ICOLD EUROPEAN CLUB

Working Group on Ageing of Concrete Dams

FINAL REPORT

Ageing of concrete in dams

Rodrigo del Hoyo Fernández-Gago. Dr, Ing Caminos.Soluziona Ingeniería.Universidad de A Coruña

José Manuel Alonso Muñoz. Ing Caminos. Soluziona Ingeniería

Fernando Martínez Abella. Dr Ing. Caminos.Universidad de A Coruña.

Manuel Herrador Barrios. Dr Ing.Caminos.Universidad de A Coruña.

(Representatives from the Spanish Committee in the Working Group).

2004

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Rodrigo del Hoyo Fernández-Gago.Dr, Ing Caminos.Soluziona Ingeniería.Universidad de A Coruña
José Manuel Alonso Muñoz. Ing Caminos. Soluziona Ingeniería
Fernando Martínez Abella. Dr Ing. Caminos.Universidad de A Coruña.
Manuel Herrador Barrios. Dr Ing.Caminos.Universidad de A Coruña.
(Representatives from the Spanish Committee in the Working Group)

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1. INTRODUCTION

The September, 1999 meeting of the European Club of National Committees on Large Dams, held in Antalaya, Turkey, agreed to set up a Working Group on Ageing of Concrete in Dams for a three-year period.

The representatives from the Spanish Committee in the Working Group carried out a study on the ageing of concrete brought about by chemical reactions, which looked into the effect different external factors have on the development of the chemical reactions as also the corresponding stress/strain ratio affecting the concretes involved in slow processes of load application.

Bearing in mind that the time-frame assigned to this specific Working Group has already expired, this final report has been drawn up to give the results and conclusions obtained to date, although its authors are well aware of the fact that its subject is considerably smaller in scope and breadth than the title of the Working Group would suggest. Notwithstanding, it was deemed preferable to close the Group's three-year life-span with this report and leave the possibility open for the European Club, if it should so wish at some future date, to carry on with the research by setting up a new working group to look into these problems.

2. AGEING OF CONCRETE IN DAMS AS A RESULT OF CHEMICAL REACTIONS

Ageing of concrete leads to both a reduced capacity to withstand loads and increased permeability to water , a process occurring progressively for a variety of reasons.

Surface cracking in the specific types of concrete used to build dams can be induced by different causes. Hydraulic retraction, for instance, takes place when water is lost from the surface of the cement paste as a result of evaporation. This problem can usually be prevented by the addition of water applied during a sprinkler curing process spread over quite a number of days.

Another cause of concrete cracking is triggered by thermally-induced stresses produced from the heat in the concrete setting process, together with an insufficient concreting process for dissipating this heat which can give rise to considerable temperature gradients if volume changes are restricted as a result of outside pressures.

In addition to their possible unsightly appearance, surface cracks also make it easier for water to penetrate the concrete, making it more sensitive to possible chemical attack.

Chemical attack includes reactions with sulphates produced when the SO_4^{2-} ions come into contact with hydrated calcium aluminates, producing calcium sulphoaluminate hydrate or ettringite (3CaO, Al_2O_3, $3CaSO_4$, $32H_2O$) and giving rise to significant expansion in the concrete because its volume is considerably greater than that of the original aluminate. The resulting acicular ettringite crystals are characteristic and easily identifiable under a microscope.

The sulphates may be present in the soil and come into contact with the foundations or else form as a result of the SO_2 in the atmosphere, and also as a result of the oxidation of sulphides, particularly iron sulphides (pyrite and pyrrhotite).

Prior to reporting on alkali-aggregate reactions, mention should also be made of the reactions occurring with the carbon dioxide in the air which, on reacting with the $Ca(OH)_2$ in the hydrated cement paste, produces $CaCO_3$, which has a smaller molecular volume causing retraction as a result of carbonation.

This phenomenon tends to remain superficial but is detrimental to any steel reinforcement existing since, in addition to causing retraction cracking, it lowers the pH of the material enveloping it.

There follows an extensive report on the chemical reactions referred to as alkali-aggregate reactions.

In 1940 and 1942 Stanton published two articles in the United States referring to the wear caused by an expansion phenomenon in certain types of concrete as a result of a reaction occurring, in the presence of water, between the alkalis in the cement and the silica. He coined the term "alkali-aggregate reaction" for this phenomenon.

Subsequently, in 1961, Hadley observed an expansion reaction similar to the above between the alkalis in the cement and dolomitic aggregates. This reaction, which can be taken as a dedolomitization process of the carbonate, can be expressed as follows:

$$CaMg(CO_3) + 2NaOH \text{ -> } CaCO_3 + Na_2CO_3 + Mg(OH)_2$$

The resulting magnesium hydroxide is expansive in nature.

The sodium carbonate thus generated can react with the $Ca(OH)_2$ in the cement producing more alkalis, thus continuing the process.

This reaction of the alkalis with dolomitic aggregate is not very common and the only reason why it has been included here is for its similarity to the way the alkalis react with siliceous aggregates.

At the end of the 1950s Plum determined the expression for the reaction process between alkalis and siliceous aggregates as follows:

$$SiO_2 + NaOH + Ca(OH)_2 + H_2O \text{ -> } (n_1\, Na_2O)(n_2\, C_aO)(n_3SiO_2)\ (n_4H_2O)$$

At the time it was believed that for silica to be reactive it had to be amorphous or poorly crystallised and be present in the aggregates. The contribution of the alkalis was fundamentally blamed on the cement. An attempt was therefore made to set up tests to determine the potential reactivity of the aggregates used and the alkali content of the cement was cut down as a result.

The C-289 and C-227 ASTM tests failed to live up to expectations in terms of effectiveness as aggregates that these tests determined as non reactive did in fact prove to react.

Between 1978 and 1982 Aardt, Visser in South Africa, Cole et al in Australia and Katroka & Glasser in Scotland published the results of their research into the effect of the calcium hydroxide in the cement paste on aggregates containing alkaline feldspars at differing stages of weathering.

As a result of all this research it was deduced that calcium hydroxide plays a highly significant role in the formation of expansive gels and, as a result of its presence in the cement paste and its freedom to move and react with certain specific aggregates, gives rise to the formation of alkalis from the aggregates. This means that even with a cement with a low alkali content, an alkali-aggregate type reaction can still occur.

