LABORATORY METHODOLOGY FOR EVALUATING THE EXPANSION PROCESS IN STRUCTURES AFFECTED BY AAR

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Abstract

This paper presents a suggestion of a new laboratory routine methodology for evaluating the expansive phenomenon of the concrete in structures affected by AAR. The experiments performed in laboratory were compared to measurements carried out by instrumentation in the field and also to the results of a numerical analysis.

The conceptual basis of the proposed method considers the effects of expansion from exposure in different conditions of temperature and humidity, establishing a regression to the environmental conditions in which it operates. The specimens tested are prepared from drilled cores, extracted from the affected structure.

The similarity of values obtained, even considering the randomness of the samples used, the measurement points in the structures and the complexity of the reactions, suggests deepening of evaluations, based on the new methodology proposed.

Keywords: laboratorial methodology, alkali-aggregate reaction, instrumentation in the structures, expansion, time to reduce the expansions

1 INTRODUCTION

This text suggests a new methodology for evaluating the time duration for the alkali-aggregate reaction (AAR) to stabilize in terms of expansion rate. These studies are based on data acquired from testing of concrete cores extracted from structures affected by this phenomenon.

The studies and results used in this paper were developed on the set of actions taken to assure the safety of traffic for over 12000 vehicles a day, on the bridge Mar Pequeno. The latter was built around the early 80 (December 19, 1981) and belongs to the expressways Immigrants complex operated under concessions, since 1998, by Ecovias.

The Mar Pequeno bridge, with two-way double lanes, 11 m wide each, has 1013 m of length. It was built in the Bay of Santos, near the Santos-São Vicente channel, on the side of the Atlantic Ocean, in a maritime environment with annual average temperature of 22.3º.

The bridge (Figure 1) consists of 33 isostatic spans, with grid type trays, each with 4 (South) or 5 (North) girder beams and 5 crossbeams, except for trays 1, 2, 3, 14, 16, 18, 20, 31, 32 and 33, which do not have intermediate crossbeams. The girders are precast concrete beams; their structure is prestressed from trays 1 to 30 and regular reinforced concrete from trays 31 to 33;

Each of the 28 intermediate supports of the bridge consists of a single column of variable section, associated with the transom beam tightly, forming a "T", and a single foundation block on top of 8 to 12 concrete piles with metallic casing. The supports number 13, 14, 15 and 16 consist of double pillars connected by intermediate beams and rest on top a single foundation block over piles. The piles are of steel pipes encasing reinforced concrete. The other supports, at the borders, consist of a beam that is associated with a foundation block, no segment of pillar.

The pavement on the structure is made of asphalt and, for the users security, New Jersey barriers were placed between the runway lanes and the pedestrians zone.

The coarse aggregates (granite type) used in the concrete, were obtain from deposits near the site.

Under a regime of privatized concession, the technical procedures consider periodic inspections with different procedures, which began in 1999. From these inspections, some cracks were observed in specific structural elements (Figure 2). These anomalies were monitored and required constant attention and testing. By 2006/2007, it was found that the crack were a result from expansions due the AAR phenomenon.

Facing those recent findings, the following actions were taken:

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- Evaluate the structural safety of the bridge and allow it to operate without traffic restrictions;
- Establish repair actions, so that the likely evolution of cracks openings does not permit aggressive actions, due to the marine environment, thus deleteriously affecting the durability of structures;
- Study the behavior and development of AAR, in order to have a possible assessment of the time required for a systematic maintenance, whereas the phenomenon and the operational safety of the structure.

That is, based on these evaluations and care, that could permit to operate the bridge safely.

