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COMPREHENSIVE ANALYSIS OF THE CONCRETE DEFORMABILITY TEST RESULTS OF PORTUGUESE LARGE DAMS

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Abstract. *Structural material characterization through testing is a common practice in structures such as large-span bridges, nuclear power stations, tall buildings and large dams, where the installed strains and stress take significant values.*

The collected data of composition and deformability test results of the concrete of several Portuguese dams, built since 1951, properly treated, allowed the establishment of correlations between the composition and the deformability properties of the full-mixed and the wet-screened concrete used in dam construction. Taking into account the laboratory and in situ *testing, correlations between some composition elements and the experimental test results and between creep coefficients of wet-screened and full-mixed concrete were obtained.*

1 INTRODUCTION

Water supply, flood control and sustainable energy production are of great importance for both developed and under development countries. Maintenance and rehabilitation issues of existing structures and important new investments in dam construction require technological advances for more efficient, sustainable and safe structures.

The terrain orography and the rock mass properties of the Portuguese region with higher hydroelectrical potential and its suitability to arch, gravity-arch and gravity dams lead to the use of concrete in several power plants. According to data from 2005, a significant amount of large dams are concrete dams (30% of the dams with more than 15 m height and 50% of the dams with more than 30 m height). The design, construction and follow-up of these dams allowed for a large accumulated knowledge[1].

Dam concrete experimental characterization has particular challenges. The use of large aggregate size in dam's concrete implies the use of large specimens to perform the tests. After mixing the components, it is a common practice to remove the larger aggregates from the concrete (wet-screening) in order to embed in situ monitoring devices and to cast smaller specimens for standard laboratory testing. The need for reliable relationships between dam concrete and wet-screened concrete is essential for project design, concrete quality control during construction, safety assessment and data monitoring throughout service life.

The characterization of concrete behaviour and the determination of the rheological model parameters to consider in the structural analysis, especially the ones related to the creep function and to the bearing capacity of the concrete, can improve the definition of the required properties for better quality control during construction and easier structural interpretation. For dam concrete, the characterization of the structural concrete (full-mixed concrete) is constraint by the large dimension of the aggregates. The wet-screened concrete, obtained from removing the larger aggregates, after mixing the components, is, therefore, widely used for testing and for embedding the monitoring devices.

There are available databases with test results from different sources[2], which are an important aid for establishing constitutive models. In this study, a comprehensive analysis was made, including the deformability test results and the concrete composition of several dams, in order to complement the characterization of the full-mixed concrete and support the interpretation of the results. The composition data and test results were collected from several published works over the years into a comprehensive database[3 to 12]. The main goal is to analyse the influencing factors of the delayed behaviour of dam concrete in Portugal, and correlate the full-mixed concrete deformability properties and the wet-screened concrete test results obtained in laboratory.

2 COMPOSITION AND DEFORMABILITY PROPERTIES OF DAM CONCRETE

2.1 General aspects

Delayed behaviour has special relevance in structural engineering, due to the increased of the deformations over time under sustained loading (creep) and due to the stress relaxation under imposed deformations, which is especially important for concrete dams. The determination of the mechanical properties through standard testing (strength and modulus of elasticity), with a good concrete quality control, allows for a first prediction of the delayed behaviour of concrete using empirical/semi-empirical formulations (§2.4).

Concrete creep is influenced by intrinsic factors, such as the properties of each component, the mix proportions and the concreting conditions, as well as by external factors, such as, for example, the loading age, the temperature and humidity conditions, and the intensity and type of loading[7].

Dam concrete composition limits the execution of a large number of experimental tests and, therefore, prediction of the delayed behaviour is still a subject under research. There are no correlations between the delayed behaviour of the full-mixed and the wet-screened concrete, mainly due to the scarce test results. This research topic has been a subject of study at the National Laboratory for Civil Engineering (LNEC) over the last few decades[6,7,8,13]. Some experimental results show a ratio of 0.6 to 0.7 between the delayed strains of the full-mixed and of the wet-screened concrete[7].

2.2 Dam concrete composition

Due to the specific use of concrete in dams, there are some characteristics that differentiate dam concrete from other concretes used in buildings and bridges. Being placed in large volumes it requires special measures to cope with the generation of heat of hydration and attendant volume change to minimize cracking[14]. For each dam a prescribed concrete is produced, according to the EN206-1[15], and its strength and deformability properties have to be characterized.

Dam concrete has a low cement content, usually between 100 and 300 kg/m^3, it is common practice to introduce addictions up to 100% of the cement content (fly ash or pozzolans are used for reducing costs, reducing the heat of hydration and to prevent alkaliaggregate reactions). The maximum size aggregate is, in general, 150 mm, and the total aggregate percentage can be as much as 60% of the total weight.