Alkali-aggregate reactions are generally classified into two groups:

– alkali-amorphous silica reactions, producing a response that can be taken in a simplified manner to be an acid-basic reaction between the alkaline pore solution and the amorphous or reactive silica in the aggregates;

– alkali-silicate reactions producing a response between the weathered silicates comprising the aggregates (feldspars for instance) and the alkaline solution. Calcium hydroxide plays an important role In this type of reaction which, as well as with feldspars, can also occur with the minerals in the interlayers of the phyllosilicates.
Hardened concrete is composed of aggregates surrounded by a cement paste containing pores filled with a solution that has a pH varying between 12.5 and 13.9 depending on the alkali content of the cement. The water filling the pores also has Ca+, Na+, K+ and SO_4^{-2} ions present.

The capacity for reaction of the aggregate particles depends on the crystalline structure involved. It is well known that quartz is formed of tetrahedrons with Si in the centre and O in the vertices. The linking of these tetrahedrons by their vertices forms highly stable crystalline structures; however structures of this type do occur in Nature in an altered state owing for instance to tectonic stresses breaking up the crystalline structure of the quartz. This phenomenon shows up in the form of the undulatory extinction detectable in an optical analysis using polarised light, inter alia.

The reaction can be represented as a penetration of OH, Na and K ions in the silica's disordered structure.

Urhan, in 1987, described this reaction as a competition between the dissolving of the silica and the formation of calcium silicate hydrate (CSH). At the onset of the cement hydration process the calcium, sodium, potassium and hydroxyl ions are absorbed through the surface of the reactive aggregate. The attack of the hydroxyl ion causes the silica in the aggregate surface to dissolve.

If the dissolving process takes place at a slower rate than the formation of the CSH, which is stable, the latter forms a layer over the aggregate and blocks the reaction. If the silica dissolving process is faster, the reaction is not blocked, the silica continues to dissolve and the K and Na ions can penetrate into the dissolved silica structure to neutralize the negative charges. The OH, Ca, Na and K ions are absorbed into the surface until a state of equilibrium is achieved. The pH reduction occurring when the hydroxyl ions are consumed gives rise to the polymerisation of the dissolved silica, producing expansive gels.

The expansion mechanism can be explained by the fact that water is absorbed by the silica gel containing alkalis as a result of the geometrical similarity of the "tetrahedral" water molecule to the silica-oxygen unit. If the absorption takes place rapidly and the volume increases faster than the gel can dissipate in the pores, internal stresses are produced leading to microcracking and expansion as a result.

Another theory sustains that the cement paste acts as a semipermeable membrane for the silicate ions. Penetration of the silica fabric by the pore fluid containing water and ions gives rise to increased pressure in the reaction zone. This hypothesis clearly fails to hold up when the cement paste cracks and can therefore no longer act as a membrane.

Chatterji et al revealed the considerable effect the presence of Ca ions has on the reaction.

It has been claimed that a process occurs whereby OH^- , K^+, Na^+ and Ca^{2+} ions enter the reactive aggregate. The degree of penetration depends on the size of the ions and on the formation of CSH (calcium silicate hydrate) on the particle surface, thereby halting the penetration process. Potassium and sodium ions can penetrate more easily than Ca ions owing to the larger size of the latter. The K, Na and (OH) ions diffuse into the reactive particle, leaving the Ca in the liquid phase. At the same time, because the structure of the silica is broken down by this ion penetration, it migrates in a dissolved form, the pace of the migration depending on the existence of $Ca(OH)_2$. If more material enters than exits (silica) expansion takes place. The research by Chatterji & Clausson-Kaas (1984) shows that expansion does not take place if $Ca(OH)_2$ is not present.

From the studies carried out on the products of the reaction (Laing, 1992) it can be deduced that the calcium is incorporated into the gel in the form of $Ca(OH)_2$ and liberates alkalis during the process, which are then in a condition to continue the feedback reaction, underlining the importance of the presence of $Ca\ (OH)_2$.

The factors affecting the development of the reaction and therefore the resulting expansion include the properties of the material comprising the concrete and the external loads, both atmospheric and structural.

On the one hand, in relation to the cement, there is the volume of alkalis present, expressed in Na_2O equivalent where (Na_2O) equivalent = Na_2O + $0.658K_2O$, which can in principle be considered as less than 0.6% of the weight of cement. In any event and as seen above, this limitation is insufficient since the alkalis may stem from the aggregate.

Where the aggregate is concerned, amorphous (opal) or cryptocrystalline aggregate tends to react more in terms of the silica than crystalline types. In any event, quartz with a damaged crystalline structure as a result of tectonic stresses, measured by its undulatory extinction, has been seen to be reactive (the angle of extinction using polarised light varies by over 25º from one zone to another).

Alkaline and calcoalkaline feldspars found in granitic aggregate, when altered as a result of chemical reactions (often by attack from acid water which may in certain cases stem from acid rain), are highly reactive. It should be pointed out that these feldspars, like the weathered phyllosilicates, are capable of supplying not only reactive silica, but also the alkalis required for the reaction. In addition, the smaller the aggregate particle size, the easier it is for the reaction to develop.

The external factors include humidity since, on the one hand, water is needed for the reaction to take place and gel to be formed and, on the other, water is the product that nurtures the expansion as its molecules are incorporated into the structure of the gel that has already formed. The authors consider that with a relative humidity of less than 80% the expansive reaction does not take place.

When, as in the case of dams, there is a substantial volume of water existing, the pace of the attack by the hydroxyl ions marks the speed of expansion as there is abundant water present to nurture the gel formed by the abovementioned attack.

In relation to atmospheric temperature, the authors consider that a specific temperature is required to produce maximum expansion speed. A rising temperature accelerates the speed of the chemical reactions, thus accelerating the speed at which the silica dissolves and also the CSH (calcium silicate hydrate) forms. As reported above, if the kinetics of this reaction are greater than that at which the silica dissolves, the expansion phenomenon is blocked. It would seem that this second effect predominates at high temperatures and, as a result, the expansion rate drops when the temperature goes above a certain value. In addition, even before this blocking process is triggered, a rise in temperature reduces the viscosity of the gel so that it can spread through the pores without provoking increased pressures.

The deduction to be made from the above is that there must be a specific temperature which produces the greatest speed of expansion, a temperature that may vary from one concrete to another. Wood (1986) and Guedon (1993) carried out tests that appear to confirm this fact.