2 RELEVANT OBSERVATIONS AND ACTIONS

The periodic inspections made it possible to observe cracks at the top of the concrete foundation blocks; primary and secondary reinforcement of the built structure are not consistent to the structural detailing design; the width of the cracks found on the surface of the concrete pile caps are above the values tolerated by Brazilian standards (ABNT-NBR 6118- 13.4.2 Limits for cracking and reinforcement protection regarding durability: The maximum opening wk of the cracks, as long as it does not exceed the values in the order of 0.2 mm to 0.4 mm under action of frequent combinations, do not have significant importance for corrosion in the passive reinforcement). A series of laboratory test performed on concrete specimens extracted from the foundation blocks (March/May 2006) confirmed that AAR had occurred.

On December/2006, an instrumentation/monitoring system (Figure 3) was installed on the beams and blocks, to safely conduct further studies and develop an efficient repair plan.

Accelerometers were installed in each section of the structure to determine its natural frequencies. The values achieved validated the computational mathematical model of the bridge (Figure 4). The comparison of the theoretical and empirical results showed a structural behavior of the bridge similar to its original design, despite the existing pathologies caused by expansive reactions.

Static and dynamic load tests (Figure 5) were carried out to assess the structural behavior and possible elastic reserve. The conclusion was that the structure was still working in spite of the existing cracks.

The three-dimensional mathematical model developed (considering an expansion rate of 50 μstrain/year) simulated (Figure 4) the effects of the concrete expansion due to the AAR in the structure of the bridge. The results were proven by checking equilibrium of tensions in three main directions.

Simultaneously, a research was conducted by contacting various international entities and professionals specialized in the field, in search for information regarding surface restoration and establishing leak protection to mitigate possible attacks on the reinforcement due to the marine environment.

The structural monitoring was concomitant with the period of repair (Figure 6), performed during the years 2009 to 2011, until early 2012 when (Figure 7) a practical stabilization of the deformations readings between selected points of the structures was observed.

3 ADDITIONAL TECHNICAL ASPECTS

During the period of knowledge exchange with the entities and specialized professionals, an important subject came into light, which is the comparison of procedures, such as monitoring, tests and evaluations, and concrete repair practices adopted worldwide and its adaptability to a Brazilian environment.

Prof. Kevin Folliard was contacted about his specific studies, and, among other advice, suggested to evaluate the remaining potential for expansion. This would involve drilling cores from the structure and curing them in a 1 N NaOH solution at 38 °C. The main goal of this test is to appraisal the potential for the AAR induced expansions in the future or remaining amounts of reactive silica in aggregates. These tests adopt the same storage of similar conditions indicated in ASTM C 1260, (1N NaOH solution). Storing the core specimens in a solution at 80 °C would provide a great availability of alkalis that can make all the remaining silica to react. The test is intended to provide an upper limit to the residual expansion due to ASR (ie. worst-case scenario).

The suggestion made by Prof. Folliard was to adopt 38 °C as the curing temperature. However, it was decided to test additional sets of specimens above the 1N NaOH solution at 23 °C , 38 °C and 50 °C (Figure 8). The specimens were seasoned at these temperatures, above the NaOH solution prepared as mentioned before. These choices, based on a mathematical regression, had the purpose of obtaining the time when further increase in crack width would be minimized (i.e. development of expansions), considering the actual temperature of the structure (in site). That is, estimating the remaining expansion capability.

The tests were performed on three series of specimens randomly drilled from the bridge (without a preference that would induce a certain preponderance). The environmental storage conditions are shown in Figure 8. The tests (Figure 9) began on March 2009, with readings and information acquired until the end of 2011, about 900 days after it started. The readings and observations were carried out systematically allowing obtaining the charts of Figures 10, 11 and 12.

4 RESULTS AND ANALYSES

The expansion rates at 23 °C (about the site's temperature) were approximately 20 εμ (micro strain), i.e., much lower than those initially adopted in mathematical models (50 εμ). Those results confirmed the future minimization of expansions.

The random sampling criterion adopted at the beginning of the experiment (without characterizing a zone and/or a special structure, or cement content or the real mix proportion used during the construction), resulted on lower expansion rates when exposed to higher temperatures. This led to assume a line connecting the peak points as the maximum curve of expansion, which led to a greater commitment, statistically speaking, since that these values will not be exceeded, throughout the exposure time.

