AAR AT PAULO AFONSO HYDROELECTRIC COMPLEX, PART II: CREEP OF CONCRETE CORES AFFECTED BY THE ALKALI-AGGREGATE REACTION

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Abstract

The aim of this paper is to present a specific study about creep tests in concrete cores drilled from several structures deteriorated by the alkali-aggregate reaction (AAR). Prior to these studies, many laboratory investigations about the deterioration process had already been conducted beyond the field observations, confirming the presence of AAR This study was carried out in order to understand the influence of AAR on this viscoelastic property and to verify the concrete behavior. The concrete cores drilled from three Power Houses of the Paulo Afonso Hydroelectric Complex, with similar aggregates and different ages, were submitted to creep tests and the resultants creep coefficients were compared and showed a fair correlation with concrete age.

Keywords: Concrete core – creep – alkali-aggregate reaction – viscoelastic

1 INTRODUCTION

Paulo Afonso Hydroelectric Complex comprises five Plants – Paulo Afonso I, Paulo Afonso II, Paulo Afonso III, Paulo Afonso IV (PA I, II, III and IV) and Moxotó. The first AAR symptoms were observed at the end of the 70s in Paulo Afonso II, when the plant was 17th year of operation. Since then, the evidence of AAR in the structures of the Plants became clearer, and includes: concrete cracking, differential displacements at contraction joints and, crushing of small concrete columns that supported cable trays. During the operational period, several anomalies were verified in the hydro generating units of Moxoto Plant, and in 1984 the suspicion of AAR existence was confirmed, leading CHESF to carry out extensive investigations.

The construction of Paulo Afonso I began in March 1949, and started commercial operation of power supply in 1954. The construction of Paulo Afonso II began in 1955. Three units of 75 MW are operating since 1961 and another three units of 85 MW each, are operating since 1967. Paulo Afonso III construction started in 1967 and is in operation since 1971. Table 1 shows some characteristics of the plants. As Paulo Afonso II HPP was built in two stages, the letters a and b were used to differentiate the two stages.

This paper presents the results of investigations regarding creep tests on concrete cores drilled from PA I, II, and III Power Plants. Another paper in this conference presents the results of how AAR concrete influences the mechanical and elastic properties [1].

2 MATERIALS AND METHODS

2.1 General

The samples were drilled from the concrete structures of the PA I, II and III HPPs, by means of rotative diamond drilling equipment and water cooled, having 200 mm in diameter. The concrete samples were wrapped in a PVC film immediately after the removal of the cores from the plants structures. In such conditions, they were placed in wooden boxes and shipped to the Concrete Laboratory of FURNAS Civil Engineering Technological Center. To run the creep tests, the cores were sawn and had their tops rectified.

The location of the boreholes was as follows:

– PA I - Cores SR1, SR3 and SR4, on the turbine operation floor (el. 144.0 m) of units 1, 2 and 3, respectively, with 3 m in vertical depth.

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– PA II - Cores SR1, SR3, SR4 and SR5, on the turbine operation floor (el. 142.0 m) of units 2, 3, 4 and 5, respectively, with 3 m in vertical depth. Core SR8, on the wall of the sluice chamber (el. 135.0 m) of unit 5, with 3 m in horizontal depth. Generating units 1 to 3 belong to PA IIa and 4 to 6, to PA IIb.
– PA III - Cores SR2, SR3 and SR4, on the turbine operation floor (el. 141.0 m) of units 2, 3 and 4, respectively, with 3 m in vertical depth.

2.2 Concrete Composition and Mixture Proportion

Petrographic analyses indicated six rock litologies as follows: biotite monzogranite, mylonite (possibly granitic rock), biotite tonalite, leucomonzogranite, diorite and hornblende monzogranite. The predominant rocks are biotite monzogranite and leucomonzogranite followed by biotite tonalite and mylonite. Litotypes biotite diorite and hornblende monzogranite are rare [2].

The, fine aggregate textures presented silty granulation, with sorted sand zones, but mainly coarse sand. Aggregates contain the following mineralogical composition as determined by optical microscopy with transmitted light: microcrystalline quartz, plagioclase (sericitized feldspar and impregnated by iron hydroxides), microcline, hornblende, biotite and opaques. Polycrystalline quartz and chert are rare. Aggregate grains roundness varies from angular to sub-rounded and angular to sub-angular grains are predominant, with medium to low sphericity characteristic of river sand.

