

# **CREEP OF POLYMER-CEMENT CONCRETE AT NORMAL AND ELEVATED TEMPERATURES**

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## **ABSTRACT**

The paper presents the results of long-term investigations of the time-dependent deformations of polymer-cement concrete (PCC) mixes at normal temperature equal to  $22\pm 1^\circ\text{C}$  as well as the results of the initial creep of the same concrete mixes at elevated temperatures equal to 50, 75, 100 and  $150^\circ\text{C}$ . At normal ambient temperature the tests lasted for 70 days and at elevated temperatures on average only for 7 hours, due to the limitation of the used test equipment. The sustained load for particular concrete mix was equal to the 25% of its average ultimate compressive load at normal ambient temperature.

## **1. INTRODUCTION**

In the last few decades the problems connected with the durability of ordinary portland-cement concrete have been increasingly frequent. Parallel to the cause assessment of the concrete decay, the interest of researchers has been mainly directed to the development of materials that would possess properties necessary for effective repair and rehabilitation of damaged concrete elements. As a result new civil engineering materials have been developed, among them also the polymer-cement mortar. The polymer-cement mortar is a normal portland cement mortar with a polymer

admixture in the amount of 5-20 weight percents with respect to the cement quantity. Since polymers used in the polymer-cement mortar adhere very well to other materials, provide good resistance to chemical and physical influences and can have significantly higher tensile strength as compared to the cement matrix, the composite material possesses suitable strength and durability characteristics, which makes it an excellent repair material.

As soon as it had been established that ordinary portland-cement concrete has poor resistance to chemical and physical attack, the improvement of mechanical and durability characteristics of the concrete used for new constructions exposed to severe environment begun to occupy the researchers. Owing to the positive experiences with the polymer-cement mortar the introduction of polymer-cement concrete (PCC) as new structural material seemed to be the logical next step. However, the potential use of PCC for structural elements depends on the results of extensive, and partially also long-term, physical, mechanical and rheological investigations.

Our research work was mainly focused on the time-dependent deformations of PCC due to creep of filmed polymer and hydrated cement paste at normal and elevated temperatures. Since at the normal ambient temperature the long-term creep tests were carried out, at the elevated temperatures equal to 50, 75, 100 and 150°C only the initial creep of the PCC was studied.

## **2. EXPERIMENTS**

### **2.1 Materials and details of mixes**

The test specimens were made of three polymer-cement concrete mixes and one ordinary portland-cement concrete mix in the role of control mix. As basic materials were used river sand and 8 mm maximum size gravel coarse aggregate, portland cement type PC 45 B corresponding to the former Yugoslav Codes JUS and commercial co-polymer based on ester acrylic acid and

styrene produced by BASF. The polymer was incorporated into concrete in the form of water dispersion. The mean particle size of the dispersion is about  $0.1\mu\text{m}$ , the pH value between 7 and 8 and its minimum temperature of film formation around  $30^{\circ}\text{C}$ . The glass transition temperature ( $T_g$ ) of the polymeric film is around  $19^{\circ}\text{C}$ , its tensile strength ranging between 7 and 10 MPa, and the deformation at the tensile strength between 500 and 800%.

Table 1: Quantities of the basic components and properties of fresh concrete mixes.

Mix	Cement [kg]	Polymeric dispersion [kg]	P/C ratio	W/C ratio	Antifoaming agent [kg]	Vebe time [sec]	Air volume [%]
MIX 0	400	0	0.00	0.55	0.0	2.0	2.5
MIX 1	400	80	0.10	0.37	2.0	4.0	2.6
MIX 2	400	120	0.15	0.34	2.0	3.3	2.6
MIX 3	400	160	0.20	0.32	4.0	3.5	2.8

At the constant quantity of portland cement for all concrete mixes, the water-cement (W/C) ratio for particular polymer-cement concrete was adjusted in order to obtain the same workability (Vebe time) as at the control mix. In this way the inhibition of the cement hydration, which is the consequence of the added polymeric dispersion [1], is totally or partially (depending on the polymer-cement ratio) compensated. In order to achieve the same porosity of the concrete mixes the antifoaming agent was added to the polymer-cement concrete mixes. The quantities of the basic components and the properties of fresh concrete mixes are given in Table 1.