The wet-screened concrete, obtained from the full-mixed concrete (structural concrete), has distinct composition and mechanical properties. Although using the same type of component materials, the proportions change significantly when the larger aggregates are removed. Firstly, because the volume occupied by the largest aggregate is replaced by cement paste and smaller aggregates and secondly because some cement paste is lost in the process of wet-screening (a small amount of cement paste remains with the larger aggregates). The 38 mm sieve is usually adopted for wet-screening the full-mixed concrete.

2.3 Maturation conditions of dam concrete

In concrete dams the heat of hydration dissipation during the set and hardening process and the early age cracking risk are a main concern. For the cracking risk assessment, it is necessary to know the development of the mechanical properties of the concrete placed *in situ*.

With laboratory tests it is possible to characterize the behaviour of concrete in controlled conditions (usually at 20°C). *In situ*, concrete temperatures can reach up to 50°C. Temperature variations determine the development of the mechanical properties (higher temperatures increase the hardening rate).

The large thickness of concrete dams allow for the hypothesis of hygrometric equilibrium within the dams body. It is considered that drying only occurs in a small part near the upstream and downstream surfaces, which can be negligible. The dam body is considered, therefore, to have no water exchange with the environment. In order to simulate those conditions the specimens are usually sealed with rolled lead sheet or, if that is not possible, the specimens are maintained at 100% relative humidity.

2.4 Delayed deformability of concrete

Mechanical behaviour of concrete is age dependent and its deformability can be divided into an instantaneous part, related the loading age, t_0, to the modulus of elasticity, $E(t_0)$, and the Poisson ratio, and a delayed part, dependent of the time under loading and related to the creep function, $J(t,t_0)$, and its inverse the relaxation function, $R(t,t_0)$.

Creep is taken as a strain increase under constant stress, $\sigma(t_0)$, and at constant temperature, T. The total strain, $\varepsilon^{total}(t,t_0)$, is the sum of the instantaneous strain, $\varepsilon^{i}(t_0)$, and the creep strain, $\varepsilon^{c}(t,t_0)$, both stress-dependent. The creep function, $J(t,t_0)$, is referred to the total strain due to a unit stress, being t the time and t_0 the age of loading. Therefore,

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

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

The creep coefficient, $\Phi(t,t_0)$, quantifies the creep strains through the proportion between the delayed strains, $\varepsilon^{creep}(t,t_0)$, at a given time, t, and the instantaneous part, $1/E(t_0)$, related to a predefined loading age, t_0.

$$\phi(t,t_0)=\varepsilon^{creep}(t,t_0)E(t_0)=J(t,t_0)E(t_0)-1 \tag{3}$$

The concrete creep function definition since early ages have been the focus of several studies from which prediction models have been developed. The most known prediction models for the delayed behaviour have been developed by Bažant, BaP[16], BP-KX[17] and the most recents, B3[18] and B4[19], by the Fédération Internationale du Béton (FIB), fib Model

Code 90[20] and fib Model Code 2010[21], by the American Concrete Institute (ACI), ACI-ASCE[22] and ACI 209R-92[23], and by Gardner and Lockman, GL2000[24].

The specific conditions to which dam concrete is subjected, close to hygrometrical isolation and with low stresses (usually below 40% of the maximum strength), imply the development of only primary and basic creep strains, for service loads[6, 7, 25].

The logarithmic expression for the dam concrete creep function,

$$J(t,t_0) = K(t_0) + F(t_0)\log(t), \tag{4}$$

has been proposed in several studies[3,6,7]. The advantages of this expression are the low number of parameters that needs to be determined, the fact that those parameters can be obtained through simple experimental tests and that it predicts a good fit to primary and basic creep. The disadvantages are the poor fit in all the range of loading time (difficulties to fit for early ages) and that it requires the parameters definition on each loading age, t_0.

The fit of every experimental results to the logarithmic creep function allowed for a direct comparison of the delayed deformability properties of several dam concretes and the study of the influence of maturation conditions, in laboratory and *in situ*, on the strain development over time.

2.5 Deformability characterization of concrete using creep cells

Creep cells are a specific technique for the *in situ* characterization of instantaneous and delayed behaviour of concrete. Creep cells are concrete cylinders embedded in the dam body, subjected to the same thermohygrometric conditions as the dam body, since the top of the cell is in contact with the structural concrete, but isolated from the stress field. With the aid of a flat-jack, it is possible to apply a given normal stress to the cell and the strains are recorded with embedded strain meters. The loading system allows for instantaneous deformability tests (used to determine the modulus the elasticity) and for creep tests, maintaining constant stress over time. The use of creep cells had its first developments in Carrapatelo dam, in 1967, and it is still usual nowadays to install these type of devices on important dams, since it allows for testing under the same thermohygrometric conditions of the structural concrete[26].