The concrete cores tested had 30 mm coarse aggregates and were mixed with plain Portland cement with no mineral admixtures. The Power Plants concrete has cement content in the range of 350 kg/m^3 to 400 kg/m^3. The registers show that the total Na_2O equivalent alkali content of the cement used in Moxoto and Paulo Afonso IV power plants was 1.0%. These power plants were built in 1977 and 1979, respectively. For PA I, PA II and PA III Power Plants, we don't have the construction registers but the cement alkali content is supposed to be lower.

2.3 Methods for assessment and analysis

The creep tests were performed according to the NBR 8224 [3] (similar to ASTM C 512 [4]), in 16.3 cm x 32.6 cm concrete samples, using strain gauges to measure the deformations. On each test specimen, 2 (two) wire strain gauges KC 70 were attached at half height and directly opposite one to another. The concrete compression strength was obtained through the NBR 5739 [5] test method, corresponding to ASTM C39 [6] in order to obtain the load to be applied on the creep tests.

The concrete samples were put in the test machines with 3 samples superpotioned in each one. The first two loading cycles of 10 MPa were applied and relieved after 60 seconds and then the first reading was done without load. The 10 MPa load was applied again and kept constant with readings done periodically. The autogenous deformation was not taken into account due the advanced age of the concrete. Temperature oscillations along time were not considered either.

As recommended by the US Bureau of Reclamation [7] for mass concrete, a curve was adjusted to the readings.

$$\varepsilon = 1/E + F(k)\ \ln(t+1), \qquad (1)$$

where:
ε = total deformation
E = elasticity modulus
F(k) = creep coefficient
t = time under loading in days
k = age at loading

As this method is specifically to determine the creep coefficient, the immediate elastic deformation was disregarded in the analysis, with emphasis being on the creep portion only.

To determine the creep coefficient, the method of minimum squares was used, through the formula:

$$F_k = \frac{\sum\left(\varepsilon_i \cdot \ln(t+1)\right)}{\sum\left(\ln(t+1)\right)^2} \qquad (2)$$

where:
F_k : creep coefficient

ε_i : specific creep determined in the test, the module inverse portion neglected
t = time under loading in days

3 RESULTS

The figures 1 to 4 present the creep tests results of each sample with the adjusted curve used to calculate the creep coefficient. The figures 5 to 8 present the adjusted curves grouped for each Power Plant. The creep coefficients are listed on Table 2 together with the age since construction completion and plotted on the Figure 9 chart.

3.1 Paulo Afonso I

For the Paulo Afonso I Power Plant the results of four samples were studied. The creep coefficients obtained ranged from 2.41 to 3.84 (10^{-6}/MPa) and an average of 3.15 (10^{-6}/MPa).

3.2 Paulo Afonso II

For the Paulo Afonso II Power Plant, five samples were tested, and for each sample two test specimens were evaluated. Out of 10 tests, four were from PA IIa and six from PA IIb. The creep coefficients obtained ranged from 2.24 to 3.34 (10^{-6}/MPa) and an average of 2.95 (10^{-6}/MPa) for PA IIa and 1,54 to 2.15 with an average of 1.53(10^{-6}/MPa) for PA IIb.

3.3 Paulo Afonso III

For the Paulo Afonso III Plant, three samples were studied, yielding a total of four test specimens. The creep coefficients obtained ranged from 1.60 to 2.45 (10^{-6}/MPa) and an average of 1.94 (10^{-6}/MPa).

4 DISCUSSION

The concrete samples were drilled from analogues locations on the power houses, with similar aggregates and exposure humidity condition, but the soluble alkali contents of the concretes are different, increasing as the age lowers, as shown in Table 3. The free expansion of concrete samples, exposed to 100% RH after one year, showed to be proportional to the concrete alkali content [2]. The actual concrete expansion rates on the structures are unknown but it is expected to be proportional to the alkali content.

The creep tests were performed with an applied stress of 10 MPa, witch is far higher than the actual stress in the structures.

The average creep coefficients obtained form the tests are higher for the older concrete suggesting that the cumulated expansion could modify this viscoelastic property.

One should be aware that the tests conditions are quite different from the actual ones hence the viscoelastic behavior of the concrete structure could be different.