## 2.2 Casting, curing and testing

From each mix,  $70.7\times 70.7\times 250$  and  $100\times 100\times 360$  mm prisms were cast in steel moulds. The

smaller ones were intended for the creep tests at elevated temperatures and the larger ones for the investigations of the time-dependent deformations at  $21\pm 1^\circ\text{C}$ . The specimens were de-moulded after 24 hours and were then for 6 days cured in water at  $20^\circ\text{C}$ . Further curing took place under controlled ambient conditions at a temperature of  $21\pm 1^\circ\text{C}$  and a humidity of 50%. Prior to the testing, the  $70.7\times 70.7\times 250$  mm test specimens were preconditioned to the subsequent elevated test temperature. For the test temperature of  $50^\circ\text{C}$  and  $75^\circ\text{C}$  the thermal preconditioning lasted 24 hours, and for  $100^\circ\text{C}$  and  $150^\circ\text{C}$  48 hours. According to /2/ this should be enough to re-establish the isothermal conditions in the specimens.

Table 2: The average compressive strengths and the sustained loads at creep tests.

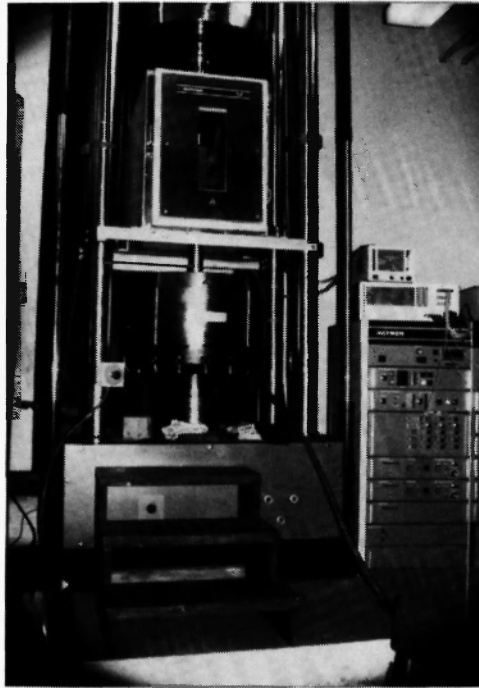
Mix	100x100x360 mm prisms		70.7x70.7x250 mm prisms	
	Compressive strength [MPa]	Sustained load [kN]	Compressive strength [MPa]	Sustained load [kN]
MIX 0	35.4	88	38.4	48
MIX 1	42.0	105	50.3	63
MIX 2	36.4	91	39.2	49
MIX 3	30.7	77	33.3	42

First the compressive tests were carried out in order to determine the magnitudes of the sustained stresses at the time-dependent deformations tests. For each concrete mix seven  $100\times 100\times 360$  mm and five  $70.7\times 70.7\times 250$  mm prisms were tested at  $20^\circ\text{C}$  /3/. At a particular combination of concrete mix and specimen geometry the sustained stress was calculated as the stress equal to the 25% of the average compressive strength. The average compressive strengths and the sustained loads are given in Table 2.

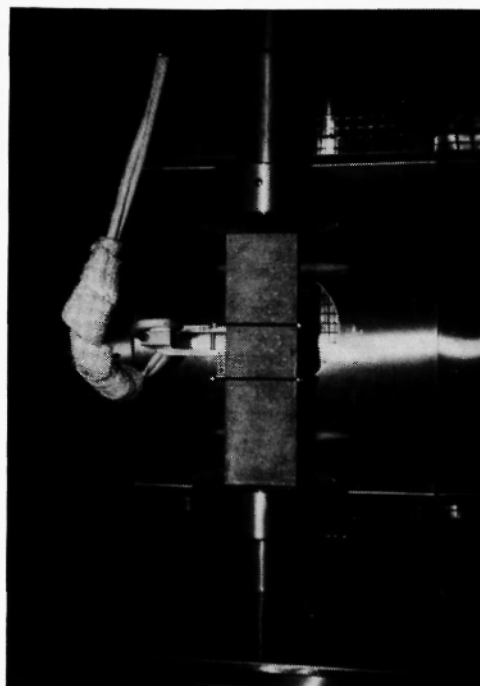
Long-term investigations of the time-dependent deformations of concrete mixes under

