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CREEP TESTS IN DAIVÕES DAM


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ABSTRACT

This paper summarises the most relevant aspects of the design and installation of the laboratory and *in-situ* setups used to determine the dam concrete deformability over time. These experimental setups aim at determining the modulus of elasticity for different ages and the creep function for the concrete used in the construction of Daivões dam. The laboratory setups have the advantage of carrying out the experimental work under relatively controlled conditions, whereas the *in-situ* setups (commonly referred to as creep cells) allow these studies to be performed under the dam actual conditions, i.e. real thermo-hygrometric conditions. The creep laboratory setup used in this work uses a rigid frame as the reaction structure and a closed hydraulic circuit which controls the applied pressure on a flat jack on the base of the concrete specimen. The strains were measured with a deflectometer, on the face of the specimens. Creep cells are composed of specimens of concrete with embedded strainmeters, installed in the body of a concrete dam (embedded in the dam concrete) during its construction, with a hydraulic flat jack underneath. During the elastic modulus and the creep tests, while the jack introduces a given compressive stress in the specimen, the embedded strain gauges measure the subsequent strains, instantly or over time, for the modulus of elasticity or creep assessment, respectively.

This paper presents the main deformability concrete test results obtained from both experimental setups, *in-situ* and laboratory, and a preliminary estimate of the creep function. Some of these results have already been used as an input to evaluate the dam structural behaviour during the first filling of the reservoir.

Keywords: Dam concrete, creep tests, semi-empirical models, laboratory, *in-situ*.

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1. INTRODUCTION

The dam-foundation-reservoir ensemble forms a complex structural system with specific characteristics conditioned by space-time circumstances, such as, for example, the properties of the rock mass foundation and the availability of raw materials for concrete production.

In the construction of large dams, it is common to use mass concrete compositions to optimize the relationship between production costs and the structural and durability requirements. For such concrete, the maximum aggregate size (often maximum aggregate size (Φ_{max}) of 150 mm) and the use of cement replacements are significantly higher than those of ordinary concrete, namely fly ash. In this context, a greater quality control (including specific laboratory testing programs) is required to characterize the concrete applied on site [1].

The larger dam concrete aggregates imply larger test specimens than usual, as well as large-capacity laboratory equipment, complicating the logistics of the tests. Due to these constraints, quality control and the characterization of dam concrete rely primarily on the results of wet-screened concrete, obtained by sieving the dam concrete (structural mass concrete) [2,3], which is the one used to embed strainmeters and used for standard-sized specimens for quality control and property characterization. Wet-screening involves removing, while fresh (wet), aggregates larger than a given diameter (typically 38 mm). Although periodic test campaigns are carried out with both types of concrete, the relationship between the properties of dam and screened concretes is still limited to instantaneous behaviour [4-9].

The phenomenon of concrete creep is particularly relevant in interpreting the behaviour of dams, as it determines the evolution of concrete deformability, contributes significantly to deformations and displacements, and induces stress redistribution over time. Since the safety control of such structures depends on modelling their behaviour, it is vital to correctly assess the creep function of the structural concrete [10,11].

This paper presents a summary of the most relevant aspects of the design and the installation of three sets of creep cells in Daivões dam and the main deformability concrete test results, obtained *in-situ* and in laboratory. The analysis of these deformability test results is also presented, including a preliminary estimate of the creep function of the creep cells concrete.

Based on the results obtained, the parameters of the basic creep law representative of the structure's long-term behaviour were estimated using the semi-empirical Double Power Law creep model, developed by Bažant and Panulla [12]. The basic creep law estimated from the experimental results has been used to estimate the viscoelastic properties of the concrete over time and to predict and interpret the structural behaviour of the dam.

2. EXPERIMENTAL WORK

2.1. Concrete composition

In the composition of the concrete for the Daivões dam, VLH IV/B (V) 22.5 cement was used, which incorporates ca. 45% of its mass in fly ash. The aggregates used in the concrete are granitic. The fine aggregates were divided into two classes, 0/1.2 mm and 1.2/5 mm, and the coarse aggregates were divided into four classes: 5/15 mm, 15/30 mm, 30/70 mm, and 70/150 mm. The admixture Muraplast FK 88i was used as a plasticizer.

The experimental work is focused on the characterization of the deformability properties of both the dam core concrete (DAM150) and the concrete wet-screened through a 38 mm sieve (SCR38), which was obtained from the previous one. Table 1 shows the values related to the particle size distribution of the aggregates used in the dam and screened concretes associated with three different groups of creep cells (GC1, GC2 and GC3). The composition of the SCR38 was estimated from the dosages of the DAM150 by removing the approximate volumes of aggregates larger than 38 mm and the volume of the surrounding mortar lost during the screening process [13].