The results presented by Barrios [8], from creep tests performed on samples drilled from Belesar Dam and Albarellos Dam, both 40 years old double curvature arch dams, show that Belesar Dam, witch is affected by AAR, has an average creep coefficient of approximately 3.0 10^{-6}/Mpa and Albarellos Dam, not affected by AAR, 1.5 10^{-6}/Mpa approximately. The Belesar creep coefficient compares well with those of PA I and PA IIa that are 51 and 41 years old respectively. The aggregates of Paulo Afonso and Belesar Dam are similar and so does the creep test conditions but the exposure to the humidity is different. While at the Paulo Afonso Power Plants the concrete core were drilled from a dry atmosphere at the turbine floor, at Belesar the cores were taken from a gallery not far from the upstream face at the lower part of the dam. This fact could explain a higher concrete expansion rate at Belesar Dam. The Albarellos average creep coefficient is lower then that of PA III that is 31 years old.

Creep tests, among all deformation tests, presents a high variability of results which together with the AAR heterogeneity turn difficult the results analysis.

5 CONCLUSIONS

The main conclusion from the creep tests performed on concrete cores drilled from the Paulo Afonso Power Plants is that the average creep coefficients obtained are proportional to the age of the concrete. This suggests that the cumulated expansion effects, along the service life of the structure, could alter the viscoelastic properties of the concrete.

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Table 1: Paulo Afonso power plants features.

Power Plant	Starting year		Generating units	
	Construction	Exploration	Quantity.	MW/unity.
PAI	1949	1954	03	60
PAIIa	1955	1961	03	75
PAIIb	1961	1967	03	85
PAIII	1967	1971	04	216

Table 2: Creep Coefficients F(k) results.

Hole	Power Plant		Creep Coefficient - F(k) ($x10^{-6}$/MPa)	
	Age (years)	Dmáx (mm)	Unit.	Average
SR1	PA I 51 years	30	2.41	3.15
SR3			3.84	
SR4			3.77	
SR4			2.57	
SR1	PA IIa 41 years	30	3.27	2.95
SR1			2.24	
SR3			2.97	
SR3			3.34	
SR4	PA IIb 38 years	30	1.61	1.53
SR4			1.54	
SR5			2.15	
SR5			1.75	
SR8			2.02	
SR8			2.10	
SR2	PA III 31 years	30	1.75	1.94
SR3			1.95	
SR4			2.45	
SR4			1.60	

Table 3: Na_2O equivalent soluble alkali content in concrete cores.

Power Plant	Age (years)	Na_2O equivalent soluble alkali content (%)
PAI	51	1.2
PAIIa	41	2.0
PAIIb	38	-
PAIII	31	2.2