consideration were carried out at the ambient conditions with a temperature of  $22\pm 1^\circ\text{C}$  and relative humidity between 55 and 75%. For these tests the loading frames capable of maintaining the required load on the specimen, despite any change in the specimen length, were used. The load was controlled by a load cell inserted between the specimen and the upper load plate of the frame; the axial strains were measured by strain gauges. For each mix 4 samples were tested. Unfortunately, the used loading frames are not manufactured in such a way that they could apply the required sustained load in the first attempt. When the load was finely applied, after two to three attempts, a considerable part of the initial creep strains already existed in the material. Therefore, the obtained long-term time-dependent deformations do not represent the virtual time-dependent behaviour of the tested concrete mixes. However, they can serve well enough for the estimation of the influence of the used polymer to the time-dependent deformations of the material.

The initial creep of the PCC mixes at elevated temperature was investigated with the help of a servo-hydraulic testing machine Instron type 1345, into which the temperature chamber with a self-adaptive temperature controller was placed (Photography 1). The time-dependent deformations of specimens were measured with the Instron 2630 Series water-cooled extensometer with a gauge length of 50 mm. First the chamber was heated to the testing temperature. Then the extensometer was placed on the specimen, which was taken out of the furnace and put between the compressive plates inside the temperature chamber (Photography 2). The temperature chamber was re-heated to the testing temperature and the specimen was left in a non-loaded position until the extensometer was completely appeased. Only then did the loading of the specimen start. Each specimen was loaded by conducting the crosshead displacement of the testing machine with a velocity of 0.25 mm per minute until the previously determined



*Photography 1: Servo-hydraulic testing machine with temperature chamber.*



*Photography 2: Creep specimen with water-cooled high-temperature extensometer.*

magnitude of sustained load was achieved. The load was then maintained for the next 6-8 hours and the appertaining strains were measured. In the described way the creep tests of the polymer-cement concrete mixes at elevated temperatures (50, 75, 100 and 150°C) and of the control mix at 20°C were carried out. For each concrete mix and each temperature 3 samples were tested. Unfortunately, the results obtained at the polymer-cement (P/C) ratio 0.15 are not reliable due to the multiple automatic shutdowns of the testing machine and will be therefore here neglected.

All specimens used at the short-term and at the long-term time deformations tests were at the moment of applying the sustained stress 28 days old.

### **3. TIME DEFORMATIONS OF PCC AT NORMAL AMBIENT CONDITIONS**

#### **3.1 Test results**

The time-dependent deformations of the control and PCC mixes due to creep and shrinkage of the composite material at an ambient temperature of  $22\pm 1^\circ\text{C}$  are for the time period between 1 and 70 days under sustained load given in Figure 1. One day after the application of the load the highest time deformation was obtained at PCC mix with the P/C ratio 0.2, followed by the PCC mixes with the P/C ratio 0.1 and 0.15. The control mix exhibited the lowest one-day deformation, which was approximately 70% lower than at the P/C ratio 0.2.

