

Basing on initial strain measurements performed by means of potentiometric sensors placed on concrete samples, and following the initial analysis of the results, the occurrence of errors in the measured values of strain was detected.

It has been concluded that ambient temperature has major influence on the results of the measurements. In order to detect the reason of the error and its magnitude, the authors performed measurements related to correct settings of the measurement equipment, eliminating all unfavorable influences one by one. After a long period of observations, a decisive influence of ambient (laboratory) temperature on shrinkage measurements had been noted. The change in lab temperature results in the change in resistance of cables connecting measurement equipment and the computer. The influence changes with the increase or decrease of temperature, as presented in Fig. 2.

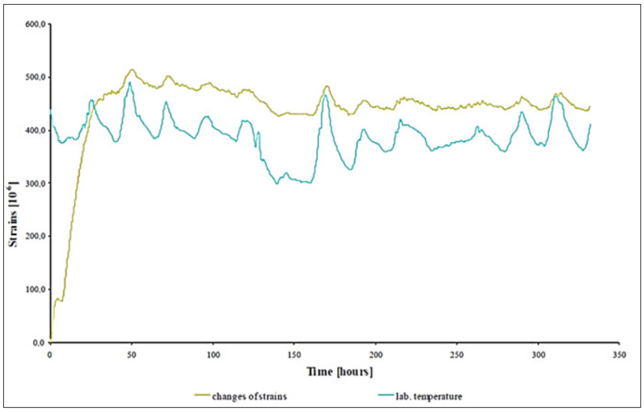

Fig. 2. Graphic representation of ambient temperature influences.

This phenomenon forced additional testing which facilitated limiting the influence of ambient temperature. The tests consisted in placing a blocked shrinkage sensor and temperature sensor in the test hall. Basing on the measurements taken, a function of relationship between shrinkage and temperature was drawn, complete with a trend line and its equation, like in Fig. 3a. Fig. 3b. presents the effect of eliminating the influences of ambient temperature on the measured shrinkage values.

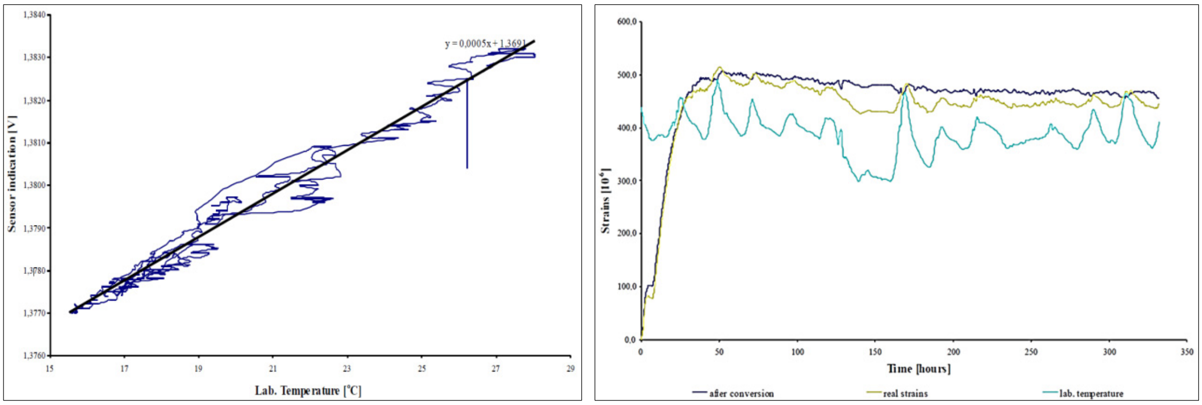

Fig. 3. (a) The influence of ambient temperature on the indications of a blocked concrete shrinkage sensor in the chamber as a function of shrinkage measurement dependent on lab ambient temperature (with the trend line and its equation).; (b) The effect of eliminating ambient temperature influences.

The designed and complete equipment is used to perform measurements (potentiometric sensors are applied) of voltage drops being a direct result of slide sensor movement, positioned and fixed onto a concrete sample. Concrete strain is transferred directly to a mobile slide of a sensor. Shrinkage measurement is taken in mV. The frequency of measurements, set in the control software, is high. Based on the calibration, the voltage measurement of strain is changed into units metric lengths.

The pattern of translation of data picked up from the potentiometric sensor can be defined by a following empirical formula:

$$\rho = \frac{VM_n - VM_0 \times 1/K}{190 \times 1000000}[\Delta 1/1][mm/m] \quad (1)$$

Where: VM_n – voltage measurement at the time of n [V]; VM_0 – voltage measurement at the point of time of zero [V]; 1/K – sensor calibration co-efficient [mm/V]; 190 – length of measurement base [mm]; 1000000 – non-dimensional value, in English bibliography defined as 1 microstrain.