Table 1 – Particle size distribution of the aggregates used in the dam concrete (DAM150) and in the respective screened concrete (SCR38)

Group of creep cell	Concrete type	Fine aggregate (kg/m^3)		Coarse aggregate (kg/m^3)				
		0/1.2 mm	1.2/5 mm	5/15 mm	15/30 mm	30/38 mm	38/70 mm	70/150 mm
GC1	DAM150	312.4	271.3	321.6	385.1	482.7		498.6
	SCR38†	410.9	348.4	489.4	586.0	146.7	-	-
GC2	DAM150	312.3	271.1	320.8	383.2	482.3		498.2
	SCR38†	425.7	363.1	488.0	582.8	146.5	-	-
GC3	DAM150	314.0	272.1	321.1	385.1	479.0		498.3
	SCR38†	426.4	362.8	487.7	584.9	145.3	-	-

† Estimated values

Table 2 shows the compositions of the two types of concrete and their main proportions by mass, respectively, for each of the three groups of creep cells. Note that c.a. 3/4 of the added water corresponds to ice, and the aggregates were pre-cooled.

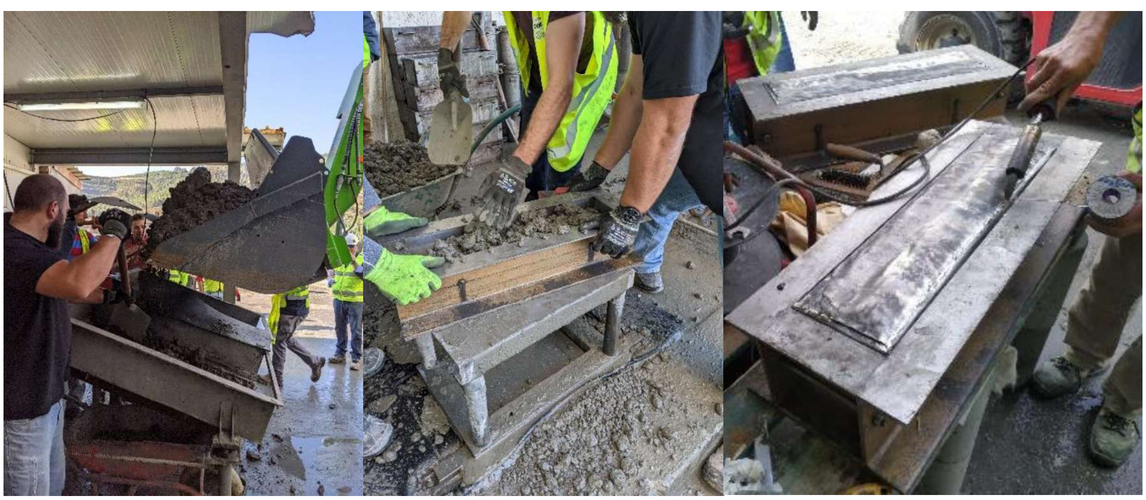
Table 2 – Dosages of the dam concrete (DAM150) and the respective screened concrete (SCR38)

Group of creep cells	Type of concrete	Cement VLH IV B (V) (kg/m^3)	Added water (kg/m^3)	Aggregate water (kg/m^3)	Total water (kg/m^3)	Additive (Muraplast FK 88i) (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water-binder ratio
GC1	DAM 150	180.0	92.1	23.8	115.9	1.8	583.5	1688.0	0.64
	SCR 38†	252.7	128.9	36.2	165.0	2.5	788.8	1222.1	0.65
GC2	DAM 150	180.0	95.6	23.7	119.3	1.8	583.6	1684.5	0.66
	SCR 38†	252.7	133.7	36.1	169.8	2.5	788.3	1217.3	0.67
GC3	DAM 150	179.9	88.5	23.7	112.3	1.8	586.1	1683.5	0.62
	SCR 38†	252.2	123.6	36.0	159.6	2.5	789.3	1217.9	0.63

† Estimated value

2.2. Laboratory tests

Along with the concrete placement, for each creep cell group (GC1, GC2 and GC3), two prismatic specimens measuring 150×150×600 mm³ were moulded with the respective SCR38 for laboratory tests at LNEC, to determine the modulus of elasticity and the creep function. The screened concrete (Figure 1a)) was compacted using a vibrating table (Figure 1b)), similar to the procedure used for compacting the specimens intended for concrete characterization and quality control. These specimens were sealed with lead foil immediately after moulding (Figure 1c)). The sealed specimens were stored in a room at an ambient temperature of 20°C ± 2°C. These specimens were used to determine the modulus of elasticity according to the standards from DIN [14] and LNEC [15].



a) Screening the dam concrete | b) Moulding and compacting the concrete on a vibrating table | c) Sealing the specimens with lead foil

Figure 1 – Preparing the specimens for laboratory testing

For performing the compressive creep tests in laboratory, specific laboratory setups were used to apply the compressive stress in the vertical direction (over the longer dimension of the prism) (Figure 2a)). These setups were composed of a rigid frame as the reaction structure equipped with a pressure compensation system involving a nitrogen bottle and hydraulic oil to maintain a constant load on a flat jack on the base of the concrete specimen, which were measured with the aid of a digital manometer (Figure 2b)). The deformations were obtained by measuring the distance between two reference bases set 388 mm apart on two parallel lateral faces of each prismatic specimen with the aid of a deflectometer (Figure 2c)). These reference bases are fixed on centred rods that pass through the entire cross-section of the specimen, perpendicular to the measurement faces.