With the increase of time under load the relation between the deformations of the control and PCC mixes changed a lot due to the much higher rate of the time deformations of the control mix during the whole time period under consideration (Figure 1). Already after 5 to 6 days under load the time deformation of control mix exceeded the deformations of PCC mixes with the P/C ratio 0.1 and 0.15, and at the P/C ratio 0.2 the same happened after 18 days. As a result of the described behaviour the 70-days increment of the time deformation of the control mix was 30, 40

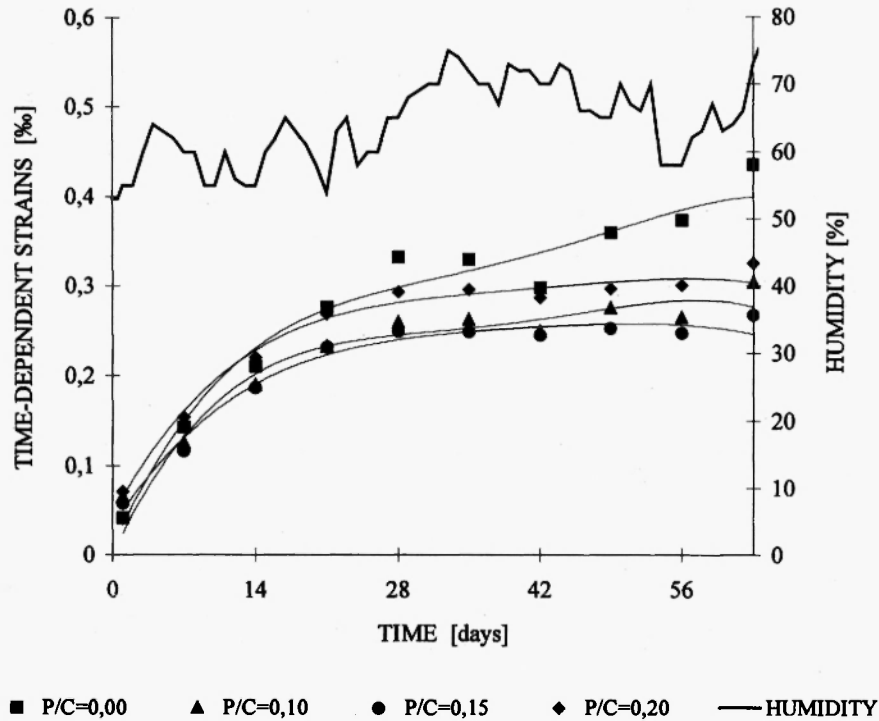


Figure 1: Long-term time deformations of ordinary and PCC concrete mixes at  $21 \pm 1$  °C.

and 45% higher than at the PCC mixes with the P/C ratio 0.2, 0.1 and 0.15, respectively.

Regarding the response of the PCC mixes to the sustained load, the time deformations obtained at the P/C ratio 0.2 were up to the 20% higher than at the P/C ratio 0.1 and up to the 30% higher than at the P/C ratio 0.15. The rate of the time deformations was considerably high only during the first 14 days. Between the 14<sup>th</sup> and 21<sup>st</sup> day a significant reduction of the rate occurred and stayed low up to the end of the tests. A minor exception was PCC with the P/C ratio 0.1, which exhibited almost the same time deformations as the mix with the P/C ratio 0.15 until the 42<sup>nd</sup> day under the load. However, later on the time deformations started to increase slightly faster than at both higher P/C ratios.

Since we did not maintain constant ambient humidity throughout the test period, also the

response of the time deformations of the concrete mixes under consideration to the variation in relative humidity has been observed. The highest influence of the changing humidity has been obtained at the control mix. For the PCC mixes the variation in time deformations due to the variation in humidity was considerably smaller, and it decreases with the increasing P/C ratio.

### **3.2 Discussion**

During the long-term tests of time deformations carried out at normal ambient temperature the polymeric binder was very likely in the rubbery range, since the test temperature was only up to 4°C above the glass transition temperature ( $T_g$ ) of the polymer. In this range the polymer molecules naturally take up a random, coiled conformation. When applying stress, the molecules tend to uncoil. The deformation changes lag behind the application of the stress and it is assumed that the rate of uncoiling at any time after the application of the stress is proportional to the molecules still coiled. The described behaviour in the polymer mass seems to be to a large extent responsible for the increase in the rate of the time deformations with the increase of the P/C ratio in the first few hours after the application of the sustained load and thus for considerably higher one-day time deformations at PCC mixes, compared to the control mix. Also the relatively fast decrease in the rate of the time deformations between 14<sup>th</sup> and 21<sup>st</sup> day under the load in the case of PCC mixes seems to be first of all related to the uncoiling process of the polymer molecules. However, at least two other influencing factors are also responsible for slower increase of the PCC mixes time deformations. The first one is hindering of the moisture exchange between the specimen and the surroundings by polymeric binder, which results in reduced contribution of drying creep and shrinkage to the total time deformations. The second one is relatively high rate of cement hydration at ages equal to or higher than 28 days /4/, which