The pattern of translating data collected from a potentiometric sensor, taking into account the influence of temperature induced error can be defined by a following empirical formula:

$$\rho = \frac{(VM_n - VM_0) \times 1/K - (T_n - T_0) \times P}{190} \times 1000000[\Delta 1/1][mm/m] \quad (2)$$

Where: VM_n - voltage measurement at the time of n [V]; VM_0 - voltage measurement at the point of time of zero [V]; T_n - temperature measurement at the time of n [°C]; T_o - temperature measurement at the point of time of zero [°C]; P - temperature influence on measurement coefficient; 1/K - sensor calibration co-efficient [mm/V]; 190- length of measurement base [mm]; 1000000 - non-dimensional value, in English bibliography defined as 1 microstrain.

2.6. The technique of taking shrinkage measurements

At one end, a potentiometric sensor with a spring slider on steel fixtures is attached to specially prepared moulds (item 2), and on the other end of the mould, on a similar steel fixture, a steel mandrel with a contact plate is mounted. (Fig. 4a.)

The mix is cast in the mould and, simultaneously, the steel fixtures are sunk into concrete. The concrete having been meticulously consolidated by hand, the steel mandrel is set by means of screw connections in such a way that the slide spring is tightened, and the slide itself is set beyond the extreme working range of the sensor. In such a position, there is a direct contact between the plate and the fixed mandrel with the sliding element of the sensor. Fig. 4b. presents a prepared, sensor equipped sample, with the concrete cast in place.

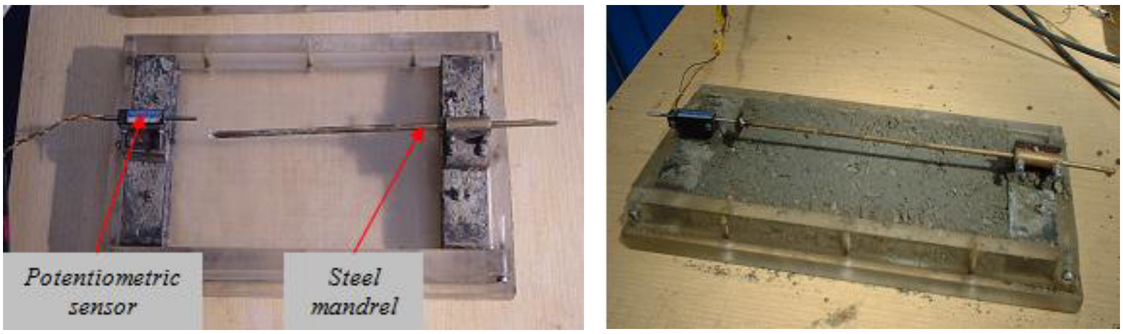

Fig. 4. (a) Moulds ready to make samples, with attached potentiometric sensor and caontact plate in steel fixtures. The status before testing.; (b) A rectangular plate, cast in concrete and equipped for concrete shrinkage testing.

The moulds, after the concrete is cast and consolidated, are placed in the climatic chamber and kept there, in appropriate temperature and humidity environment for a length of time allowing for proper measurement of concrete shrinkage. When the tests are over, the moulds are emptied and cleaned of the remains of concrete. Concrete samples are placed on a still grid in the climatic chamber (Fig. 5a.)

One of the transverse sides is loosened in the moulds so that bonds which may block the process of concrete mix swelling are removed. The climatic chamber is set to appropriate parameters of temperature and humidity, treating those parameters as if they were ambient.

The chamber is shut, and the measurement equipment is turned on. Potentiometric sensors are supplied with direct current from a supply device set to 3.7V, and voltage drops, resulting from the movement of the sensor slide are measured. The change in sample length resulting from concrete strain evokes a change in electrical current parameters (voltage) which, after the calibration, are translated to the units of length. Two multiplexers, which are part of Atewin measurement equipment, and the specially designed terminal rail make it possible to supply current to all sensors used in the measurements, and collecting results from the chosen channels.

The equipment used to measure concrete shrinkage has the capacity of measuring voltage with the precision range of 0,0001V which, taking into account the sensor calibration factor, makes it possible to measure strain down to 0,00025 mm.

The frequency of taking measurements and the order of recording the results have been set by numerical software (Fig. 5b) which makes it possible to select and record data from appropriate sensors in any given time span. The software was designed so that the voltage measurement is taken separately from individual sensors, by means of opening an access channel to each individual sensor, then the value of the reading is recorded in an appropriate file, the channel is closed, the measurement system stabilizes for 10 seconds, and the next channel and sensor are opened. The measuring equipment has an option of using 10 potentiometric sensors at a time, and taking measurements with the frequency of 100 to 110 seconds.