a) General overview of the specimens in the creep press

b) Pressure transducer coupled with the oil/nitrogen bottle to maintain a constant load

c) Measurement of the deformation with a deflectometer

Figure 2 – Laboratory testing for determining the creep strains

The ages in which the specimens were tested are presented in Table 3. This table shows the ages of the modulus of elasticity tests and the ages at which each specimen started to be under constant load (since the loading age, the specimen was no longer subjected to the modulus of elasticity test).

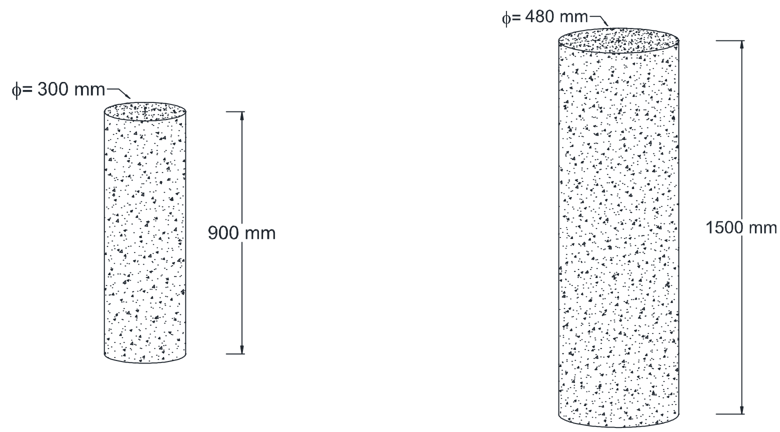
Table 3 – Ages for laboratory testing (modulus of elasticity and creep loading ages) of the screened concrete (SRC38) prismatic sealed specimens related with each creep cells group

Concrete mixture	Age (days)					
	Modulus of elasticity test					Constant loading (creep test)
GC1	8	14	32	96	-	96
GC2	8	14	33	-	-	33
GC3	7	17	28	102	797	797

2.3. *In-situ* tests

The creep cells are setups specifically designed to characterise the deformability properties of concrete under the thermo-hygrometric conditions of the site. Each cell consists of a concrete cylinder embedded in the dam body, with its longitudinal axis in the vertical direction. The dimensions of the cylinder are a function of the concrete type (Figure 3). The mould consists of an expanded polystyrene (EPS) tube, which allows the desired cylindrical shape to be obtained and creates a partition between the test specimen and the surrounding concrete (Figure 4a)). Through a flat jack with an attached load system, the cylindrical specimen is subjected to a constant stress, and the associated deformation is measured by a strainmeter embedded in the cylindrical specimen. The placement of the strainmeters is a sensitive task, because it is a challenge to ensure their centrality, verticality and integrity, especially during the placement and the vibration of the concrete.

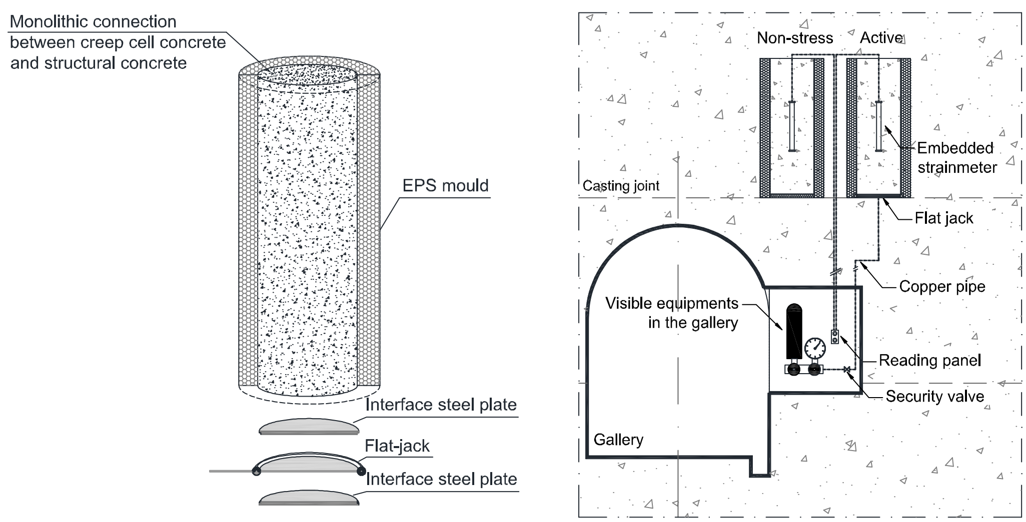
This type of equipment allows to determine both the instantaneous and the long-term concrete deformability, using a hydraulic flat-jack capable of applying rapid load and unload cycles. In Daivões dam, three groups of creep cells were installed. Each group is composed of one cell of dam concrete (DAM150) and one cell of screened concrete with a 38 mm sieve opening (SCR38), both with loading system (active cells), paired with two other similar cells, without loading system (corrector cells). Carlson-type electrical resistance strainmeters were used, with A20 model (with a 50 cm gauge length) used for dam concrete cells and A8 model (with a 20 cm gauge length) for the screened concrete cells [16,17]. Figure 4b) shows the complete schematic of a set of creep cells (active and corrector cells), including the components of the load system embedded in the dam body (see also Figure 5a)) and the accessible equipment installed in the gallery niche (see also Figure 5b)).