results in higher increase of compressive strength and modulus of elasticity than at the ordinary concrete. The consequence is reduced contribution of basic creep to the total time deformations.

#### 4. INITIAL CREEP OF PCC AT ELEVATED TEMPERATURE

##### 4.1 Test results

The time-dependent deformations due to the creep of PCC mixes at elevated temperatures are for the P/C ratio 0.1 presented in Figure 2, and for the P/C ratio 0.2 in Figure 3. The Figures show as a comparison also the creep strain-time curve of the control mix at 20°C. It is assumed that in such a short period of time the material shrinkage does not influence the time-dependent deformations of the test specimens.

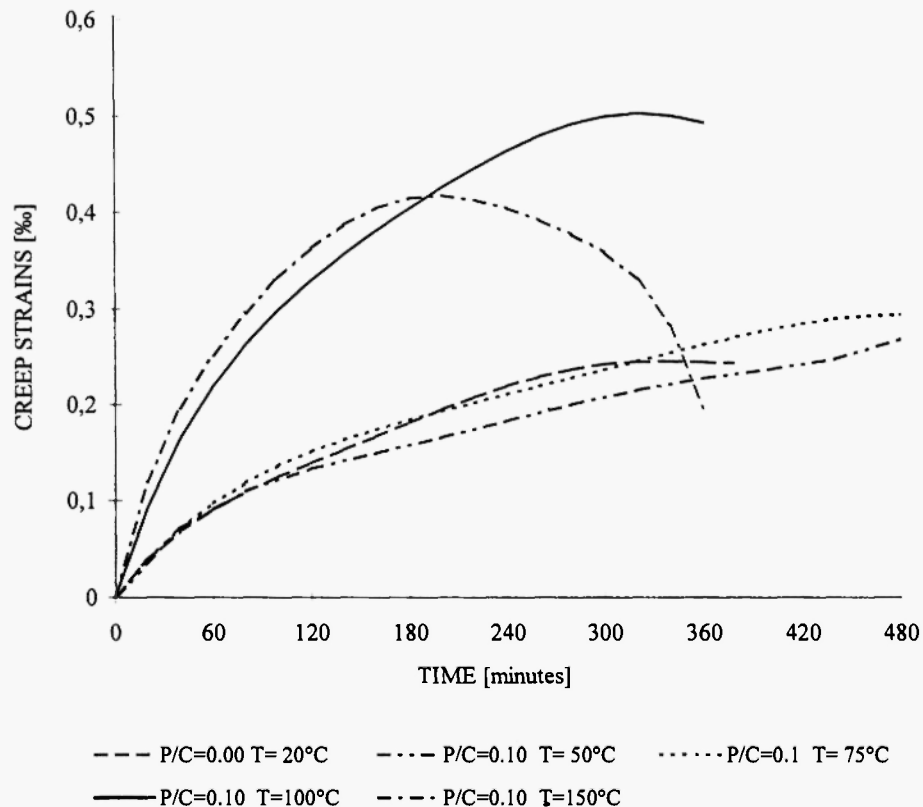


Figure 2: Initial creep deformations of PCC with P/C ratio 0.1 at elevated temperatures.