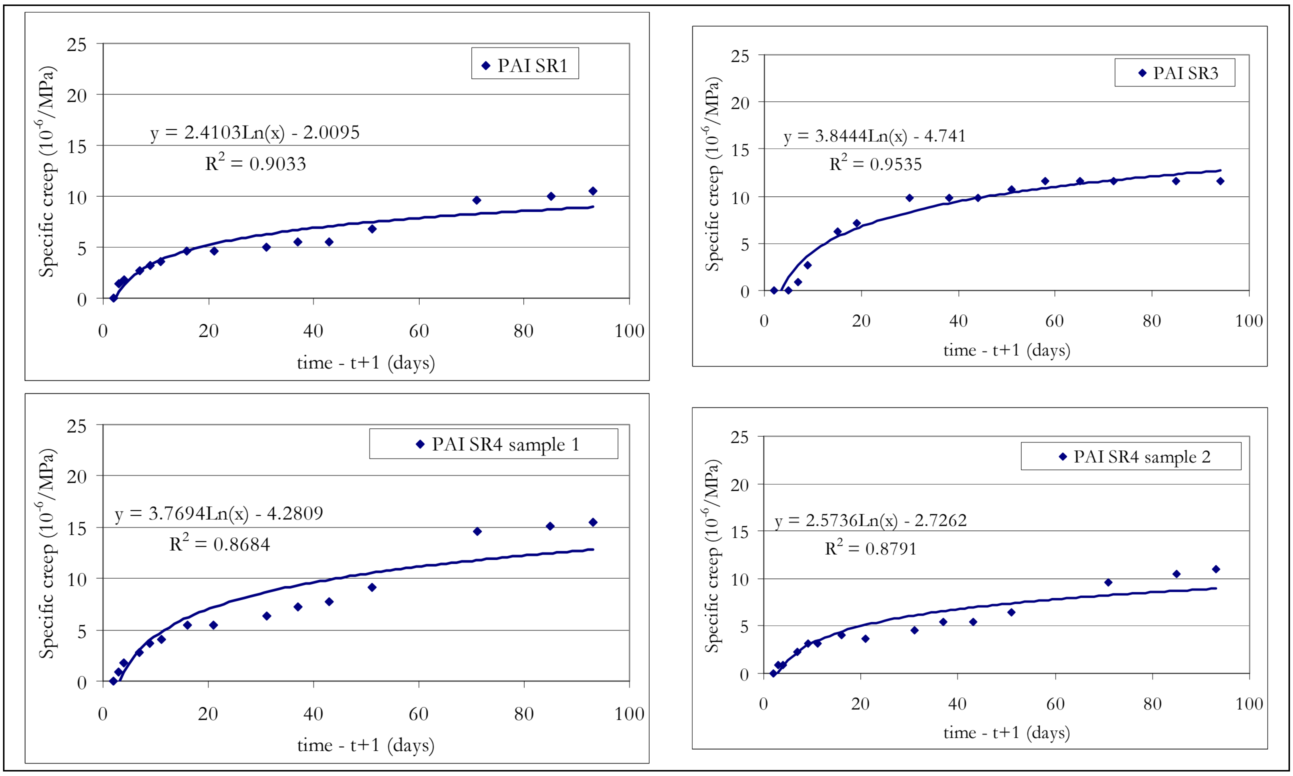

Figure 1: Specific creep results from PA I samples tests.