Generally, there are two types of creep cells, the full-mixed concrete cells (structural concrete) and the wet-screened concrete cells. Besides characterizing the deformability of full-mixed concrete, it is possible to study its relation with the wet-screened concrete and, also, the influence of the *in situ* conditions.

3. DEFORMABILITY TEST RESULTS OF DAM CONCRETE

3.1 Composition of the analysed concretes

The main difficulties of concrete behaviour characterization with experimental tests are related to the amount of variables involved, namely the types of materials used, and therefore to its properties, the contents of each component and the casting and the curing conditions. In Table 1 several available elements from each dam concrete are presented. In Portugal, the first use of fly ash added to the mix occurred in Alqueva dam and, since then, the percentage of this addiction has grown to more than 100% of the cement content. The water-binder ratio varied from 0.70 on Picote dam (1958) to 0.34 on Torrão dam (1988). The granitic aggregates are the most used, due to the location of the dams and to the good characteristics of this type of rock.

Dam	**Year**	**Aggregate type**	**D_{max} (mm)**	**Contents (kg/m^3)**						**Proportions (by weight)**
				b		**w**	**a**	**g**	**s**	**c:v:w:a:g:s**
				c	**v**					
Castelo de Bode	1951	Gravel from Zêzere river	n.a.	220	0	n.a.	2147	1611	536	1.0 : 1.0 : 0.0 : n.a. : 9.8 : 7.3 : 2.4
Venda Nova	1951	Granite	n.a.	225	0	n.a.	2130	1675	455	1.0 : 1.0 : 0.0 : n.a. : 9.5 : 7.4 : 2
Salamonde	1953	Granite	n.a.	250	0	n.a.	1992	1554	438	1.0 : 1.0 : 0.0 : n.a. : 8.0 : 6.2 : 1.8
Cabril	1954	Granite	150	220	0	130	2064	1652	411	1.0 : 1.0 : 0.0 : 0.59 : 9.4 : 7.5 : 1.9
Caniçada	1955	Granite	n.a.	250	0	n.a.	2080	1680	400	1.0 : 1.0 : 0.0 : n.a. : 8.3 : 6.7 : 1.6
Bouçã	1955	Metamorphic	n.a.	250	0	n.a.	n.a.	n.a.	n.a.	1.0 : 1.0 : 0.0 : n.a. : n.a. : n.a. : n.a.
Picote (w/c=0.5)	1958	Granite	n.a.	200	0	100	n.a.	n.a.	n.a.	1.0 : 1.0 : 0.0 : 0.50 : n.a. : n.a. : n.a.
Picote (w/c=0.7)	1958	Granite	n.a.	200	0	140	n.a.	n.a.	n.a.	1.0 : 1.0 : 0.0 : 0.70 : n.a. : n.a. : n.a.
Vilarinho das Furnas	1972	Granite	150	225	0	n.a.	n.a.	n.a.	n.a.	1.0 : 1.0 : 0.0 : n.a. : n.a. : n.a. : n.a.
Régua	1973	Gravel	75	210	0	105	2010	1604	405	1.0 : 1.0 : 0.0 : 0.50 : 9.6 : 7.6 : 1.9
Cahora Bassa	1975	Gneiss	150	215	0	127	2165	1716	449	1.0 : 1.0 : 0.0 : 0.59 : 10.1 : 8 : 2.1
Aguieira	1981	Granite	150	225	0	113	2104	1703	401	1.0 : 1.0 : 0.0 : 0.50 : 9.4 : 7.6 : 1.8
Fronhas	1985	Gravel from Alva river	100	220	0	80	2075	1670	405	1.0 : 1.0 : 0.0 : 0.36 : 9.4 : 7.6 : 1.8
Crestuma	1985	Gravel	38	300	0	150	1920	1437	483	1.0 : 1.0 : 0.0 : 0.50 : 6.4 : 4.8 : 1.6
Torrão	1988	Granite	150	185	0	63	2122	1568	554	1.0 : 1.0 : 0.0 : 0.34 : 11.5 : 8.5 : 3.0
Alto Lindoso*	1992	Granite	150	150	0	77	2187	1554	633	1.0 : 1.0 : 0.0 : 0.51 : 14.6 : 10.4 : 4.2
			150	150	0	63	2187	1554	633	1.0 : 1.0 : 0.0 : 0.42 : 14.6 : 10.4 : 4.2
			150	180	0	83	2187	1554	633	1.0 : 1.0 : 0.0 : 0.46 : 12.2 : 8.6 : 3.5
			150	150	0	73	2187	1554	633	1.0 : 1.0 : 0.0 : 0.49 : 14.6 : 10.4 : 4.2
Alqueva[†]	2002	Green schist	150	158	39	102	2288	1638	650	1.0 : 0.8 : 0.2 : 0.52 : 11.6 : 8.3 : 3.3
			150	157	41	75	2407	1712	695	1.0 : 0.8 : 0.2 : 0.38 : 12.2 : 8.6 : 3.5
			150	164	41	104	2317	1667	650	1.0 : 0.8 : 0.2 : 0.51 : 11.3 : 8.1 : 3.2
			150	158	39	102	2288	1638	650	1.0 : 0.8 : 0.2 : 0.52 : 11.6 : 8.3 : 3.3
			150	159	40	71	2352	1663	689	1.0 : 0.8 : 0.2 : 0.36 : 11.8 : 8.4 : 3.5
Alto Ceira II	2013	Granite	63	117	143	151	1970	1193	777	1.0 : 0.5 : 0.6 : 0.60 : 7.6 : 4.6 : 3
Baixo Sabor (upstream)[†]	2014	Granite	150	111	110	129	1955	1434	521	1.0 : 0.5 : 0.5 : 0.58 : 8.9 : 6.5 : 2.4
			150	110	110	128	1962	1434	528	1.0 : 0.5 : 0.5 : 0.58 : 8.9 : 6.5 : 2.4
			150	110	110	133	2041	1431	610	1.0 : 0.5 : 0.5 : 0.60 : 9.3 : 6.5 : 2.8
Maximum value			150	300	143	151	2407	1716	777	-
Mininum value			38	110	0	63	1920	1193	400	-