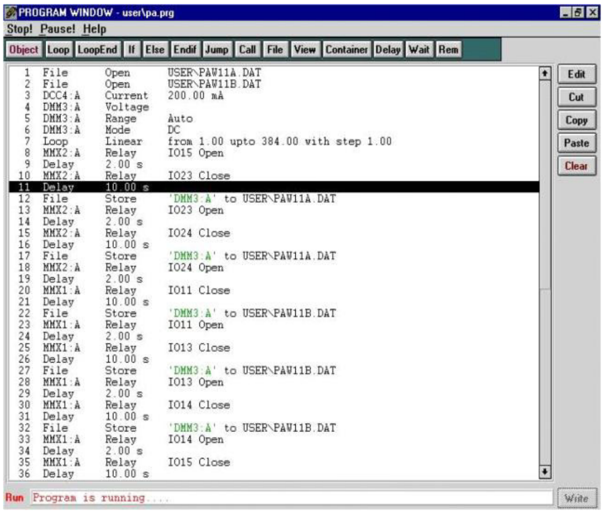

Fig. 5. (a) Concrete samples, positioned in the climatic chamber, with attached potentiometric sensors.; (b) A diagram of the control software responsible for power supply to potentiometric sensors, and for recording data with appropriate measurement frequency.

When a concrete sample is properly equipped, tests may begin. The testing equipment and sampling and recording software is turned on, and data is collected in prescribed time intervals. Results are recorded in appropriate files, and then translated – in accordance to the empirical formula presented above – from electrical current into metric units.

Owing to the huge volume of the recorded results, we have limited the presentation to three consecutive measurements taken in 10 minute intervals. The time intervals for measurements may be set in any way the user regards it fit. The first column presents times of measurement in seconds, after the testing has started, the third column presents the measured values of voltage increase or drop in mV, from consecutively linked sensors attached to concrete samples.

The results (measured in mV) from column 3 can be translated into metric values thanks to the empirical formula, and a graphic presentation of concrete shrinkage can be performed.

High frequency of measurements makes it possible to separate all the phases in the initial period of concrete shrinkage of concrete mixes.

3. Shrinkage in changeable w/c ratio concrete

As it was mentioned above, the amount of water influences the course of hydration of cement and concrete shrinkage. The types of concrete which were tested had constant amount of cement, namely 400 kg, and constant percentage content of aggregate; 0-2mm sand – 34%, 2-8mm gravel – 31%, 8-16mm gravel – 35%. The w/c ratio was the only changeable parameter (the amount of water in the cement mix) and, consequently, the concrete consistency was changeable. Concrete samples were placed in a climatic chamber for 4 days, where climatic conditions were constant throughout the tome of testing. The test results are presented in Fig. 6.

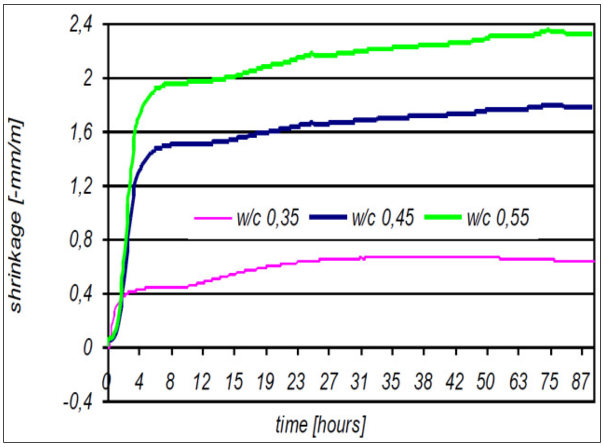

Fig. 6. Shrinkage in changeable w/c ratio concrete, humidity: 35%; temperature: 20°C.

4. Shrinkage in concrete with superplasticizer admixture

Tests were performed on concrete without chemical admixtures, the superplasticizer that was used was FM in the amount of 1,45% in concrete mix, FM 6 superplasticizer in the amount of 1,45% in concrete mix, and the amount of water used in the mix reduced by 20%. Constant amounts of cement and 0-8mm aggregate were used. Concrete mix content is presented in Table 2.

Table 2. Concrete mix content.

Concrete mix	Cement	Water	0-2 mm sand	2-8 mm gravel	Admixture
Amount per 1 m^3 of concrete	330	150	440	1530	4,41

The sample was kept in a climatic chamber for 4 days, at the temperature of 20oC and humidity of 35%, see figure 7a.