If the state of stress is compressive, this reduces the expansion rate and electric fields also affect the speed of expansion caused by an alkali-aggregate reaction.

The cathodic protection of the reinforcement , which aim is to produce an outwards difference of potential in opposition to that causing the corroding of the reinforcement, produces a concentration of alkalis in the proximity of the iron bars which can give rise to expansion reactions in the area next to the reinforcement.

So-called electrochemical leaching designed to expel the Cl^- ions from the concrete may give rise to a faster process of alkali-aggregate reaction.

This section of the report has covered some of the external factors currently considered to have most effect on the development of an alkali-aggregate reaction, even though it is very difficult to quantify the individual effect each one of them has on the concrete of a particular dam. It is obvious that a totally dry concrete (with a low proportion of moisture content in its pores, in the region of 30 or 40%) would not be capable of developing any expansion effect but how can the concrete of a dam be successfully kept in a totally dry state?

At the present time, with the current knowledge of alkali-aggregate reactions as reflected in the literature available worldwide, appropriate measures can be taken to prevent the process occurring. Consequently, the use of low-alkali content cements, the use of non-reactive aggregates, and the most widespread solution of the use of appropriate additives may lead to future problems being prevented in the concrete currently being produced.

Since it is sometimes difficult and economically prohibitive to use non-reactive aggregates, the use of additives capable of preventing the problem is becoming increasingly common. The puzzolanic action , when portlandite $Ca(OH)_2$ is fixed, reduces the availability of Ca^+ ions that play an important role in the development of alkali-aggregate reactions. Silica fume also appears to have a beneficial effect on preventing alkali-aggregate reactions.

But it is a different story for old concrete forming part of a dam in operation. With the state of the art as it currently stands it is not yet known how to introduce puzzolanic elements, for instance, which would be capable of fixing the $Ca(OH)_2$ and halting the reaction, into concrete that has already hardened,.

One of the measures to take could involve controlling the water using waterproofing sheeting and grouting processes, bearing in mind that a waterproofing treatment may stop water entering, but it will also stop it leaving. Consideration could also be given to the method whereby a waterproof membrane is applied over a drainage layer, designed to allow water to escape from the concrete but not allowing external water to enter.

There is also the possibility of considering that a waterproof surface prevents water from circulating and consequently ions from moving around, which could be another way of holding the reaction in check.

In the opinion of several experts, in certain specific cases the practice of lowering the temperature of the concrete with the use of light-coloured coatings to cut down a rise in temperature caused by insolation could help to keep the phenomenon under control. Even so, in line with the statements made above, a rise in temperature is also capable of curtailing the expansion process so the consequences obtained from applying a solution of this kind appear to be somewhat dubious.

The practice of using anchorage to induce high stresses, in addition to being costly, may involve other problems if in fact it proves practicable at all.

All the above methods are expensive, particularly bearing in mind the scant experience available with the results that could be obtained.

In some instances, without the expansion problem being eliminated, it is possible to prevent the effect of the expansion by making incisions to allow the structure to dilate freely. Thus, without combating the cause of the actual problem itself, its negative consequences are avoided.

3. SPECIFIC PROBLEMS OF AGEING CAUSED BY EXPANSION ANALYSED IN THIS REPORT

The three dams referred to from here onwards in the report were concreted using siliceous aggregates (two of them granitic aggregate while siliceous slate was used in the Portodemouros spillway), together with Portland cement containing no fly ash.

Salas Dam is a buttress dam with a maximum height of 50 m, extending into two lateral gravity dams on each bank. It was built between 1969 and 1973. As from 1975 cracks were detected in some of the buttresses. It was subsequently established that all the cracked lifts had been concreted between August 15 and 30, 1970. By means of levelling processes and the installation of appropriate instruments (extensometers, etc.) the existence of expansion in the lifts indicated was confirmed.

Portodemouros Dam is a rockfill design with a 93-m high clay core. It has a lateral spillway comprising a 20-m high gravity dam.

This dam was built between 1969 and 1972. In 1973 some cracks were detected in the concrete of the spillway prompting the installation of condition surveying equipment (electrical extensometers, rod-based mechanical strain gauges, themocouples, etc.) to check whether the cracking was caused by expansion of the concrete.

Belesar Dam is a 130-m high, arch dam complete with two gravity abutments. Construction was completed in 1963.

An extensive report on the dam behaviour drawn up in 1991 and 1992 confirmed that it had undergone displacement in a downstream direction, which began at the end of the 1980s and was detected through irreversible movements in the pendulums. Some of the electrical extensometers installed during the dam construction process recorded concrete expansion estimated to be occurring at a rate of between 5 and 25 x 10^{-6} per year.

The fact that the reaction did not show up until 20 years after the dam was brought into service plus the fact that the downstream face was painted on completion of construction work (1963) meant the waterproofing effect created by the painting process could be assumed to have deferred the appearance of the phenomenon.

In all three study cases, silica gels were found to be present with a high capacity for absorbing molecules of water stemming from the alkali-aggregate type reactions in which the presence of calcium hydroxide had played a decisive role. In the odd case ettringite was also found to be present, capable of collaborating in the development of the expansion phenomenon. It should also be stressed that undulatory extinction phenomena were apparent in the quartz content of the granitic aggregates involved.

It should further be stressed that if puzzolans (fly ash) were in fact used, the quantity was minimal (less than 7% of the weight of the cement).

4. INFLUENCE OF THE TEMPERATURE ON THE DEVELOPMENT OF EXPANSION PROCESSES AS DEDUCED FROM THE DATA RECORDED BY CARLSON EXTENSOMETERS ENCASED IN THE DAM CONCRETE

Belesar Dam was provided with Carlson electrical extensometers. Each set of extensometers included a corrector extensometer encased in a block of concrete cut off from the stresses transmitted by the structure.

The strains these extensometers measured in the concrete were consequently the result of thermal effects and other types of load such as autogenous expansion.

The graphs representing the evolution of the unitary strain recorded over time in these extensometers were subjected to different analyses, as also was their temperature. The analyses were carried out over different periods.

The readings provided by the extensometers installed in specific buttresses in Salas Dam were also analysed . They were installed in boreholes created for the purpose once the expansion problem had been detected.