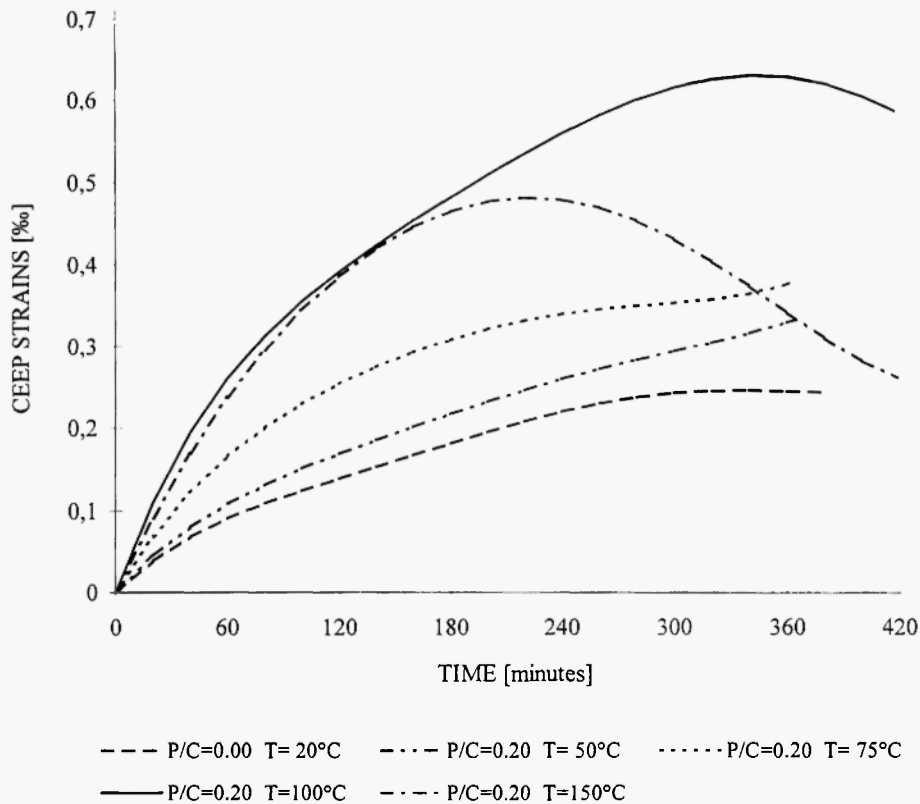


Figure 3: Initial creep deformations of PCC with P/C ratio 0.2 at elevated temperatures.

The behaviour of PCC with the P/C ratio 0.1 at 50 and 75°C is in the first hour under sustained load identical to the behaviour of the control mix at 20°C. In the next five hours the differences between the three strain-time curves are still not significant, yet the PCC creep strains are at 75°C between 0.01 and 0.04‰ larger than at 50°C.

However, as opposed to the control mix response, the creep rate of the PCC is approximately constant throughout the last six hours of the test duration for both testing temperatures. With the increase of the test temperature from 75 to 100°C the creep velocity of PCC with the P/C ratio 0.1 is increased for more than two times during the first four hours under sustained stress. Even though after that the creep velocity starts to decrease considerably, the increment of strain due to

concrete creep is after 5 hours still more than 100% larger than at 50°C and at 75°C. At the temperature of 150°C the creep of PCC with the P/C ratio 0.1 is more intensive than at 100°C only in the first two hours and then it starts to slow down. It achieves its maximum value, which is about 17% lower than the maximum creep strain at 100°C, between the 3<sup>rd</sup> and the 4<sup>th</sup> hour under sustained stress. After that the time-dependent strains start to decrease with time.

At PCC with the P/C ratio 0.2 the relationship between the time-dependent deformations and the temperature seems to be very similar to that at the P/C ratio 0.1, yet the creep strain-time curves are shifted towards the larger strains (Figure 3). Also at the P/C ratio 0.2 the smallest creep strains appertain to the test temperature of 50°C. The creep velocity is during the first 3 hours between 4 and 2 times higher than at the P/C ratio 0.1, which makes the strain at the P/C ratio 0.2 after 3 hours higher for about 0.32‰. After that the creep-time curve at the P/C ratio 0.2 starts to approach the curve obtained at the P/C ratio 0.1, thus after 6 hours under sustained load the difference is only 0.1‰. The creep strains obtained at the P/C ratio 0.2 and a temperature of 75°C are up to 0.09‰ larger as compared to the strains of the same concrete at 50°C. The same phenomenon as at the P/C ratio 0.1 can also be noticed at P/C ratio 0.2 and at a testing temperature of 150°C. At this temperature the strains due to creep reach the maximum value also between the 3<sup>rd</sup> and the 4<sup>th</sup> hour, and then they decrease with time. However, while the maximum creep strain at 100°C is at the P/C ratio 0.2 about 28% larger than at the lower P/C ratio, at 150°C the difference is only 9%.