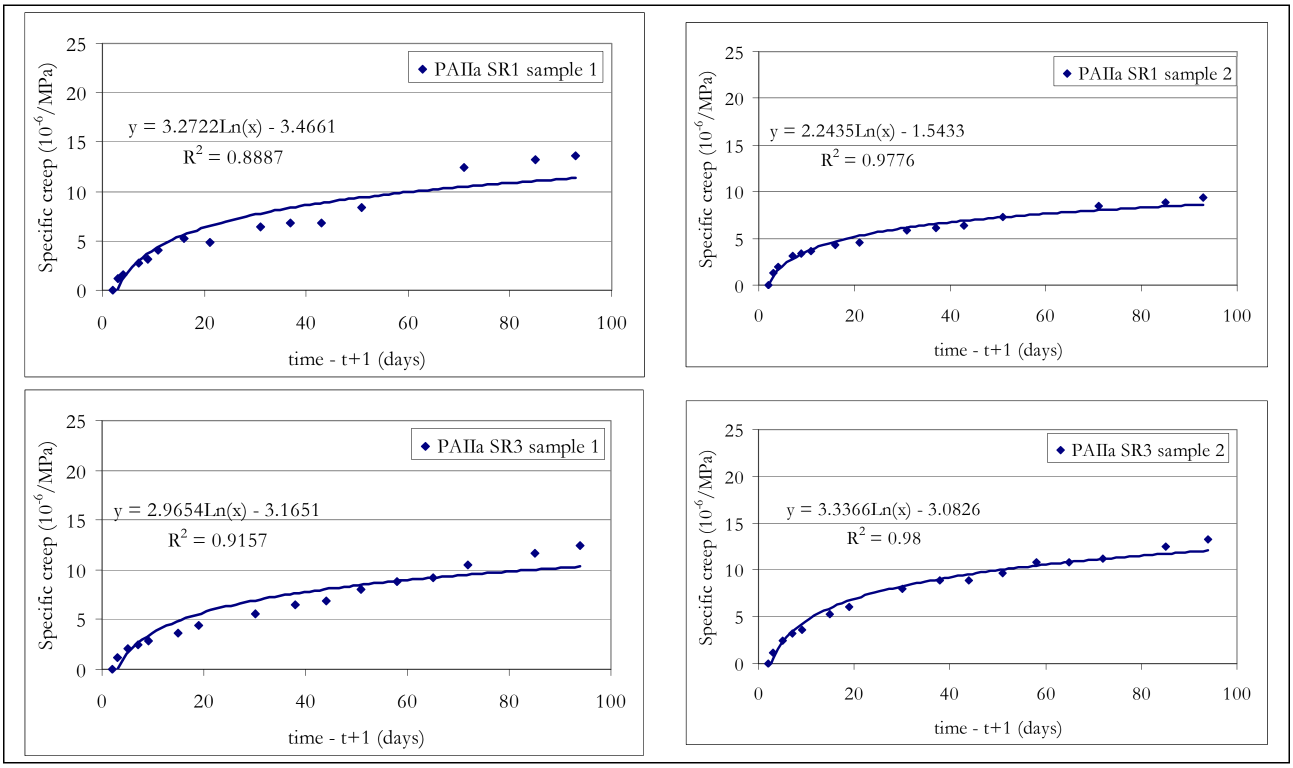

Figure 2: Specific creep results from PA IIa samples tests.

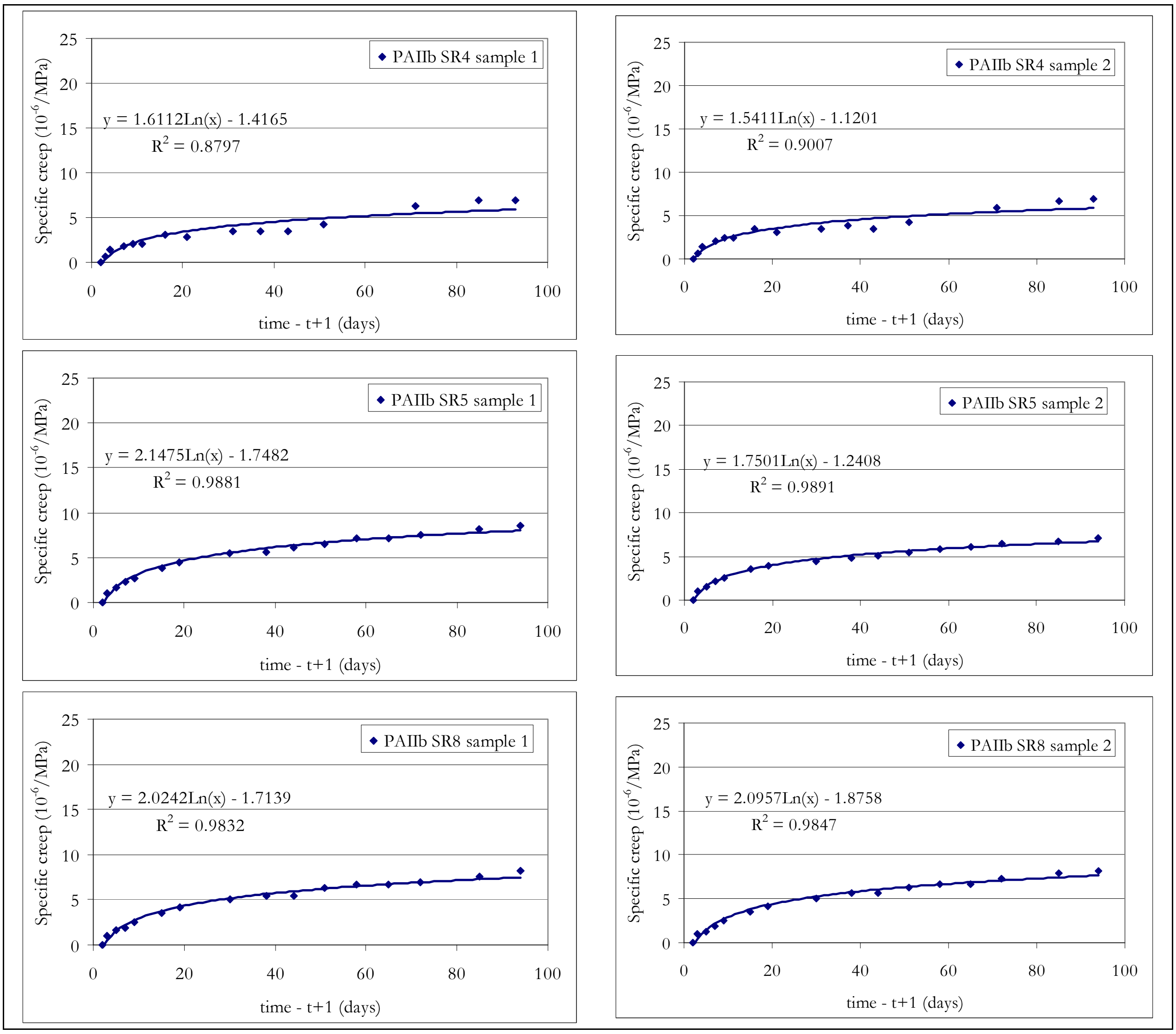

Figure 3: Specific creep results from PA IIb samples tests.