D_{max} – maximum size aggregate (MSA)
b – binder content (b=c+v); c – cement content; v – fly ash content; w – water content; a – aggregate content; g – coarse aggregate content; s – fine aggregate content; n.a. – not available

Table 1: Concrete composition of several Portuguese dams.

[†] The different compositions are related to the different batches used for tests

3.2 Synthesis of the creep test results

The available creep tests results are diverse and were organized by dam, type of concrete (wet-screened and full-mixed), maturation conditions (laboratory and *in situ*) and concrete age. In Figure 1 some creep test results and the correspondent fit to the logarithmic creep function (dashed lines) are presented.

Table 2 presents a summary of the fitted parameters of the logarithmic function to the experimental results of the total strains (sum of instantaneous strains and the creep strains). The parameter values of $K(t_0)$ and $F(t_0)$ and, therefore, of $J(1000,t_0)$ and $\Phi(1000,t_0)$ have a large variation due mainly to the different compositions and components used over the years. For example, for the full-mixed concrete *in situ*, the creep coefficient for a loading age of 365 days and 1000 days under loading, varied from 0.16 to 0.67.

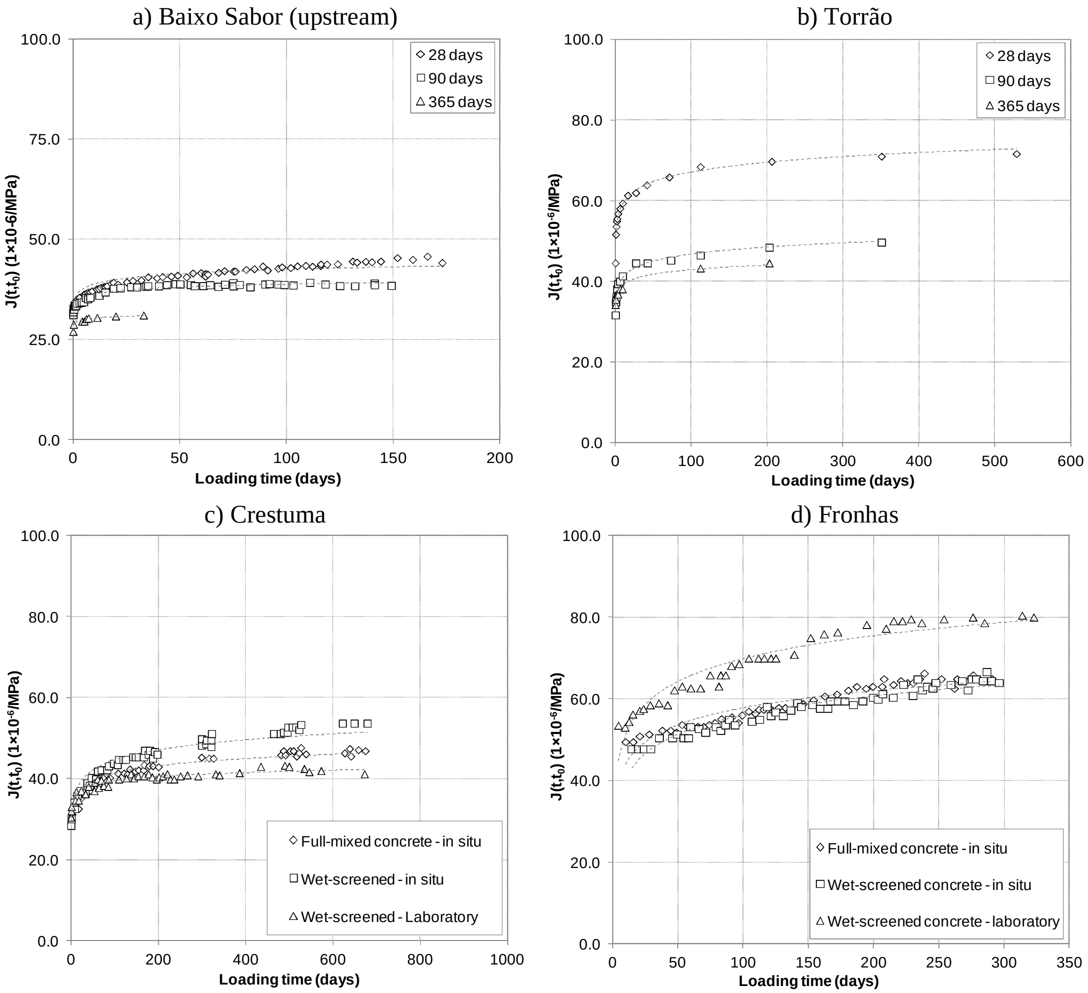


Figure 1: Creep test results: a) full-mixed concrete of Baixo Sabor upstream dam, *in situ*; b) full-mixed concrete of Torrão dam, *in situ*; c) concrete of Crestuma dam, loading at age of 35 days; d) concrete of Fronhas dam, loading at age of 28 days

	Concrete type	**Curing conditions**	**t_0 (days)**	**$K(t_0)$ (1×10^{-6}/ MPa)**	**$F(t_0)$ (1×10^{-6}/ MPa×days)**	**$J(1000,t_0)$ (1×10^{-6}/ MPa)**	**$\Phi(1000,t_0)$**
Minimum values	**Wet-screened**	**Laboratory**	28	32.5	1.47	42.8	0.33
			90	28.8	1.05	41.6	0.24
			365	26.0	0.28	35.4	0.09
		In situ	28	29.6	2.65	62.2	0.53
			90	44.0	3.01	64.8	0.49