a) Specimen for screened concrete: Ø300 mm×900 mm

b) Specimen for dam concrete: Ø480 mm×1500 mm

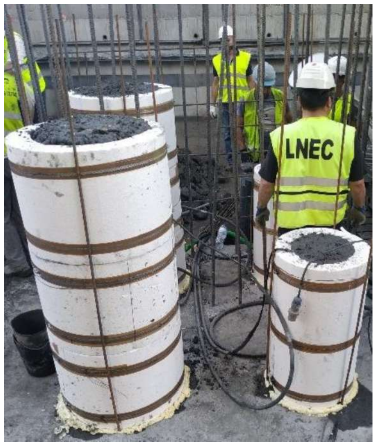
Figure 3 – Dimensions of creep cells for each type of concrete



a) Active specimen

b) Embedded and accessible elements of a group of creep cells

Figure 4 – Schemes of the creep cells systems in Daivões dam



a) Installation of a group of creep cells, which were eventually embedded in the dam concrete

b) Accessible elements located in the niche of the dam gallery

Figure 5 – Images from the creep cells systems in Daivões dam

The on-site modulus of elasticity test consisted of performing three load and unload cycles in each active cell and recording the corresponding strain variations measured by the embedded strainmeters. The load variations were applied in increasing or decreasing steps of 5 and 10 bar until the upper and lower test stresses were reached. The maximum stress considered in each test corresponded to a pressure of 30 bar for younger ages and 50 bar for later ages, also depending on the system's response. The stress applied to each type of cell was calculated from the pressure applied to the load system, considering the ratio between the flat jack's diameter and the cross-sectional area of the cell's specimen. The conversion coefficients between the oil pressure in the load system (in bar) and the applied stress (in MPa) are 0.088 and 0.087 for the integral concrete cells and the screened concrete cells (with a 38 mm sieve), respectively (Table 4). The maximum test stresses were calculated based on the compressive strength test results available from similar concrete elements, with a maximum stress limit considered at each age corresponding to approximately one-third of the compressive strength obtained from cylindrical specimens at the same age, up to a maximum limit of 50 bar.

Table 4 - Conversion between oil pressure in the load system and the voltage applied to the specimen

Cell type	Maximum pressure (bar)	Contact zone diameter of the pad (m)	Pad area (m²)	Cell diameter (m)	Cell area (m²)	Conversion factor	Applied stress (MPa)
Dam concrete	50	0.450	0.159	0.480	0.181	0.088	4.4
Screened concrete	50	0.280	0.062	0.300	0.071	0.087	4.4

The loading speed sought to replicate laboratory procedures [14,15]. The tests to determine the modulus of elasticity were conducted quickly enough to avoid the influence of autogenous volume variation and concrete creep strains. For performing the creep tests, the load was maintained constant through the external hydraulic system housed in a niche within the dam's gallery (Figure 5b)). This system consists of a bottle containing pressurized oil. Each bottle is connected through a copper tube/pipe to the flat jack placed at the base of each active creep cell.

The ages in which the creep cells group were tested are presented in Table 6. This table shows the ages at which each specimen was subjected to the modulus of elasticity test and the ages at which these started to be under constant load. A few tests were not successful because the loading system was not functioning properly.

Table 6 – Ages for *in-situ* testing (modulus of elasticity and creep loading ages) of the dam and screened concrete (DAM150 and SRC38) for each group of creep cells

Concrete mixture	Age (days)					
	Modulus of elasticity test					Constant loading (creep test)
GC1	7	14	32	96	679	96
GC2	7	14	35	99	637*1	35
GC3	7	18	28	102	746*2	746*2

*1 only the SCR38 cell was tested because the DAM150 cell loading system was not working
*2 the loading system was not working for both SCR38 and DAM150 cells; thus, it wasn't possible to perform this test

3. PRESENTATION AND ANALYSIS OF RESULTS

3.1. Modulus of elasticity

In Figure 6, the average values of the modulus of elasticity obtained from sealed specimens are compared with those obtained from the average values of GC1, GC2 and GC3 creep cells. These results show that the values of the elastic modulus are higher for the *in-situ* specimens when compared with the specimens cured in the laboratory environment; that is, the development of the elasticity modulus occurs faster on-site than under controlled conditions at 20°C, especially at younger ages (7 to 28 days).