Carlson extensometers were used in all the cases studied. It is a well-known fact with this type of apparatus that, given the arrangement and design of its electrical resistances and admitting that the coefficient of thermal dilation is the same for concrete as for steel (the extensometer's electrical resistances are made of steel), the component of the strain caused by variations in temperature is directly eliminated from the reading. The following deductions can be made from the 53 corrector extensometers installed in Belesar Dam together with the information provided between 1963 (when the dam was subjected to load) and 1995.

Readings from nine of them were disregarded since the data provided referred to only a small number of years or showed anomalies leading us to believe that the data was unreliable.

In 22 of the extensometers, functioning acceptably over an extended period of time, significant expansion was detected that generally increased as from a certain date in the 1970s.

In all these extensometers the temperature recorded by them was seen to range each year between values close to 10ºC, in general slightly lower, and values over 20ºC. The annual thermal wave was a little over 10ºC.

In a further 22 corrector extensometers where expansion was not detected, the maximum annual temperature recorded by the extensometer was in all cases less than 20ºC, the majority of them under 15ºC. The annual thermal variation in all except one of them was less than 5ºC.

This report reproduces the strain and temperature graphs recorded by the extensometers detecting expansion and those corresponding to other gauges that failed to detect any expansion.

The conclusions to be drawn from this analysis are as follows:

– the annual thermal variation in all the extensometers recording expansion was greater than 10ºC (there was an odd case when it was slightly less);

– the annual thermal variation in all but one of the extensometers not recording expansion was less than 5ºC;

– the annual thermal variation in the gauges recording a type of expansion that decreased over time was also small.

The deduction to be made from these observations is that a specific thermal variation appears to be required for expansion to develop.

The data recorded by the extensometers over the period 1990 to 1998 was subjected to further analysis.

The following temperature-related groups could be formed from the results of these extensometers.

1) Extensometers recording temperatures that never exceeded 15ºC or did so on very few occasions. In these extensometers the annual temperature variation did not reach 5ºC.

There were 16 corrector extensometers where this was the case and in all of them the expansion recorded was non-existent or minimal (5×10^{-6} per year maximum)..

2) The extensometers recording temperatures exceeding 15ºC every year (tending to reach or exceed 20ºC every year) showed an annual variation in the region of 10ºC.

These extensometers generally detected an expansion that was equal to or greater than 10×10^{-6} each year, and in many cases the value recorded was equal to or greater than 20×10^{-6} per year.

Ten of the 18 extensometers in this situation recorded an annual expansion equal to or greater than 20×10^{-6}, in six of them this ranged between 5 and 15×10^{-6} per year while the malfunctioning of another two, even though it appeared that expansion had occurred, did not allow us to quantify this.

By way of conclusion to these analyses it would appear the deduction can be made that expansion would not occur provided the temperature of the concrete could successfully be kept below 15ºC.

In further, more detailed analyses of the evolution of the "non-thermal" deformation, i.e. the strain facilitated directly by the Carlson extensometers installed in Belesar and Salas Dams, it was observed that the expansion becomes apparent when there is a gradual decrease in the temperature recorded in this case by the actual extensometer, in other words, in the period from October to January.

This fact was also corroborated in Salas Dam when the effect was analysed of the irreversible elevation of the buttresses possessing expanding lifts as compared to the adjacent buttresses free of this problem. It was observed that the relative elevations appeared in the abovementioned period (October to January) when the atmospheric temperature drops. This relative elevation was measured by comparators installed at the crown in the joint between buttresses.

For illustration purposes the report includes the graphs drawn up on the data supplied by two Belesar Dam extensometers and one in Salas Dam plus two comparators in the same Salas Dam.

One possible explanation of this phenomenon would be the fact that the gel develops at high temperatures (providing the right conditions for the reaction to take place) but the appearance of the gel coincided with the onset of lower temperatures, opening up fissures and microcracks and leaving space for the gel to penetrate. Consequently, as the gel gradually penetrated when it found the space for this in the cracks opening up, it prevented the thermal contraction or retraction from occurring in the concrete as the result of the drop in temperature which the Carlson extensometers recorded as "non-thermal" expansion.

It could also be that the gel formation process develops at any temperature, but an intake of water is required for the gel to increase its volume and this intake of water is produced when cracks open up as a result of a drop in temperature.

The above arguments would seem to indicate that if the concrete could successfully be kept at a low temperature, avoiding seasonal variations, i.e. by a cooling process in summer, this might perhaps lower or prevent the expansion phenomenon.

5. INFLUENCE OF HUMIDITY ON THE DEVELOPMENT OF EXPANSION BASED ON LABORATORY-RUN SAMPLE TESTS

Given that the expansion phenomenon requires the presence of water circulating through the concrete, tests were carried out to try to quantify its effect.

The tests were run on cylindrical samples extracted by a diamond bit that was 160 mm in diameter in a 450-mm long bore.

Measuring round bases were fixed to two opposing pairs of generatrices and the variations in their lengths measured to determine the unitary strains they had experienced.

The measuring instrument used for this was an elongation gauge fitted with a 10^{-3}-mm precision sensor made by the Lisbon Civil Engineering Laboratory.

The test carried out is described below.

Twelve (12) samples were taken from an area of the dam that had experienced expansion and the unitary strains were measured at regular intervals in the following conditions:

a) two samples were left exposed to the elements;

b) two samples were subjected to dripping with rainwater and another two dripped with water from the reservoir (one drop every 10 cm per minute in each generatrix);

c) two samples were subjected to shower cycles using rainwater over two hours then 54 hours without wetting followed by a further two hours of shower with reservoir water (intermittent rain)

d) two samples were given totally waterproofed surfaces achieved by applying a 2-mm minimum coating of synthetic resin and fibreglass.

For each sample the averages were obtained for the strains measured in the four generatrices and a graph was drawn up on them which also showed the strains measured in each individual generatrix.

The site chosen for the test was the actual Belesar Dam, in the area beneath the crown path, near to the right abutment. The test commenced on 25/3/1996 and the data available up to June, 2003 were analysed. In November or December, 2000 the samples were transferred to one of the dam's galleries that has virtually constant temperature and humidity conditions (15ºC and 99%). The waterproofing layer was removed from the protected samples.