			365	33.2	1.52	43.8	0.41
	Full-mixed		28	29.4	1.57	46.0	0.49
			90	33.8	1.11	41.5	0.26
			365	24.7	0.49	32.6	0.16
Maximum values	**Wet-screened**	**Laboratory**	28	73.6	8.25	125.7	1.46
			90	48.0	5.65	77.0	1.03
			365	40.7	3.56	61.6	0.66
		In situ	28	59.1	6.78	94.4	1.51
			90	48.2	4.58	79.8	0.63
			365	41.3	2.62	56.8	0.71
	Full-mixed		28	68.2	6.03	103.0	0.96
			90	57.4	2.54	73.5	0.58
			365	35.2	2.01	46.7	0.67

Table 2: Minimum and maximum parameter values of the logarithmic function fit to creep test results of concrete of several dams

4. COMPREHENSIVE ANALYSIS OF THE EXPERIMENTAL RESULTS

4.1 Comparison of the obtained results from different dams

The diversity of the concrete composition makes it difficult, or even impossible, to find a direct relation between the component properties and contents and the mechanical properties of the hardened concrete. Despite that, the comparison between results can give a general overview of the properties development over time.

Figure 2 presents the modulus of elasticity values obtained in 15 dams (Castelo do Bode, Venda Nova, Picote, Cabril, Régua, Vilarinho das Furnas, Cahora Bassa, Aguieira, Pracana, Torrão, Fronhas, Crestuma, Alqueva, Baixo Sabor (upstream) and Alto Ceira II). These results are referred to wet-screened concrete obtained in laboratory tests. Except for some results from Alqueva and Cabril dam, the modulus of elasticity varies, approximately, between 23 GPa to 35 GPa, at the age of 90 days, and between 27 GPa to 40 GPa, at the age of 365 days. An important feature is the significative development rate at latter ages (between 90 and 365 days of age). The major variability of this mechanical property is due to the modulus of elasticity of the rock used and to the coarse aggregate content. The majority of the analyzed dams used granitic aggregates (70%), but the modulus of elasticity of granitic rocks can vary widely also.