#### **4.2 Discussion**

The creep of PCC at elevated temperatures is a function of numerous influencing factors; some of them accelerate and others hinder the creep process. Regarding the influence of the

thermoplastic polymers there could be no doubt that the presence of the polymer binder in the concrete structure intensifies the creep at temperatures above  $T_g$  of the polymer. Thermoplastic polymers become soft and deformable upon heating. Above  $T_g$  of the polymer first a rubbery intermediate zone is often observed, followed by the liquid-like viscous region. In the viscous region the viscous flow, i.e. the molecular segments gradually sliding past each other over an extended period time, is the origin of the time-dependent deformation of the polymer. According to the physical properties of the used styrene-acrylate polymer we can assume that at temperatures equal to or higher than 50°C the viscous flow of the polymer prevails, though at 50°C the rubbery behaviour contribution could be significant.

During the first few hours under sustained load the viscous deformations of the PCC occur due to viscous flow of the cement gel and filmed polymer, as well as due to delayed elasticity of the mineral aggregate and solid products of the cement hydration. By elevating the test temperature from 20°C to 50 or 75°C the viscous flow of the softened plastic is certainly not reduced. Therefore, it is likely that the reduced flow of the cement gel and smaller delayed elasticity are responsible for the roughly equal creep magnitude at the P/C ratio 0.1 and temperatures of 50 and 75°C, as compared to the creep of the control mix at 20°C. During the preconditioning period the exposure of the PCC with the P/C ratio 0.1 to the elevated temperature (50 or 75°C) accelerated hydration of cement and caused rapid moisture loss. Due to the moisture loss, effective reduction in disjoining pressure yielded closing up of the gel structure and elevating of the surface energy of the cement gel. Consequently, the strength of the hydrated cement paste was considerably improved. The creep of the PCC with the P/C ratio 0.2 at 50 and 75°C can be attributed to the same processes in the structure of the cement and polymeric binder as at the lower P/C ratio. However, excellent water retention capacity during the curing phase, due to two

times higher polymer quantity, provides more moisture for the thermally activated cement hydration during the preconditioning period. On the other hand, since at the P/C ratio 0.2 the filmed polymer inhibits the cement hydration considerably /4/, the volume of the hydrated cement paste prior to the application of the load is likely to be lower than at the P/C ratio 0.1. Thus we can assume that the significantly higher creep magnitude at the P/C ratio 0.2 is first of all caused by the viscous flow of the softened polymeric binder. The minor creep increase can be attributed also to the higher delayed elasticity.

Not only the viscous flow of the polymer but also the enhanced micro-cracking of the hydrated cement paste as well as of a transition zone /5/, the latter represents the interfacial region between the particles of coarse aggregate and the hydrated cement paste, are primary responsible for the extremely high magnitude of the initial creep at 100 and 150°C. Since in this temperature region also the limited decomposition of the cement hydration occurs due to the loss of the chemically combined water /2/, it can also contribute to the high creep magnitude. However, it is difficult to explain the phenomenon obtained at 150°C, its initial phase has been observed already at 100°C, that after achieving the maximum value of the creep deformation the time-dependent deformations of the PCC start to decrease with time. To our knowledge, the aforementioned behaviour is not reported for the ordinary concrete mixes in the temperature region from 100 to 150°C. Thus it is likely for the phenomenon to be linked with the thermal movement of the polymer molecules inside the hydrated cement paste with very low porosity due to low water-cement ratio (Table 1).

## **5. REFERENCES**

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