The *in-situ* results for screened concrete show higher values than those obtained in the laboratory, with the difference being more pronounced at ages up to 28 days, when the effect of temperature on binder hydration is more significant (Figure 6). Moreover, the manual compaction of the concrete in the creep cells may have resulted in the larger aggregates to became in contact with one another, creating a rigid internal structure that leads to higher elasticity modulus values. This effect is more evident at younger ages, when the cement paste has not yet developed significant rigidity.

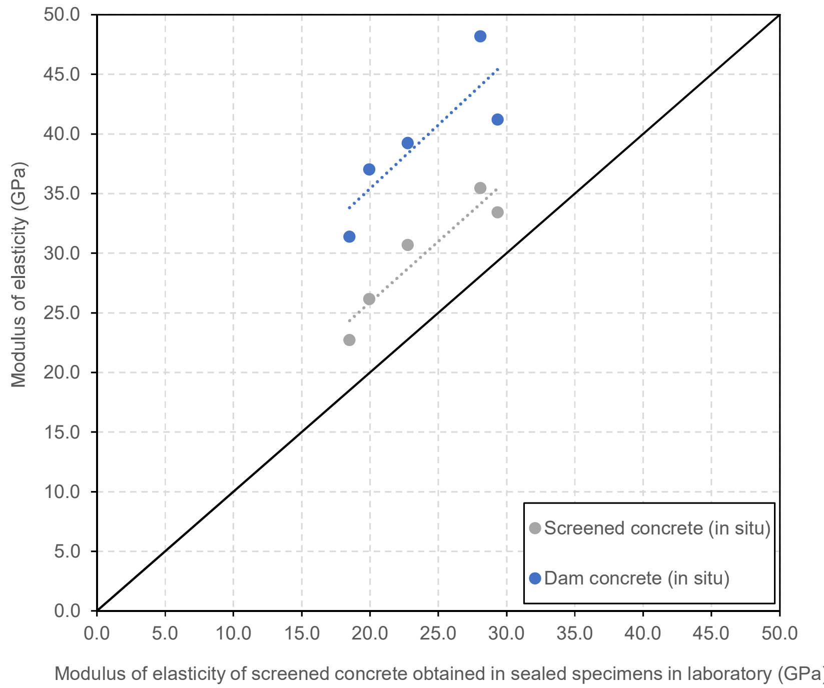


Figure 6 – Comparison of the modulus of elasticity results in laboratory (xx axis: screened concrete prisms) with the *in-situ* results (yy axis: screened concrete cells and dam concrete cells) (average values)

3.2. Creep strains

Creep corresponds to the increase in strain over time under constant stress, $\sigma(t_0)$, in conditions of constant temperature. The instantaneous strains, $\varepsilon^i(t_0)$, and creep strains, $\varepsilon^c(t, t_0)$, depend on the magnitude of the stress, with the creep function, $J(t, t_0)$, representing the total strain per unit of stress. Here, t represents the time elapsed since concreting, and t_0 represents the loading age, that is, the age of the concrete at the time of loading. Thus, we have:

$$\varepsilon(t,t_0) = \varepsilon^i(t_0) + \varepsilon^c(t,t_0) = J(t,t_0)\ \sigma(t_0) \tag{1}$$

$$J(t,t_0) = \frac{1}{E(t_0)} + \frac{\varepsilon^c(t,t_0)}{\sigma(t_0)} \tag{2}$$

In order to quantify the creep of concrete, the specific strains are calculated from the strains measured in each specimen, i.e., the strain per unit of stress from the beginning of the creep test. The strains measured in the active specimen correspond to total strains, $\varepsilon^{total}(t, t_0)$, and the free strains measured in the corrector specimen correspond to strains due to temperature variations and autogenous deformations, $\varepsilon^{corr}(t)$. The corrected total strains, $\varepsilon^{total\ corr}(t, t_0)$, and the specific total strains, $\varepsilon^{total\ spec}(t, t_0)$, are given by:

$$\varepsilon^{total\ corr}(t,t_0) = \varepsilon^{total}(t,t_0) - \varepsilon^{corr}(t) \quad (3)$$

$$\varepsilon^{total\quad spec}(t,t_0) = \frac{\varepsilon^{total\ corr}(t,t_0)}{\sigma(t_0)} \quad (4)$$

Based on the results of each of the terms in equations (3) and (4) for the *in-situ* (creep cells) and corresponding laboratory results, a comparison between the total specific strains of screened concrete obtained in laboratory and *in-situ* is presented in Figure 7. There are no results for the GC3 creep cell group because the creep test in this group (for both SCR38 and DAM150) was unsuccessful. This creep cells group was supposed to be constantly loaded from the age of ca. 2 years old (see Table 6), but its loading system lost the ability to maintain the load. Thus, only the laboratory results are available for this loading age ($t_0 \approx 2$ y.o.). As for the other loading ages ($t_0 \approx 1$ month old for the GC2 related specimens and $t_0 \approx 3$ months old for the GC1 related specimens), Figure 7 shows that the creep values obtained in laboratory and *in-situ* are of the same order of magnitude, despite significant variations in load and temperature occurring *in-situ* throughout the tests, particularly in the screened concrete from the GC2 creep cell.