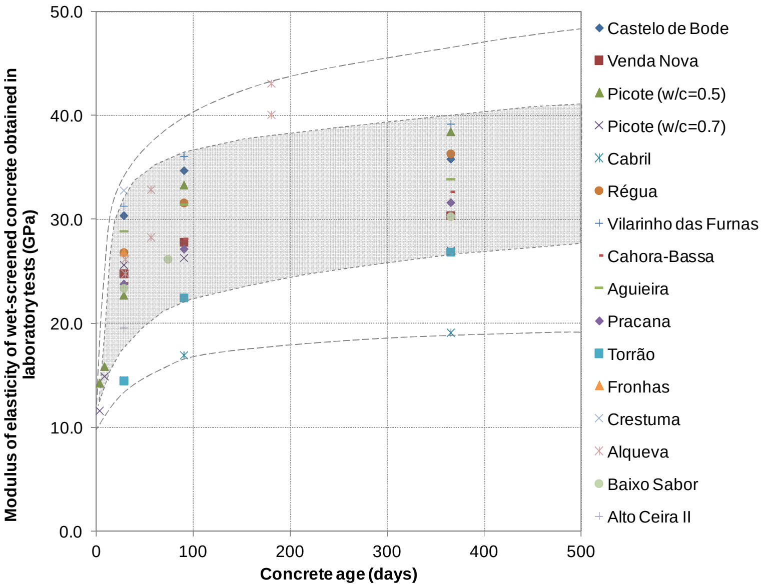
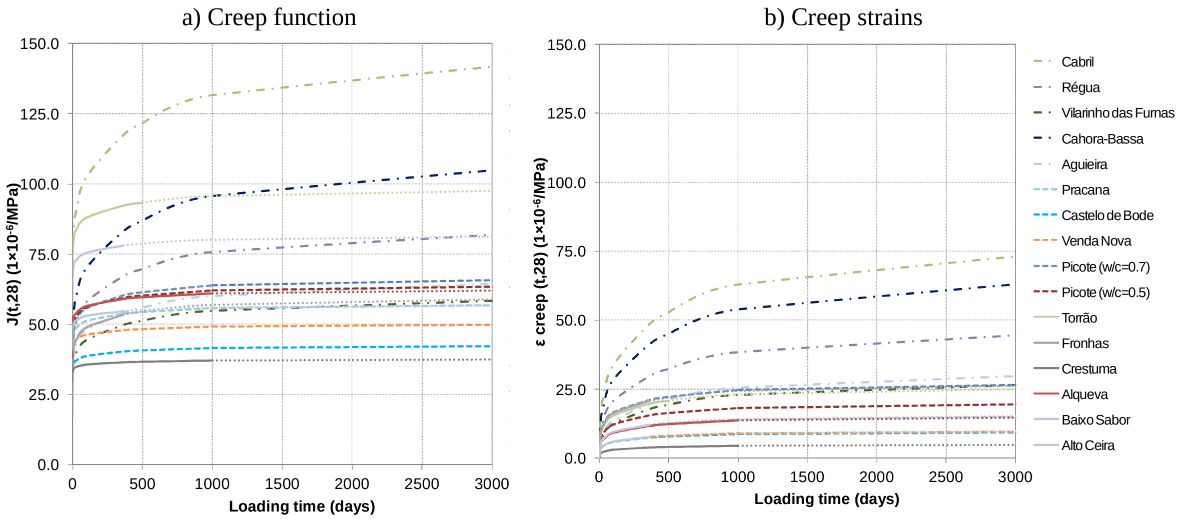


Figure 2: Wet-screened concrete modulus of elasticity results of several dams obtained from laboratory tests

Figure 3 presents the creep functions and the correspondent creep strains fitted to experimental results obtained in laboratory tests of wet-screened concrete at the age of 28 days, for several dams (the dashed lines are the extrapolation values to 3000 days under loading). The creep function values are scattered mainly due to the variation of the modulus of elasticity, which influences the instantaneous part ($1/E(t_0)$). The values of delayed strains, ε^{creep}, after 3000 days under loading (about 8 years) range between 5×10^{-6}/MPa to 25×10^{-6}/MPa.


a) Creep function

b) Creep strains

Figure 3: Representation of the creep function (a)) and the correspondent creep strains (b)), fitted to laboratory creep test results of wet-screened concrete at the age of 28 days

4.2 Influence of composition on the deformability properties of dam concrete

The integrated analysis of the composition data and the deformability test results allow the assessment of the influence of each component's content and its ratios with the mechanical properties of the hardened concrete. The analysis presented in this work refers only to concrete with granitic aggregates and to 28 and 365-day ages.