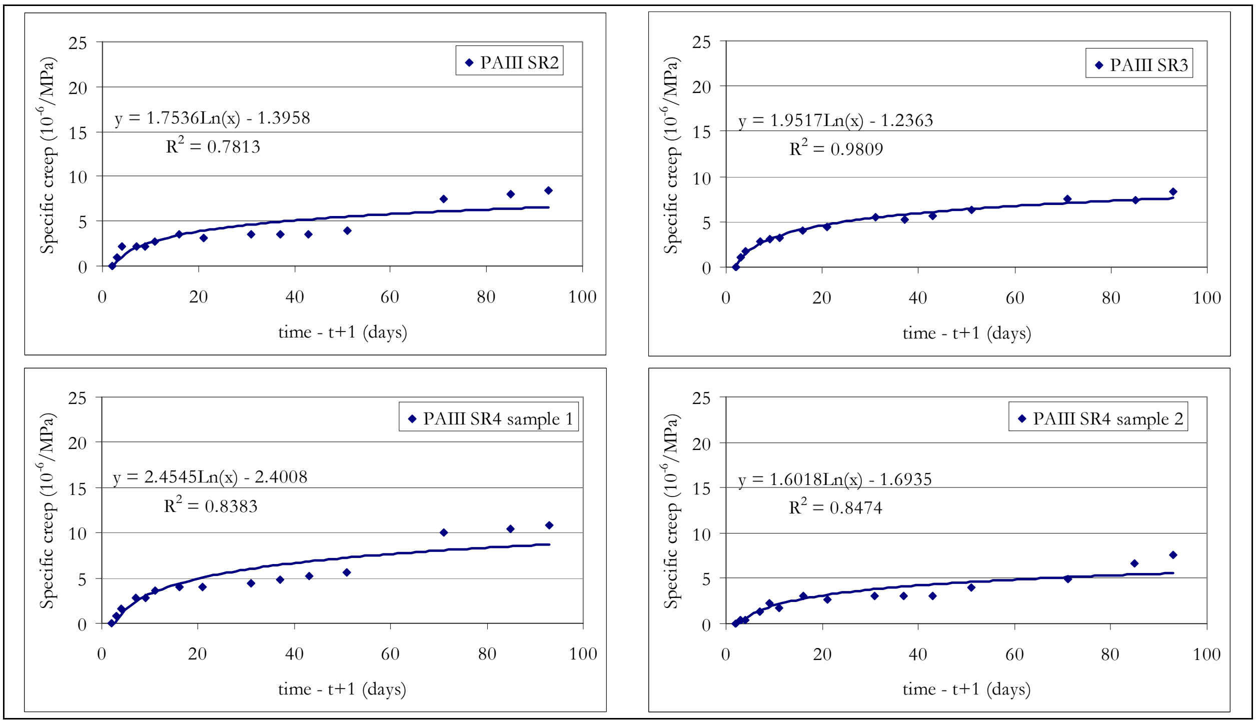

Figure 4: Specific creep results from PA III samples tests.