It is important to consider that to develop a standard method would be important to minimize the randomness of the sampling criterion.

In 2011, it was proven that the expansion of all samples exposed to different temperatures allowed to characterize the level of stabilization (minimizing the rate of the expansions). On this basis, a physical-mathematical analysis was performed in order to complete the mathematical regression models and determine the expected duration of the concrete expansion at bridge's structure.

5 DATA ANALYSIS FROM THE CONCRETE CORES EXPERIMENTS

Since the procedure used for carrying out the experiments is innovative and not yet standardized, the goal was to interpret the results achieved, based on a regression analysis, that showed the trend of expansive behavior for an average temperature around 21 °C.

The values for the unit deformation, obtained from the experiment, showed a decelerated uprising in the first phase, followed by stabilization and subsequent fall. A possible model to represent this behavior is the Gauss curve, which represents the hydration of cement-binder systems as shows the work "Modeling Hydration of Cementitious Systems", published in the Journal of the American Concrete Institute Materials ACI, March-April/2012 [6].

The model adopted was calculated by the Equation 1:

$$\varepsilon = \varepsilon_{max} e^{\frac{-(t-t')^2}{2a^2}} \qquad \text{e.g. (1)}$$

In this equation, "ε" is the unit deformation calculated by regression, "ε_{max}" is the maximum unit deformation calculated, "e" is the Euler number, equal to 2,71828, "t" is the time elapsed until the unit deformation occurs and "t'" is the time necessary to reach the maximum unit deformation. Having found the function that correctly represents the observed behavior, it would become possible to estimate the duration of the phenomenon for various scenarios, both to the average temperature of the region, e.g. 22.3 °C, as for other possible scenarios with higher or lower temperatures.

This procedure indicated error for about 10%, between subsequent readings of the cases. This expectation can change slightly depending on the values dispersion, since the samples were obtain from regions of the structure subjected to different condition of normal stress, levels of heat (which affects temperature) and degree of moisture.

The equation was, then, applied for the studied case, using temperatures of 23 °C, 38°C and 50 °C. Although there was some dispersion, caused by the complexity of conducting the tests, in a controlled temperature condition, over many months, it was possible to observe the occurrence of several cycles of expansion in every specimen. This behavior is compatible with the characteristics of the alkali-aggregate reaction, since the formation of cracks facilitates the attack and changes qualitatively the expansions.

According to the tests results, and being coherent with the proposed methodology, it appears that the expansions feature reduction trends. Assuming a constant temperature of 21 °C in the region where the bridge is settled, the maximum estimated value of the expansion was within 720 days after the start of the tests.

This duration was very similar the one observed during the measurements obtained from structure monitoring [3] (Figure 7).

6 SUGGESTED METHODOLOGY- PROPOSAL TEST METHOD

The results obtained, in view of the difficulties of estimating, in a reasonable time period, the stabilization of the deformation resulting from the ASR expansion, and to evaluate the period and costs of a satisfactory maintenance of the structures, led the authors to propose the methodology described hereafter.

6.1 Purpose

This procedure covers the determination of the length variation of mortar and/or concrete specimens, extracted from structural elements and/or parts of them, over a period of exposure under certain controlled conditions of temperature and humidity in a laboratory. The volume change determinations do not relate to those produced by external pressures or forces applied onto the specimens. The measurements concern the expansive effects arising from autogenous reactions within mortar and/or concrete specimens, more specifically from alkali-aggregate reactions.

6.2 Concept-Terminology

The procedures suggest that: the remaining expansion must be understood as the expansion, due to AAR, which can still occur after the extraction and preparation of cores, until the expansions, measured in these specimens, become statistically asymptotic over time.