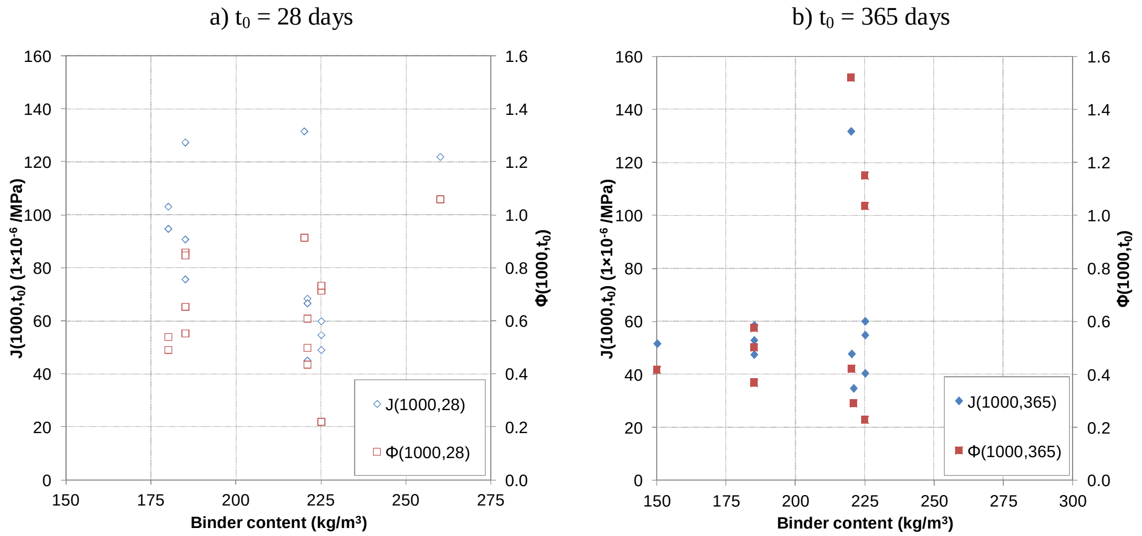
In Figure 4 the correlation between binder content (b) and the creep function, $J(1000,t_0)$, and the creep coefficient, $\Phi(1000,t_0)$, 1000 days under loading, for loading ages of 28 and 365 days is presented. The relation between these quantities does not show a trend or a strong correlation. It is important to recognize that the binder content is the sum of cement content and fly ash content, which can influence the results. Figure 5 shows the correlation between water-binder ratio (*w/b*) and $J(1000,t_0)$ and $\Phi(1000,t_0)$. Also in this case, the available data presents a large variation between the two quantities, with no clear trend. The definition of water content in some references is not obvious, since it is not clear if it refers only to added water to mix or it includes the humidity of the aggregates.

4.3 Correlation between full-mixed and wet-screened concrete deformability

With the available data, obtained from the tests performed in creep cells installed in Torrão, Fronhas, Alto Lindoso and Baixo Sabor (upstream) dams, it was possible to establish a correlation between wet-screened concrete deformability properties, obtained in laboratory tests, and wet-screened and full-mixed concrete deformability properties, obtained *in situ* tests. For this comparison only concrete with granitic aggregates were considered (Figure 4 to Figure 6).

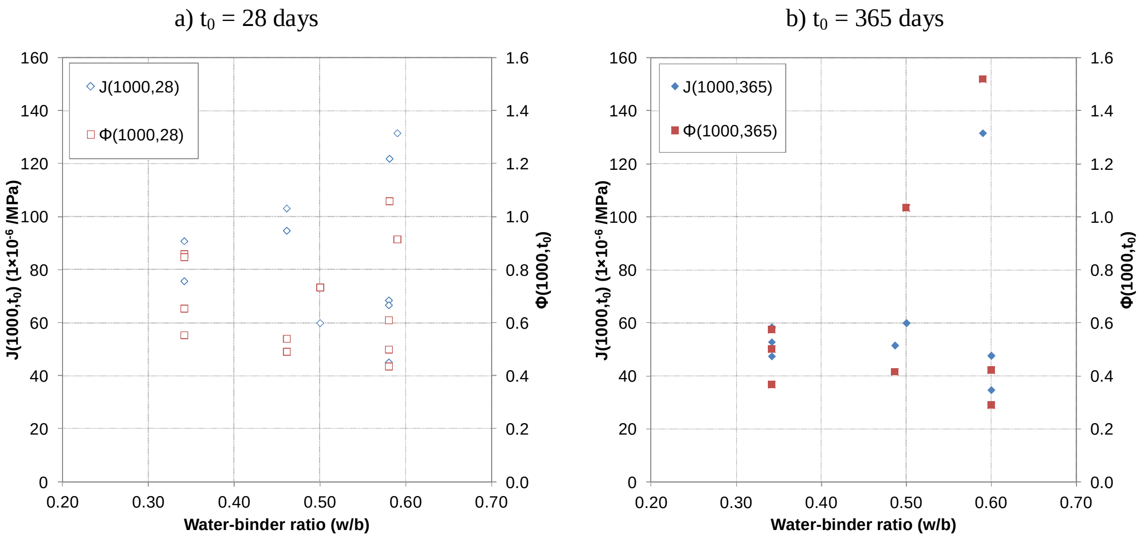
It is shown that, despite the variability of the concrete compositions, of the properties of each component and, specially, of the water-binder ratio and the fly ash addictions, there is clear and strong correlation between the deformability of wet-screened concrete and the full-mixed concrete from which it was obtained (Figure 6). The correlations present high coefficient of determination, R^2, except for the *in situ* modulus of elasticity of the full-mixed concrete, where the coefficient of determination is 0.64.