5.1. WATERPROOFED SAMPLES AND OTHERS EXPOSED TO THE ELEMENTS

In the waterproofed samples the average strains were seen to follow a cyclical pattern that could be assimilated to the thermal variation curve in the absence of irreversible expansion. In 1999 and 2000 a tendency to contract was observed in the two samples. As from the time when they were moved to the gallery and their waterproofing was removed, expansion was detected in one of them that was slightly less than 100 $x10^{-6}$/year and higher than this value in the other.

The behaviour displayed in the initial months by the samples exposed to the elements described a strain curve going in the opposite direction to the thermal evolution, but in line with the temperature in the final months. In general it can be stated that these samples did not experience expansion or irreversible retraction until such time as they were transferred to the gallery. From then onwards (2001) slight expansion could be said to be detected.

5.2. SAMPLES SUBJECTED TO CONSTANT DRIPPING

Samples 9 and 4 were subjected to rainwater dripping and numbers 10 and 13 to dripping by water taken from the reservoir. The reason why both rainwater and reservoir-generated water was used was owing to the fact that the two types of water have a different pH value, in addition to the possible solutes present in the reservoir water.

Once the time-dependent changes in the unitary strains had been plotted it was observed that samples 4 (rainwater) and 13 (reservoir water) did not show signs of any significant expansion or retraction, even though in year 4 sample 4 could be said to show signs of slight retraction. However, samples 9 (rainwater) and 10 (reservoir water), which showed very little strain between March and November, 1996, indicated expansion in the region of $200x10^{-6}$ between December, 1996 and March, 1997 and thereafter, with variations in line with the thermal variations, maintaining a residual expansion ranging approximately from 150 to 200x 10^{-6}. None of these four samples showed signs from 2001 onwards of expansion once they were moved to the gallery.

These findings give the impression that expansion took place during the winter of 96-97 and that subsequently no irreversible expansion occurred during that first year. The phenomenon did not repeat itself in successive years (almost as if the irreversible expansion had finished), perhaps because the products causing the gel to form (alkalis and free silica, etc.) had become spent.

The effect of the dripping could have accelerated the reaction.

It can be assumed that samples 4 and 13 possessed no reactive aggregates.

5.3. SAMPLES SUBJECTED TO INTERMITTENT RAIN

These samples were submitted to a two-hourly shower of water every three days. Numbers 8 and 5 were showered with rainwater and numbers 11 and 12 with water from the reservoir.

All four samples behaved in a very similar fashion with signs of expansion in the region of $100x10^{-6}$ developing between October, 1996 and March or April, 1997. This expansion remained up to June, 1998, at which time retraction and expansion processes succeeded each other, with retraction achieved in the winter of 99-00 (always compared to the March, 1996 scenario at the start of the study).

The behaviour of these samples gave the impression that an initial irreversible expansion took place similar to that of two samples subjected to permanent dripping, but that its irreversible effect subsequently disappeared (in the space of two or two and a half years after commencement of the test).

Once installed in the gallery, irreversible expansion was observed in the four samples, giving the impression of a tendency to reach maximum values of 150 to 250 x 10^{-6} (the strain-time curve appearing to have a horizontal asymptote).

5.4. CONCLUSIONS

The following conclusions must be taken with certain reservations since only a small number of samples were analysed, the expansion phenomenon was heterogeneous and occurred in the presence of reactive aggregates and, finally, the measuring and control procedures used for some of the parameters were not the most ideal.

1) Waterproofing the samples can be said to curb the expansion phenomenon and when the protection is removed the expansion process starts up again.

2) The findings obtained would appear to point to the existence of limited residual expansion in the concrete involving maximum values starting from the March, 1996 scenario ranging between 200 and 400 x 10^{-6} approximately.

3) In spite of the fact that expansion did not appear to develop in the corrector extensometers at temperatures below 15ºC and without any seasonal variations, the behaviour of the samples gives the impression that the effect of humidity is far more important since in the gallery with quasi constant temperatures of ≈ 15ºC some of the samples developed substantial expansion because the humidity level was close to 100%.

6. RESPONSE OF DAM CONCRETE SUBJECTED TO LOADS APPLIED VERY SLOWLY

As a result of the expansion phenomena located in several dams, consideration was given to the need to check on their structural safety when subjected to this kind of load that was not taken into account in the design because it appeared as a result of reactions that were not predictable at the time the dams were designed.

In 1981 a study was carried out on one of the buttresses of Salas Dam where two lifts were suffering from expansion problems. A finite elements model was used in which the expansion phenomenon was assimilated to a thermal rise. The study revealed that if a modulus of elasticity was taken for the concrete with the value that had been determined during the construction phase, in line with standardised tests, or was determined by universally accepted formulae relating it to the characteristic strength, the calculation came up with very high stresses that were not in keeping with the observations made at the dam site.
A distinctly lower modulus was then applied, corresponding to a very slow load application, obtained from different literature sources, including the schedule of conditions for the design of reinforced concrete and mass concrete construction work applicable at the time.

With expansion problems in other dams recently appearing the decision was taken to research the matter more thoroughly. To this end it was planned to carry out a set of tests on cylindrical samples extracted using a 160-mm diameter diamond bit on a 450-mm long bore.

These samples were first taken from the top part of the right abutment of Belesar Dam and subsequently from a lower part of the dam. Expansion had been detected in both areas but the concrete used in the second area, i.e. the bottom of the dam, was better quality (higher compression strength) than in the abutment area.

Tests were also run on samples taken from the left abutment area of Albarellos Dam. Expansion has not been detected in this dam in which fly ash in the proportion of 25 to 30% of the weight of cement was used to produce the concrete.

A number of load-bearing frames were installed in one of the galleries in the foundations for Belesar Dam. This gallery has a virtually constant temperature all year round (≈ 15ºC) with humidity in the region of 99%. This same gallery was used as from January, 2001 to house the samples subjected to testing to determine the effect humidity has on the expansion phenomenon.

The samples from each area (Belesar abutment, Belesar and Albarellos arches) were grouped into pairs as two samples were placed in each load-bearing frame.

Some of the samples were subjected to constant loads of 25, 50 and 100 kg/cm^2 in Belesar and of 50 and 100 kg/cm^2 in Albarellos while others were subjected to a variable load involving stepped increments of 1, 3 and 8 kg/cm^2 every 14 days for the Belesar abutment and of 3 and 8 kg/cm^2 every 14 days for the samples in the Belesar and Albarellos arches.