A decrease in instantaneous strains over time can be clearly observed, which is mostly explained with the increase in modulus of elasticity with time, which results in lower deformation rates over time for older loading ages.

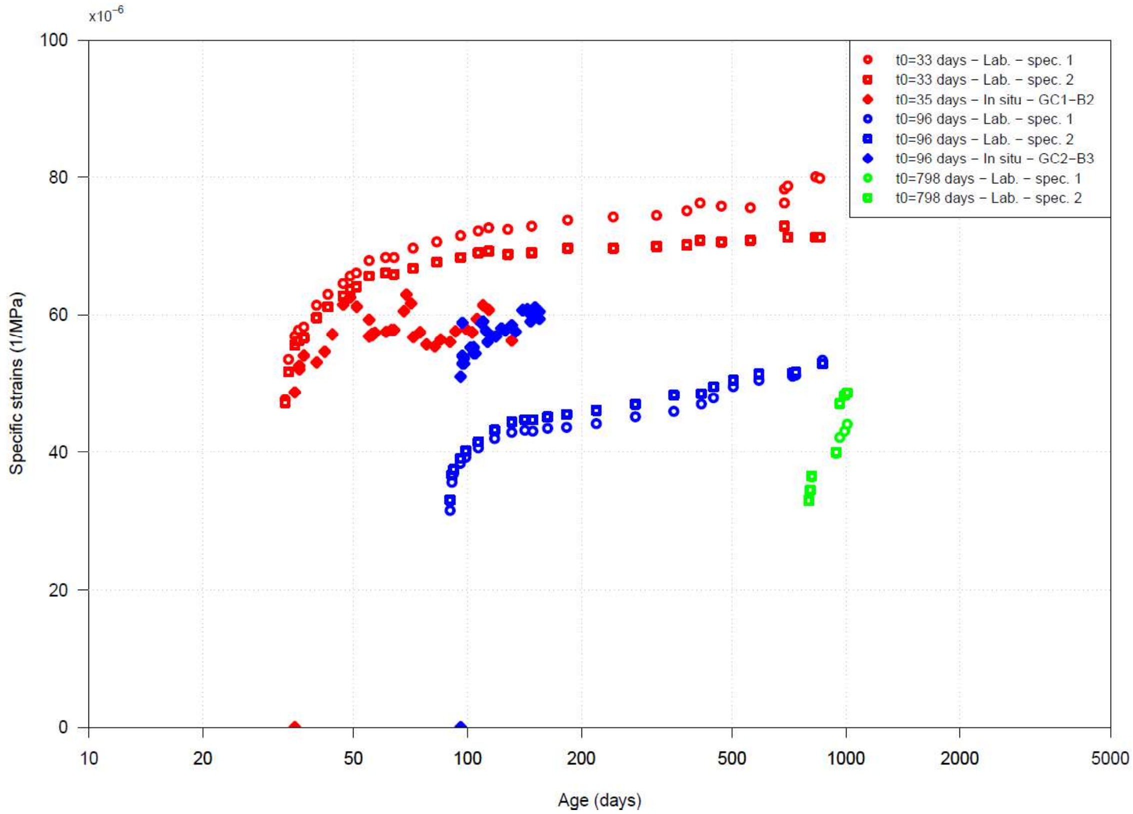


Figure 7 – Comparison between the laboratory and *in situ* (creep cells) results for the creep tests carried out on screened concrete

4. ESTIMATION OF CREEP FUNCTION

4.1. Bažant e Panula (BaP) creep function fit

Creep prediction models are associated with functions that have specific characteristics, chosen to represent the physical phenomenon of concrete creep. The parameters of these functions, typically determined from known material properties and, when available, adjusted to experimental test results, provide an estimate of creep strain values within certain assumptions.

In the Bažant and Panula (BaP) model [12], the creep function, $J(t, t_0)$, is given by the sum of the elastic component, $1/E_0$, basic creep, $C_0(t, t_0)$, and drying creep, $C_d(t, t_0, t')$.

One of the distinctive aspects of this formulation is the consideration of the concrete's maturation process in the basic creep component by multiplying a power of the age at loading, t_0, by a power of the time under load, $t-t_0$.

$$J(t,t_0) = \frac{1}{E_0} + C_0(t,t_0) + C_d(t,t_0,t') \quad (5)$$

$$C_0(t,t_0) = \frac{\phi_1}{E_0}(t_0^{-m} + \alpha)\ (t - t_0)^n \quad (6)$$

where E_0, φ_1, m, α e n are parameters dependent on the intrinsic characteristics of the concrete. Since, in the case of dams, the concrete does not, in practice, lose water to the outside, the drying creep component may be considered negligible compared to the basic creep values.