6.3 Significance and Use

Measurements of length variations will allow evaluating the potential of expansion that can occur in parts of structural elements represented by cores extracted from such elements. Measurements should be taken from specimens stored in four different temperatures. It will allow correlating the accelerated exposure conditions with measurements made in specimens stored at room temperature under moist condition. The specimens should be stored under controlled temperature and humidity conditions, however, avoiding immersion in water, as indicated in Table 1.

6.4 Apparatus and instruments

Containers, tanks, or hermetic storages should be used to guarantee the required environmental conditions. It is recommended to use a pair of meters, fixed externally and diametrically opposed to each specimen, the Strain-Meter type that can be connected to a continuous recording reading apparatus of at least 500 microstrains, and minimum reading < 3 micro strains. Use metal rings not affected by corrosion, with inner diameter of 16 cm, and appropriate external diameter to allow the setting of extensometers and proper thickness to give rigidity to the bolting. Screws in contact with the surface should avoid punching of the specimens to eliminate any risk of cracking during the procedure and damaging the fixing point, and must be for thin support shoe. Preferably adopt a box reading terminal for coupling the cables from the reading system to the deformations and temperature readings that are compatible with the capabilities of measuring meters. The moisture from each of the tanks should be controlled in order to meet the required exposure condition.

6.5 Specimens

Specimens with the specific dimensions (Table 1) should be drilled from the structure, by using a diamond disk, with orthogonal top and bottom cylinder axis.

6.6 Storage conditions

After the preparation of specimens, installing the meters and getting the initial readings (item 6.7), the specimens must be stored in containers. The solution of 1N NaOH should be put at the bottom of the tank.

6.7 Test procedure

In order to check the response of reading and fixing measurements for the specimens, right after the set-up preparation, identification and mounting system installation of meters, the specimens should be kept in air-conditioned environment with a constant temperature around 23 + 0.5°C for 48 hours. After that period, the strain and temperature reading should be taken immediately. The specimens should be placed, after the first reading, in an environment with temperature of 38 + 1.0°C for another 48 hours. Right after that, the second reading will occur, measuring deformation and temperature every couple of meters, where the devices have been installed, each diametrically on the specimen.

Proceed with a comparison of the values obtained in the experiment with an adopted average coefficient of thermal expansion, taken from similar aggregates mineralogy concretes. If the readings do not show a similar behavior, check the fixing and support system.

Store the specimens in environmental conditions as listed in Table 1. Make initial readings of moisture, temperature and deformation.

Every day, for 5 days in a row, make readings of moisture, temperature and deformation. If the readings are not constant, the readings should be recorded, including the identification for each specimen, storage conditions, date, time, operator, and their own readings of moisture, temperature and deformation.

Compare these readings of the first 5 days with the corresponding checks indicated previously. If they are not consistent, repeat the procedures. If no anomalies occur, make readings every week, during the first 3 months, every two weeks during 6 months, and monthly in the subsequent period.

The readings will be stopped after the deformations have stabilized (compatible with the minimum reading of extensometers), and/or according to the engineer's decision, whoever is in charge.

Check systematically the required conditions of temperature and humidity. Establish monitoring charts to evaluate the gradients and the deformations stabilization. At the end of each test, using the tested specimens, perform an additional test to determine its modulus of elasticity. Petrographic examination should be performed on the fragments of the concrete cylinders to characterize the signs of AAR, and possible others deleterious attacks. With another part of the fragments, carry out another test for specific weight and absorption characteristics.

7 COMMENTS

This paper presented a suggestion of a new laboratory routine methodology for evaluating the expansive phenomenon of the concrete in structures affected by AAR.

The basis of the proposed method considers the effects of expansion from exposure in different conditions of temperature and humidity, establishing a regression to the environmental conditions in which it operates.

This methodology was based on data acquired from testing of concrete cores extracted from Mar Pequeno Bridge-SP and showed good results.

8 REFERENCES

[1] Report of the USA trip December (2007): ANDRIOLO/ECOVIAS;

[2] Recomendations of Prof. Dr. Kevin J. Folliard (2007): University of Texas-USA- 2007-ECOVIAS.