Two samples from each of the three extraction areas were kept load free in the gallery and their time-dependent strain in the gallery was measured as reference for expansion not subjected to loading.

6.1. ANALYSIS OF THE RESULTS OBTAINED IN THE TESTS ON SAMPLES SUBJECTED TO INCREASING LOADS, UP UNTIL 31/12/02

This analysis was designed to determine the stress/strain ratios of the concrete that should be taken into account in the event of loads applied slowly at the rate of 1, 3 and 8 kg/cm^2 every 14 days.

Strain measurements were obtained from the readings by mechanical elongation gauges taken on the measuring bases placed on four generatrices of each sample.

In order to determine the strains to be used to calculate the modulus of elasticity, or rather the apparent modulus of elasticity, the expansion-induced strain needs to be eliminated. The structural analysis of a dam gives, on the one hand, the strain caused by the usual loads (its own weight, hydrostatic pressure and temperature), including the instantaneous elastic deformation, and also the creep-induced strain, the result of the load application speed, which is considerably slower than the loading speed of the usual laboratory tests run on samples to obtain the modulus of elasticity. On the other hand, expansion is introduced as an external load, simulated in the calculation as an irreversible thermal rise which induces strains.

The expansion to be taken into account in each case will be the expansion measured in the load-free samples placed in the test gallery under the same temperature and humidity conditions (practically invariable over time) to which the samples under load were subjected.

The theory was admitted that a linear relationship exists between the expansion and the state of stress in the direction in which the expansion is measured, as indicated in the graph, with the result that:

$$\varepsilon = \varepsilon_0 - \frac{\sigma}{\sigma_0}\varepsilon_0$$

Values ε_0 and σ_0 are established for each individual case.

The report now analyses the results of the tests.

6.1.1. Results Obtained in the Tests on the Samples Taken from Belesar Dam Abutment Subjected to Recent Loads

The first samples analysed were those where load increments of 1 kg/cm^2 every 14 days were applied.

Date	Sample 29	Sample 31
28/02/2000	$\sigma = 20\ kg/cm^2$ $\varepsilon = +60 \times 10^{-6}$	$\sigma = 20\ kg/cm^2$ $\varepsilon = +110 \times 10^{-6}$
17/06/2002	$\sigma = 80\ kg/cm^2$ $\varepsilon = -310 \times 10^{-6}$	$\sigma = 80\ kg/cm^2$ $\varepsilon = -320 \times 10^{-6}$

Expansion measured in the samples not subjected to loads in the gallery between 28/02/02 and 17/06/02

Sample 28	230×10^{-6}	
Sample 27	300×10^{-6}	Accepted average: 260×10^{-6}

According to the studies expounded in the doctorate thesis by Manuel Herrador, the most appropriate inhibition pressure of the expansion for these tests on the concrete used in the right abutment of Belesar Dam can be taken to be 70 kg/cm^2.

The following values were admitted for samples 29 and 31:

370 S.29

$\Delta\sigma = 60\ kg/cm^2$ $\varepsilon =$ Average 400

430 S 31

The average stress to which the concrete was subjected over the period under study can be admitted to be 50 kg/cm^2 and will be:

$$\varepsilon_{exp} = \varepsilon_o - \frac{\sigma}{70}\varepsilon_o = 260\left(1 - \frac{50}{70}\right) \times 10^{-6} = 75 \times 10^{-6}$$

Thus the load-induced strain can be admitted to be

$$\varepsilon = 400 + 75 = 475\ x\ 10^{-6}$$

$$\mathrm{E} = \frac{\sigma}{\varepsilon} = \frac{60}{475\ x\ 10^{-6}} = 126{,}300\ kg/cm^2$$

Taking samples 33 and 32, subjected to load increments of 3 kg/cm^2 every 14 days, it was found that in the period between 31/10/99 and 22/02/01 there was a load increase of $\Delta\sigma$ = 135-33 =102 kg/cm^2 and a strain measured in the two samples of 840 x 10^{-6} (an acceptable value according to the graphs for the two samples).

Bearing in mind that the inhibition pressure was achieved on 28/04/00 and throughout this period (31/10/99 to 28/04/02) reached a value of $\varepsilon_o \approx 50 \times 10^{-6}$ in the load-free samples, the corresponding ε_{ex} will be $\varepsilon_{oy} = 50(1 - \frac{50}{70})\, 10^{-6} = 14 \times 10^{-6}$, a value considered to be negligible as it falls within margins of error.
Consequently, in this particular case the result will be:

Next to be analysed were samples 34 and 35 subjected to a load increment of 8 kg/cm^2 every 14 days in the period between 24/05/99 and 28/02/00.

$$\varepsilon = \frac{\sigma}{\varepsilon} = \frac{102}{840\ x\ 10^{-6}} = 122{,}000\ kg/cm^2$$

An $\Delta\sigma$ of 150 kg/cm^2 and a strain of 850 x 10^{-6} were obtained in sample 35 and of 950 x 10^{-6} in sample 34.

Admitting an $\varepsilon = 900\mathrm{x}10^{-6}$, the result obtained was that $\mathrm{E} = \frac{150}{900}\, x10^{-6} = 165{,}000\ kg/cm^2$.

In this case the expansion effect was disregarded given the short time it took before the inhibition load was achieved.

An analysis of the data provides the possible deductions listed below.

a) For loads with a 14-day cycle application speed equivalent to 3 kg/cm^2 or less, corresponding to an annual strain in the order of 600 x 10^{-6}, the value of the modulus of elasticity applicable to a calculation using these concretes will be 125,000 to 130,000 kg/cm^2.

b) If the load increases by 8 kg/cm^2 on a 14-day cycle, the applicable modulus will be 160,000 to 170,000 kg/cm^2.

c) Bearing in mind that the laboratory-measured moduli for these concretes (applying a rapid load test) ranged between 234,000 kg/cm^2 and 291,000 kg/cm^2 with an average value of approximately 265,000 kg/cm^2, the following considerations can be made:

- for a load increase of 3 kg/cm^2 or less every 14 days, corresponding to an approximate strain increase of 600 x10^{-6} over one year, the modulus of elasticity to be used for the calculations can be in the region of 50% of the measurement taken for it in the rapid test;

- if the load is applied at a speed equivalent to an increment of 8 kg/cm^2 every 14 days, the modulus to be used can be between 60 and 65% of the laboratory value obtained for it (rapid test).