5. Shrinkage in concrete with microsilica admixture

Microsilica was dosed in the amounts of 5%, 10%, 15%, adding it to the concrete mix. Vicorete 5-600 chemical admixture was also added to make sure the consistency of concrete is consistent. In that case it has been assumed that the percentage share of aggregates in the concrete mix will be constant, as well as the constant amount of water and consistency of concrete. Figure 7b. shows shrinkage in concrete with microsilica.

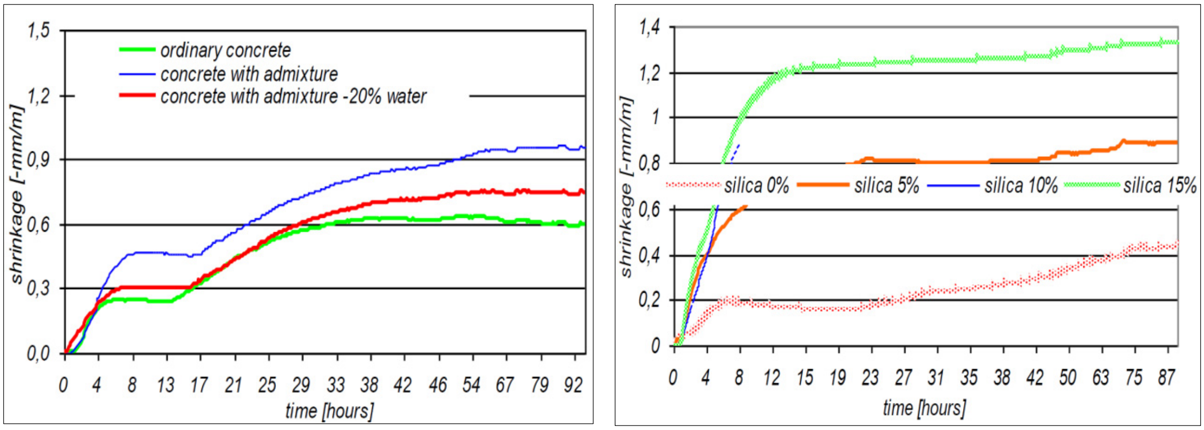

Fig. 7. (a) Shrinkage of concrete without admixtures; with chemical admixture; with chemical admixture – 20% of grout water. Humidity: 35%; temperature: 20°C. ; (b) Shrinkage in concrete with microsilica. Humidity: 85% temperature: 20°C.

6. Conclusions

The innovative solution in civil engineering of testing concrete proposed by authors led to the interesting conclusions. Basing on the tests, it seems that the magnitude of shrinkage is primarily influenced by relative ambient humidity of the environment where the concrete sample is kept. It is possible to identify subsequent phases of shrinkage: from plastic shrinkage, through expansion to drying shrinkage. The higher the humidity the longer the expansion lasts, and this phenomenon is related to the amount of water and rate of drying of concrete – for lower ranges of humidity the expansion lasts shorter, while drying shrinkage begins more rapidly – see Fig. 3a and 3b. Another crucial aspect is whether there is access to humidity provided by the environment which, as in Fig. 7b, was 85%, the system was fully hydrated, and drying shrinkage occurred only after a few days. The admixture influences concrete shrinkage in two ways: when it is added, the amount of water in concrete mix, which has drastic influence on shrinkage, can be reduced, though using admixture without water reduction will greatly increase its intensity. Concrete without admixtures hydrates very slowly and does not show significant shrinkage strain, while adding a superplasticizer facilitates increased dispersion of cement and liquidity of the mix, because the admixtures, modifying forces among grains of cement, result in breaking up bigger agglomerates into smaller ones, releasing water contained in them. Moreover, it has been observed that adsorption to C3A is preferred, as it is the most reactive mineral stage of cement, and to the products of hydration. Over time, the effects of the superplasticizers disappear, nonetheless resulting in crucial changes to the process of cement hydration in its initial stages, as shown in Fig. 3a. Adding microsilica to concrete increases shrinkage a few times, though with amounts higher than 105, those changes prove to be rather small but, on the other hand, plastic shrinkage takes longer, usually 3 to 4 hours, and ends when the time of cement bondage is over.

The amount of water has significant influence on shrinkage, though one should not forget the course of cement hydration. It may be expected that with higher values of the w/c ratio, hydration becomes faster and more dramatic, the amount of water evaporated from the mix is bigger, and therefore, compared with the situation presented in Fig. 7a, where using the admixture increased concrete shrinkage, it is advisable to reduce the amount of water to a minimum and to use chemical admixture, as the intensity of shrinkage will be lower.

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