Based on the former results, it is possible to conclude that the *in situ* modulus of elasticity of the full-mixed concrete are always greater than those obtained for the laboratory wet-screened concrete, due, mainly, to the larger aggregate content. The full-mixed concrete creep coefficients are, in general, smaller than the creep coefficients of laboratory wet-screened concrete, especially for younger ages.


a) t_0 = 28 days

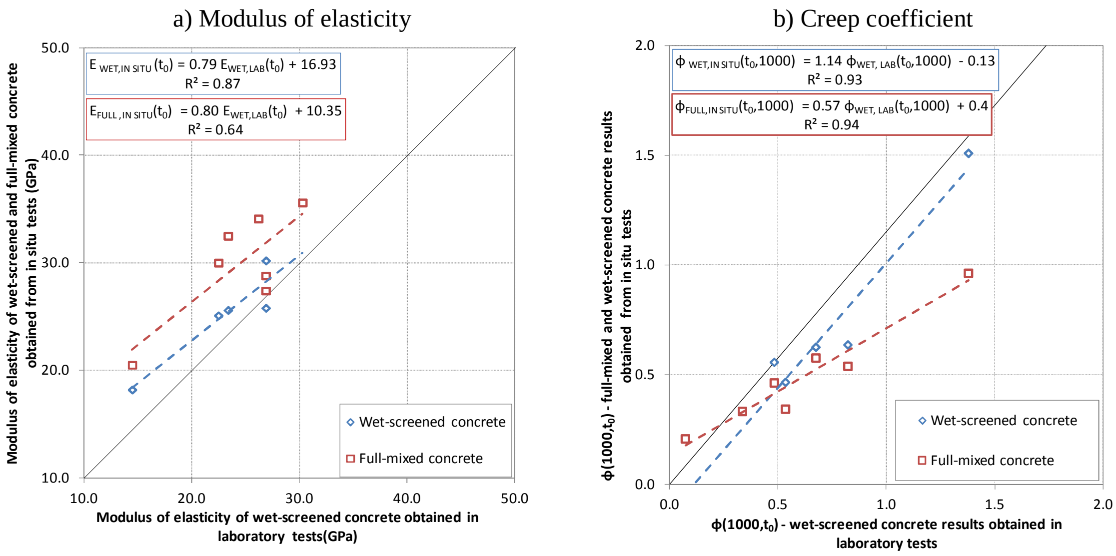
b) t_0 = 365 days

Figure 4: Correlation between binder content (b) and creep function, $J(1000,t_0)$, and creep coefficient, $\Phi(1000,t_0)$, 1000 days under loading, at the age of 28 days (a)) and 365 days (b)), for concrete with granitic aggregates


a) t_0 = 28 days

b) t_0 = 365 days

Figure 5: Correlation between water-binder ratio (*w/b*) and creep function, $J(1000,t_0)$, and the creep coefficient, $\Phi(1000,t_0)$, 1000 days under loading, at the age of 28 days (a)) and 365 days (b)), for concrete with granitic aggregates


a) Modulus of elasticity

b) Creep coefficient

Figure 6: Correlation between deformability properties of full-mixed and wet-screened concrete with granitic aggregates obtained in laboratory and *in situ*: a) modulus of elasticity; b) creep coefficient for 1000 days under loading, for several loading ages

5. CONCLUSIONS

The purpose of the present study was to built a comprehensive database concerning deformability test results, composition data, testing conditions (laboratory and *in situ*) and the type of concrete (full-mixed and wet-screened), obtained from several dam's concrete. This type of information is especially important for dam concrete design, due to difficulties inherent to the characterization of full-mixed concrete (with large aggregates). The analysis showed that there is a strong correlation between the deformability properties of full-mixed and wet-screened concrete. For further studies and to validate the obtained correlation, it is important to extend this database to other dams.

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