[3] Structure inspection and monitoring reports (2007-2011)- IEME/ECOVIAS.

[4] Expansion tests reports (2009-2011): CESP/ECOVIAS.

[5] Physical-Mathematical analysis - Prof. Dr. Haroldo de Mayo Bernardes (2012): ECOVIAS..

[6] Modeling Hydratation of Cementitious Systems, Proceedings of the Materials Journal of American Concrete Institute ACI.

TABLE 1: Characteristics of specimens and environmental conditions for storage during the tests.

<table>
<tr><th>Cure condition</th><th>Temperature ^oC</th><th>Humidity (%)</th><th>Number of Specimens</th><th>Dimensions of the Specimens</th></tr>
<tr><td>A (Normal)</td><td>23 ± 0.5</td><td rowspan="4">≥ 75</td><td rowspan="2">3</td><td rowspan="4">Diameter ≥ 3* M.S.A
Max. Size. Aggregate

Length-Height ≥
2* Diameter</td></tr>
<tr><td>B- at 38 ^oC</td><td>38 ± 1.0</td></tr>
<tr><td>C- at 50 ^oC</td><td>50 ± 1.0</td><td rowspan="2">2</td></tr>
<tr><td>D- at 60 ^oC</td><td>60 ± 1.0</td></tr>
</table>

FIGURE 1: View of the bridge over the sea in the Santos Bay, on the Santos-Sao Vicente channel.

FIGURE 2: Visual observations of the cracking pattern in blocks.

FIGURE 3: Aspects of the monitoring system adopted.

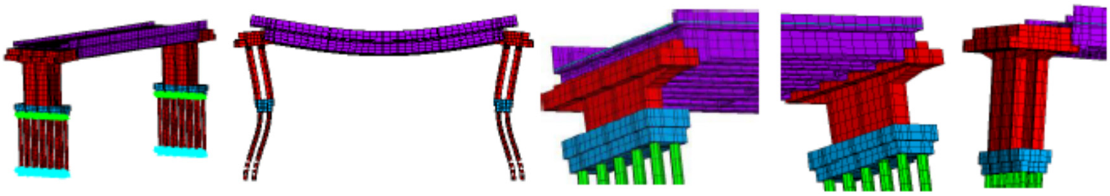

FIGURE 4: Graphic illustrations of the computational model adopted to estimate the behavior of structures.

FIGURE 5: Aspects of static loading and dynamic testing carried out on the structure.

FIGURE 6: Aspects of surface repairs in order to provide the water tightness of structural elements.