6.1.2. Results Obtained from the Tests on Samples Taken from the Bottom of Belesar Arch Dam Subjected to Increasing Loads

The samples from frame B 5, subjected to an 8 kg/cm^2 load increase every 14 days, were analysed in two stages:

between 10/03/02 and 29/06/02 and between 29/06/02 and 27/09/02.

Date	Stress	
10/03/02 29/06/02	- 64 kg/cm^2 128 kg/cm^2	$\Delta\sigma$ = 64 kg/cm^2
27/09/03	184 kg/cm^2	$\Delta\sigma$ = 56 kg/cm^2

AVERAGE STRAIN (x10^{-6})			Δ STRAIN		
Date	Sample 1	Sample 2	Sample 1	Sample 2	Average
10/3/02	-100	-250	300	330	315

29/06/03	-400	-580			
27/10/02	-730	-100	330	430	380

For the expansion rate of $\varepsilon_o = 40 \times 10^{-6}$ (until it reached 90 kg/cm^2 on 30/04) and the average stress for the period of: $\frac{64+96}{2} = 80\ kg/cm^2$:

$$\varepsilon_{\exp} = \varepsilon_o - \frac{80}{95} \quad \varepsilon_o = 6.5\ x\ 10^{-6}$$

This value can be disregarded.

For loads from 64 to 128 kg/cm^2:

$$\mathrm{E} = \frac{64}{315\ x\ 10^{-6}} = 203{,}000\ kg/cm^2$$

For loads from 128 to 184 kg/cm^2:

$$\mathrm{E} = \frac{56}{380\ x\ 10^{-6}} \approx 150{,}000\ kg/cm^2$$

but in any event there was a large variation from one sample to another.

For one of them .... $\frac{56}{300} = 170{,}000\ kg/cm^2$

while for the other......... $\frac{56}{430} = 130{,}000\ kg/cm^2$

It can therefore be deduced that the possible variation is ± 15% if a value of 150,000 kg/cm^2 is taken.

The laboratory tests led the authors to the deduction that the modulus for this concrete is 300,000 kg/cm^2 (rapid test) and it could therefore be admitted that the modulus of elasticity to be taken for a load application speed equivalent to 3 kg/cm^2 or 8 kg/cm^2 every 14 days could be between 50 and 60% of the value determined in the laboratory.

6.1.3. Results Obtained from the Tests on Samples Taken from Albarellos Dam Subjected to Increasing Loads

The Carlson extensometers in Albarellos Dam did not register expansion of any kind, nor were any displacements recorded either in the pendulum capable of leading to the belief that expansion phenomena existed in the concrete.

In spite of the foregoing, an expansion of 40 x 10^{-6}/year was in fact found in one of the samples located in the gallery and not subjected to loading and of 140 x 10^{-6} in the other.

In the samples put under a constant load and subsequent to the strain occurring that can be considered instantaneous, in spite of the loads to which they were subjected, when it came to applying them, expansion strains with values of 40 x 10^{-6}/year and 25 x 10^{-6}/year were in fact recorded in the samples subjected to a load of 50 kg/cm^2 and of 25 x 10^{-6}/year in the two samples put under a constant load of 100 kg/cm^2.

The figure attached represents the extreme expansion values plus the one that could be accepted as the intermediate, load-dependent expansion value for this particular concrete in a saturated environment.

The fact that this expansion is produced when the samples are subjected to a saturated environment suggests, in principle, that the scenario involved (transfer to a saturated environment by a dry concrete in an environment that is also dry inside the abutment - the location of the gallery from which the samples were extracted) could be the cause of the expansion. Notwithstanding, it would seem that further revision and analysis needs to be done on these samples to determine whether there exists a different cause justifying this expansion.

It should be borne in mind that the inhibition pressure is greater than 100 kg/cm^2 .

The stress/strain curves for the samples subjected to variable load also reflect an initial expansion, and the "zero strain" condition was not recovered, for load increments of 3 kg/cm^2 every 14 days, until the value of 45 kg/cm^2 was obtained in one case and 27 kg/cm^2 in another.

For 14-day cycle loads of 8 kg/cm^2, however, the stress/strain curve was virtually a straight line right from the beginning.

Analysis of the first case ($\Delta\sigma$ = 3 kg/cm^2 every 14 days) produced the following result:

Date	Stress	Strain		$\Delta\varepsilon$
		Sample 1	Sample 2	
17/08/02	σ = 45 kg/cm^2	$\varepsilon = 0$	ε = -50 x10^{-6}	

14/04/03	σ = 96 kg/cm^2	ε = -170 x10^{-6}	ε = -230 x10^{-6}	170x10^{-6}
	$\Delta\sigma$ =51 kg/cm^2			

Admitting for such a load that ε_{exp} = 25 x 10^{-6}/year, for two thirds of the year it would be ε_{exp} = 17 x 10^{-6} therefore

$$E = \frac{\sigma}{\varepsilon} = \frac{51}{(170+17)\cdot 10^{-6}} = 270{,}000\ kg/cm^2$$

For a load of $\Delta\sigma$ = 8 kg/cm^2 every 14 days, expansion has a negligible effect and the values obtained for E in the attached graphs were accepted:

E_1 = 261,000 kg/cm^2 E_2 = 281,000 kg/cm^2

therefore, the average value will be E_1 = 270,000 kg/cm^2.

The E values obtained in the laboratory from the rapid test give an average value of E_1 = 387,000 kg/cm^2 whereby it can be accepted that the values for E to be applied in the calculations involving load application rates of 3 to 8 kg/cm^2 every 14 days will be 70% of the laboratory-measured values obtained by the rapid test method.

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Standard Tests

Standard laboratory tests were carried out on standardised cores (15 cm in diameter, 30 cm long) in order to compare the results obtained in the tests run inside the gallery. The test procedures used for these cores were as laid out in the following standards:

- ultimate compression tests: UNE 83-304-84
- modulus of deformation tests: ASTM C469

The ultimate values obtained in the cores subjected to modulus of deformation tests are attached to this report, as also the moduli of deformation estimated by the electronic strain gauge equipment in the elastic field (up to 40% of the ultimate load) obtained in the ultimate compression tests.