The prediction of the elasticity modulus over time can be obtained by considering the time under load, t-t_0, as equal to 0.1 days,

$$\frac{1}{E(t_0)} = \frac{1}{E_0} + \frac{\phi_1}{E_0} 10^{-n}(t_0^{-m} + \alpha) \quad (7)$$

It should be noted that the expressions of the BaP prediction model were calibrated based on various experimental tests available in the literature, covering different types of concrete [12].

In the absence of creep test results, the parameters of the creep law can be estimated using two distinct methods. The first method allows for estimating the creep function based on the 28-day compressive strength, $f_{c,28}$ (in MPa), and the concrete composition [12]. The second method considers only the 28-day compressive strength $f_{c,28}$ (in MPa) as the material's intrinsic characteristic [18], using expressions (8) to (11).

$$\phi_1 = 0.3 + 152.2\ {f_{c,28}}^{-1,2} \quad (8)$$

$$\alpha = 0.05 \quad (9)$$

$$m = 0.28 + 47.541\ {f_{c,28}}^{-2} \quad (10)$$

$$n = 0.115 + 0.183\ {f_{c,28}}^{3,4} \times 10^{-6} \quad (11)$$

In this work, given the specific characteristics of dam concrete and the availability of creep test results, the BaP model parameters should be adjusted considering this information. The parameters φ_1, m, n e α were adjusted by minimizing the difference between the creep calculated by the model and the experimental results of the creep function for loading ages of 35 and 96 days.

The adjustment also considered the estimate of the elasticity modulus and the experimental results obtained over time. The initial estimate of the parameters φ_1, m, n e α for the minimization process was obtained by considering, in expressions (8) to (11), the average compressive strength of the mass concrete at 90 days (24.5 MPa).

The estimate of the parameter E_0 was derived from expression (7), considering the average elasticity modulus at 680 days (48.2 GPa), to achieve a better long-term approximation.

The preliminary expression (12) represents the creep function that fits the experimental results, and it is shown graphically in Figure 8. Figure 9 shows the evolution over time of the corresponding elasticity modulus.

$$J_{BaP}(t,t_0) = \frac{1}{E_0} + \frac{\phi_1}{E_0}(t_0^{-m} + \alpha)(t - t_0)^n = \frac{1}{58.4} + \frac{4.80}{58.4}(t_0^{-0,30} + 0.01)(t - t_0)^{0.54} \quad (GPa^{-1}) \quad (12)$$

The adjusted parameter values are presented in Table 7, where it is evident that the parameters adjusted by the two methods have considerably different values. This difference is primarily due to the fact that the behavior of the concretes used to calibrate expressions (8) to (11) in the prediction method differs greatly from dam concrete, particularly the concrete used in the Daivões dam, which incorporates high content of fly ash.

Table 7 – Preliminary estimate of the parameters for the Bažant and Panula (BaP) creep function for the creep cells dam concrete

Parameter	BaP prediction model + E(t_0)	Preliminary adjustment + E(t_0)
E_0 (GPa)	67.1	58.4
φ_1	3.58	4.80
m	0.36	0.30
n	0.12	0.54
α	0.05	0.01

Figure 8 shows the specific strain values obtained in the mass concrete cells, the preliminary estimate of the creep function, $J(t, t_0)$, and the preliminary estimate of the evolution of instantaneous strains, $1/E(t_0)$, obtained by fitting to the average experimental results for loading ages of 35 and 96 days for cells GC2 and GC1, respectively. Figure 9 presents the corresponding elasticity modulus values obtained through preliminary fitting, along with a comparison to the experimental results obtained in the mass concrete creep cells.