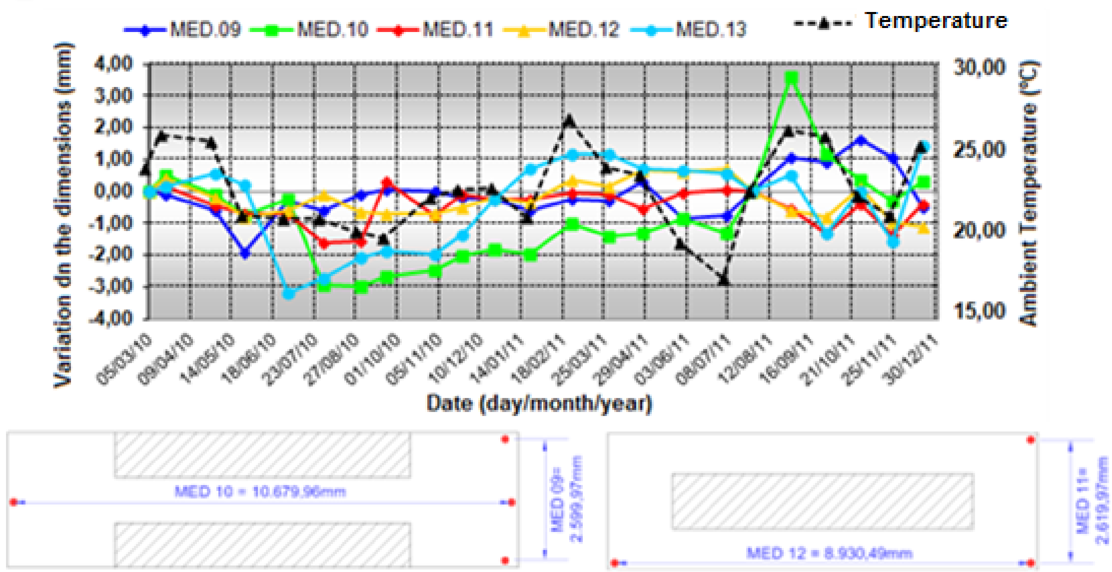

FIGURE 7: Measurements of the deformation between points (far more than 2.5 m) of some blocks affected during the period 05/March/2010 and 30/Dec/2011.

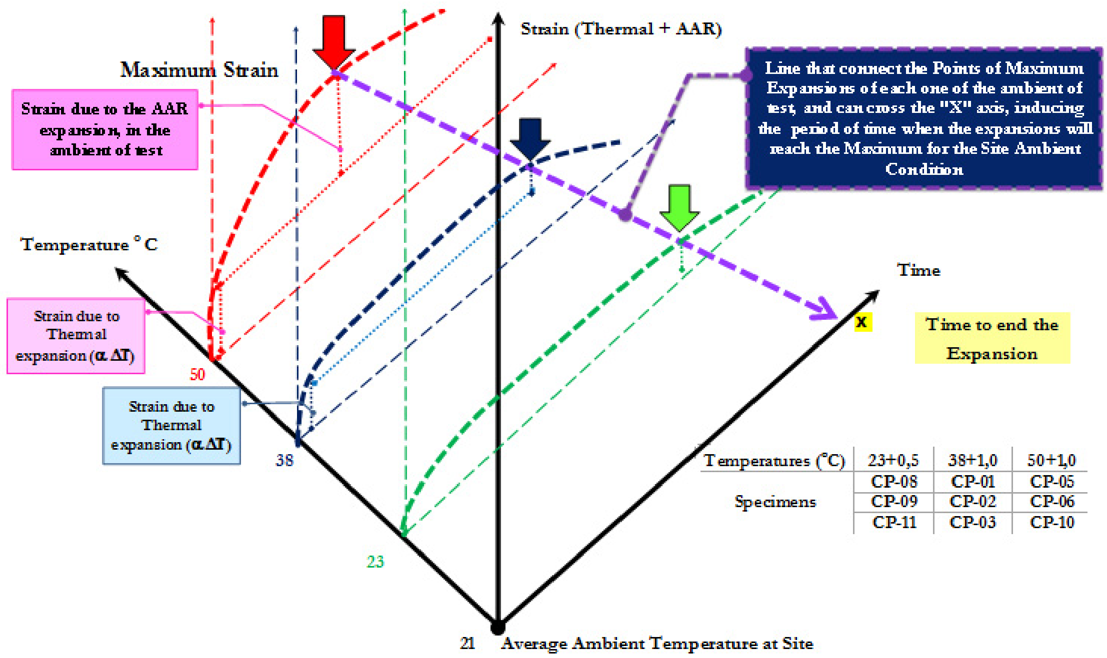

FIGURE 8: Example of the simulation using the results of expansions measurements on specimens cured under different temperature conditions.

FIGURE 9: Aspects during the carrying out of the tests, showing the rings for the measurement of deformations, the exudation of AAR gels, curing tank, the reading terminal and the reading apparatus.