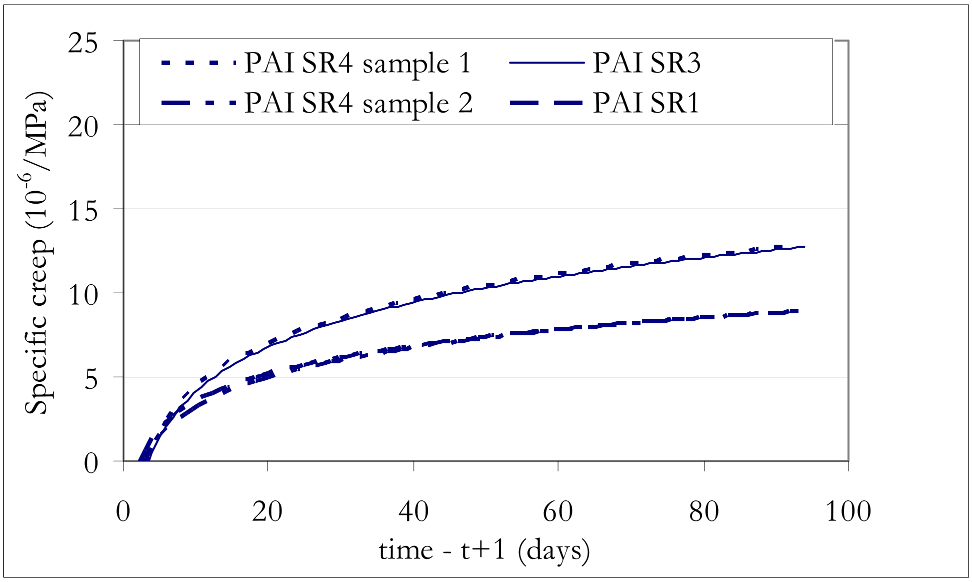

Figure 5: Specific creep adjusted curves from PA I samples tests.

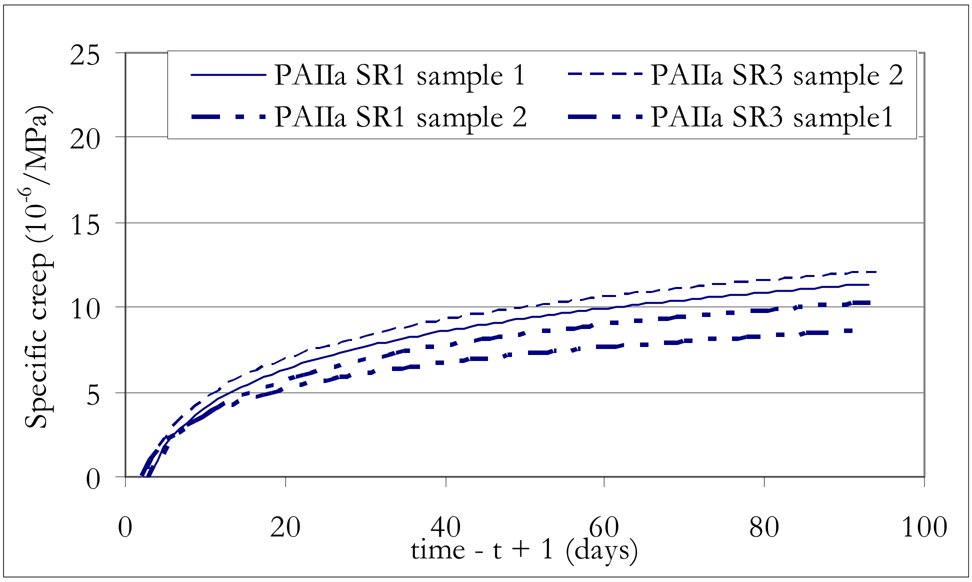

Figure 6: Specific creep adjusted curves from PA IIa samples tests.

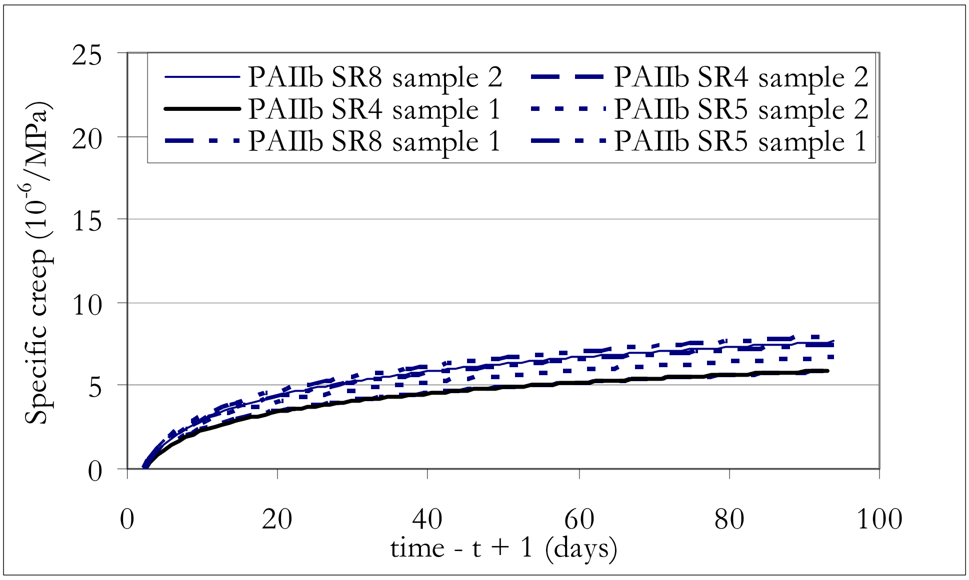

Figure 7: Specific creep adjusted curves from PA IIb samples tests.