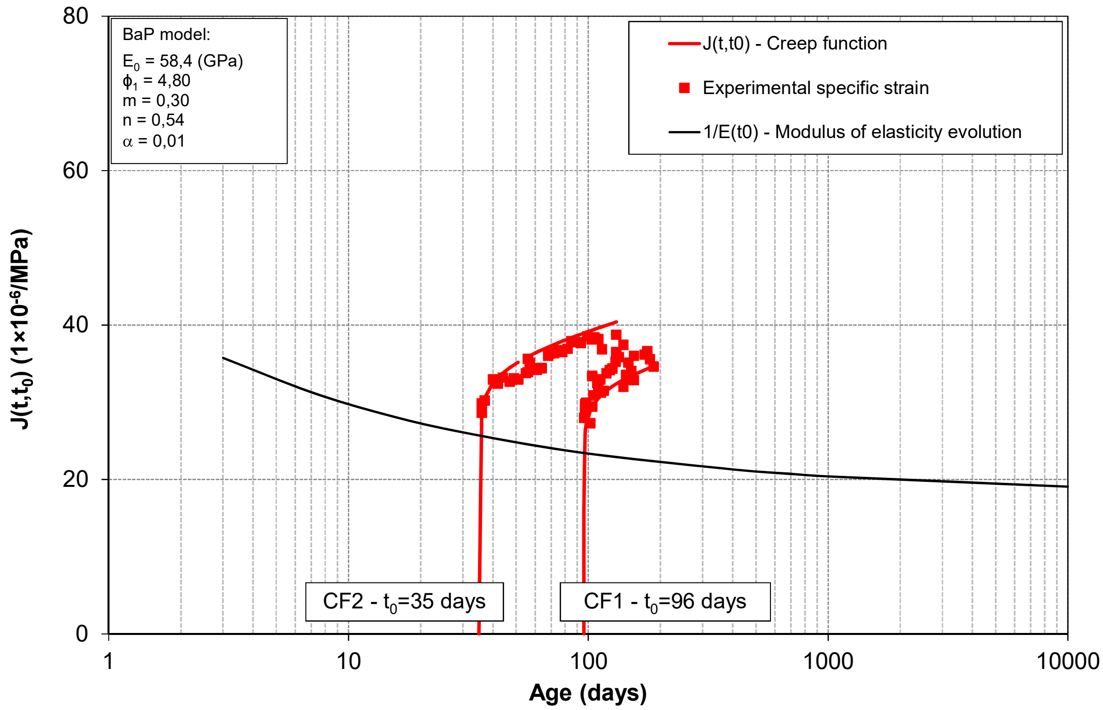


Figure 8 – Preliminary adjustment of the creep function and test results for the dam concrete creep cells

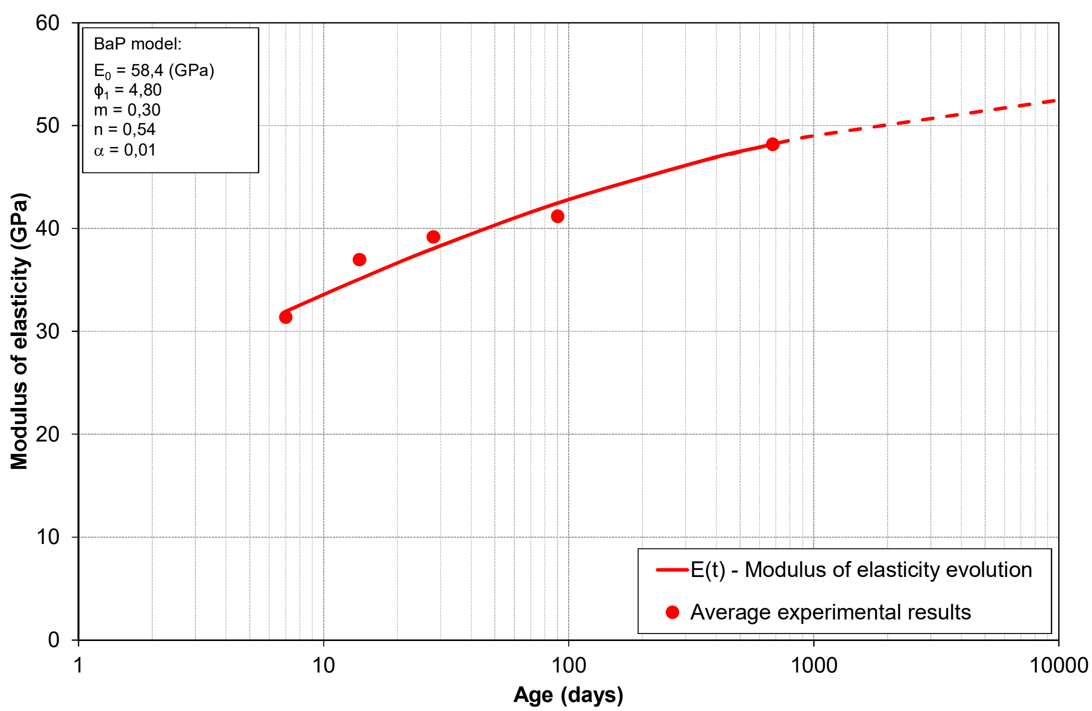


Figure 9 – Modulus of elasticity according to the preliminary adjustment of the creep function and results obtained for the dam concrete creep cells

The preliminary creep function fits well with the experimental results. The creep strains predicted by the creep function show a reasonable long-term development (Figure 8). The prediction of the elasticity modulus evolution from the creep function indicates an increase in value for ages beyond 680 days (Figure 9).

5. CONCLUSIONS

The relevant aspects of the project and installation of the three groups of creep cells at the Daivões dam and laboratory creep test setups were described. The results of the concrete deformability tests conducted *in-situ* and in laboratory are presented and briefly analysed. A preliminary estimate of the integral concrete creep function for the creep cells is also displayed.

As expected, in the creep tests, the strain increased instantaneous upon compressive load application, then gradually slowed, stabilizing over the long term. It was also concluded that the values of specific strain and the long-term creep coefficient for both integral and sieved concrete are low when compared to values calculated based on prediction models for concrete structures.

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