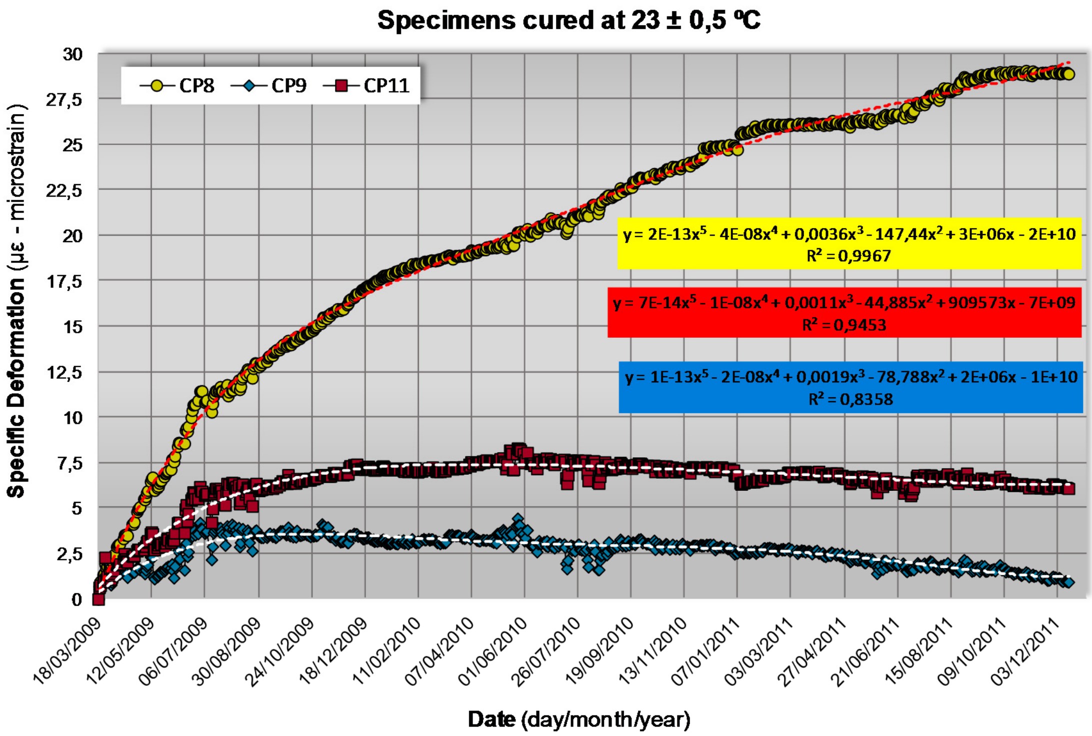

FIGURE 10: Deformation graphs obtained based on the readings during the tests to 23°C.