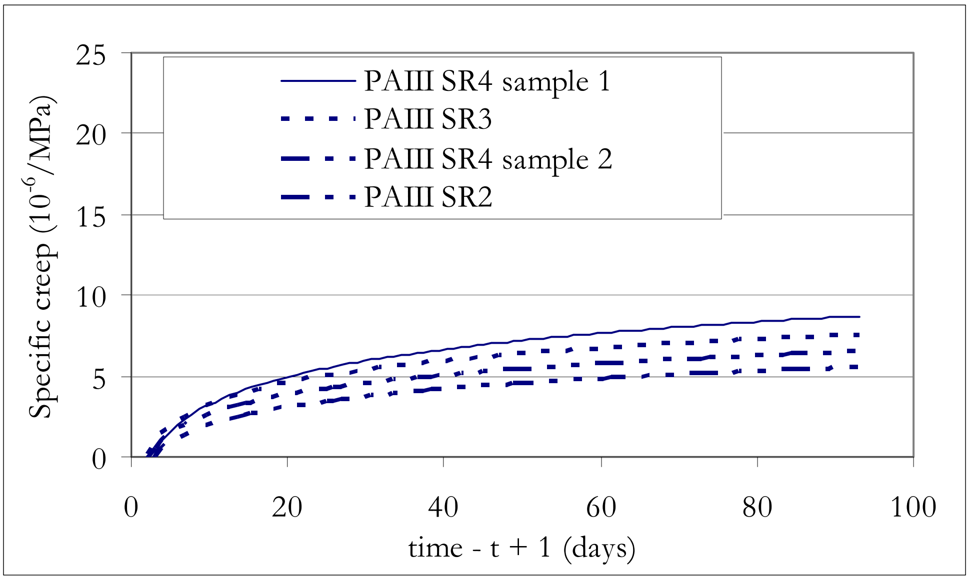

Figure 8: Specific creep adjusted curves from PA III samples tests.

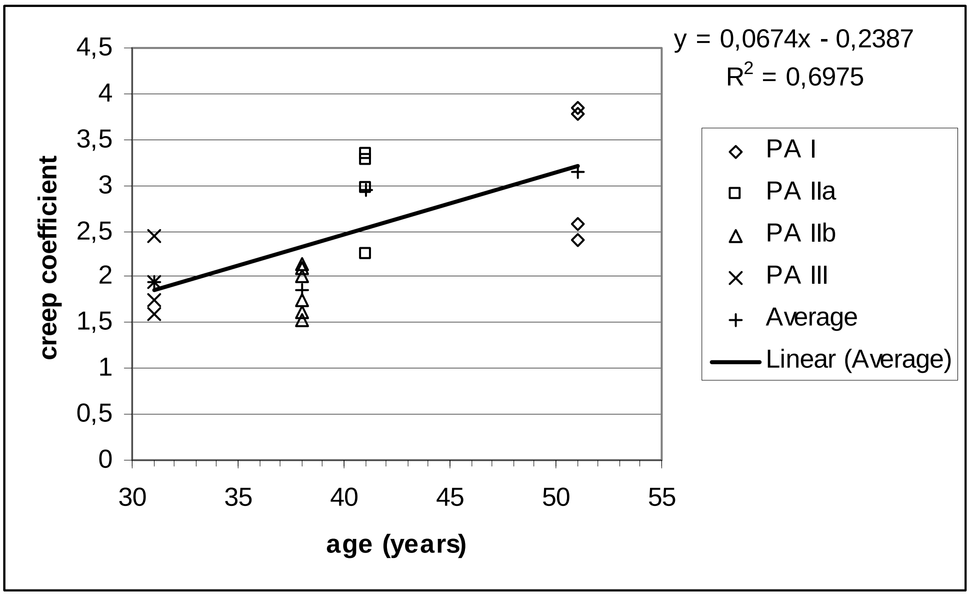

Figure 9: Creep Coefficients x time.