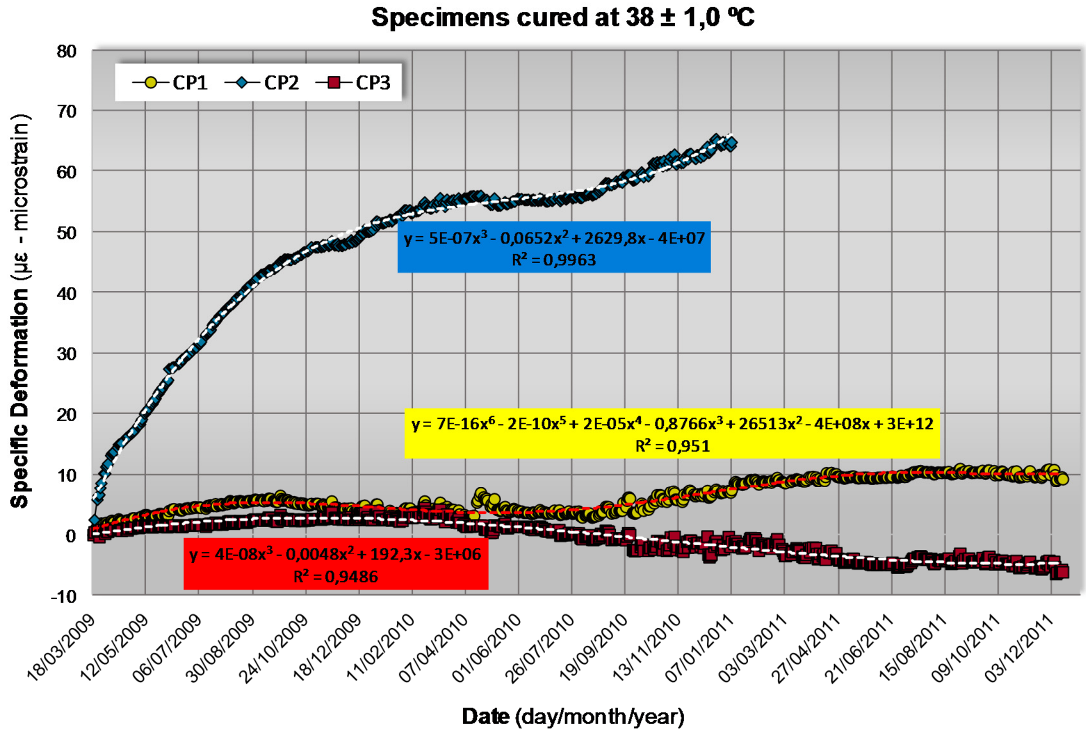

FIGURE 11: Deformation graphs obtained based on the readings during the tests to 38ºC.

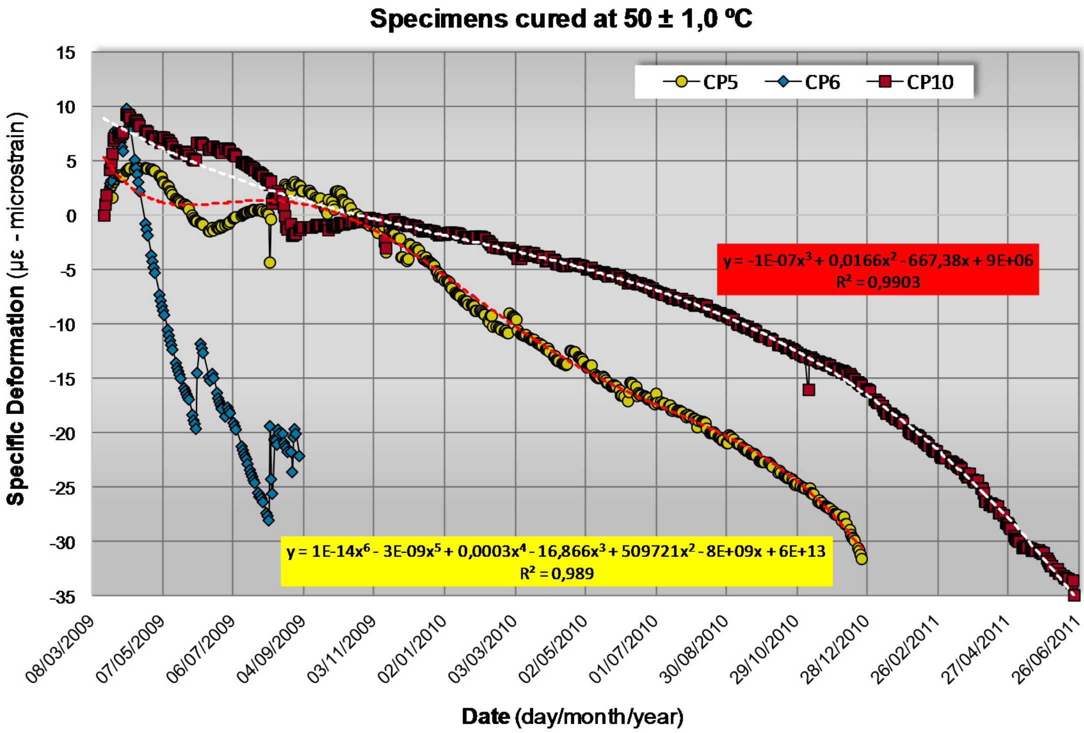

FIGURE 12: Deformation graphs obtained based on the readings during the tests to 50ºC.