Belesar (Abutment Concrete)

CORE	TEST TYPE	MODULUS OF DEFORMATION (MPa)	ULTIMATE STRESS (MPa)
B161	ASTM	23390	37.1
	UNE	24720	

B165	ASTM	28890	31.7
	UNE	29160	
B162	UNE	29020	38.4
B167	UNE	23700	32.9

Belesar (Arch Concrete)

CORE	TEST TYPE	MODULUS OF DEFORMATION (MPa)	ULTIMATE STRESS (MPa)
B201	ASTM	31600	38.3
	UNE	32700	
B206	ASTM	23100	29.4
	UNE	25900	
B202	UNE	37700	35.3
B203	UNE	29200	36.6

Albarellos

CORE	TEST TYPE	MODULUS OF DEFORMATION (MPa)	ULTIMATE STRESS (MPa)
A204	ASTM	32800	50.9
	UNE	34300	
A205	ASTM	39600	47.7
	UNE	42500	
A201	UNE	41700	55.3
A202	UNE	41400	46.6

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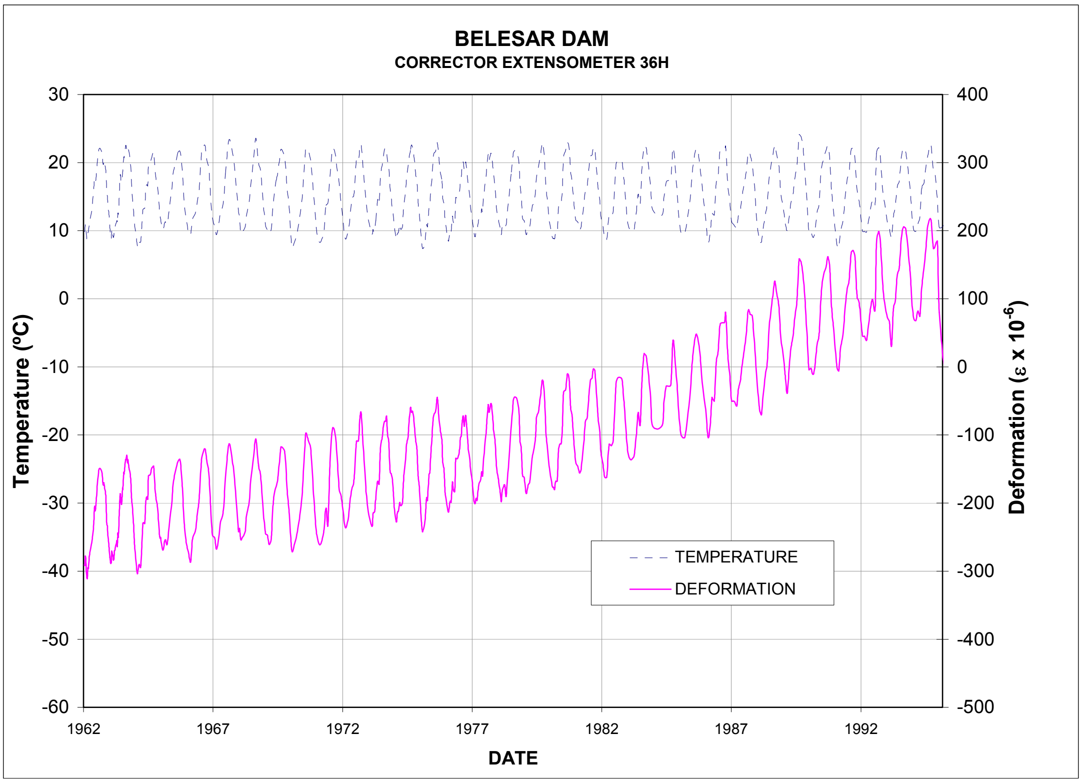
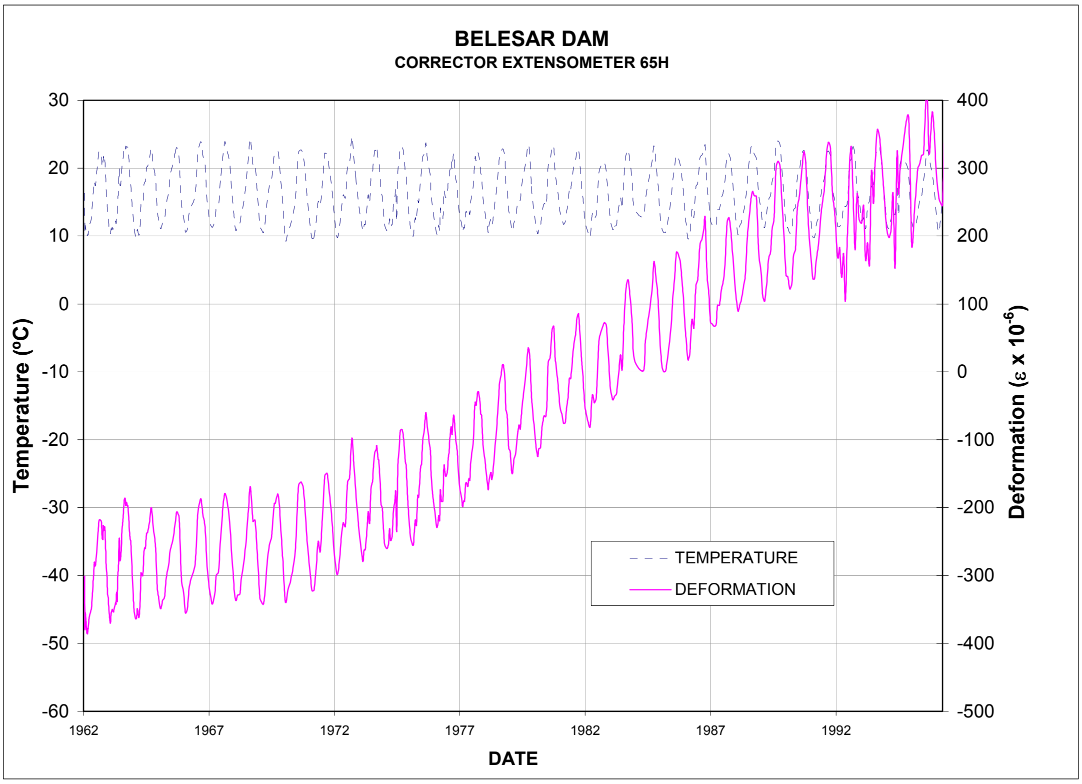
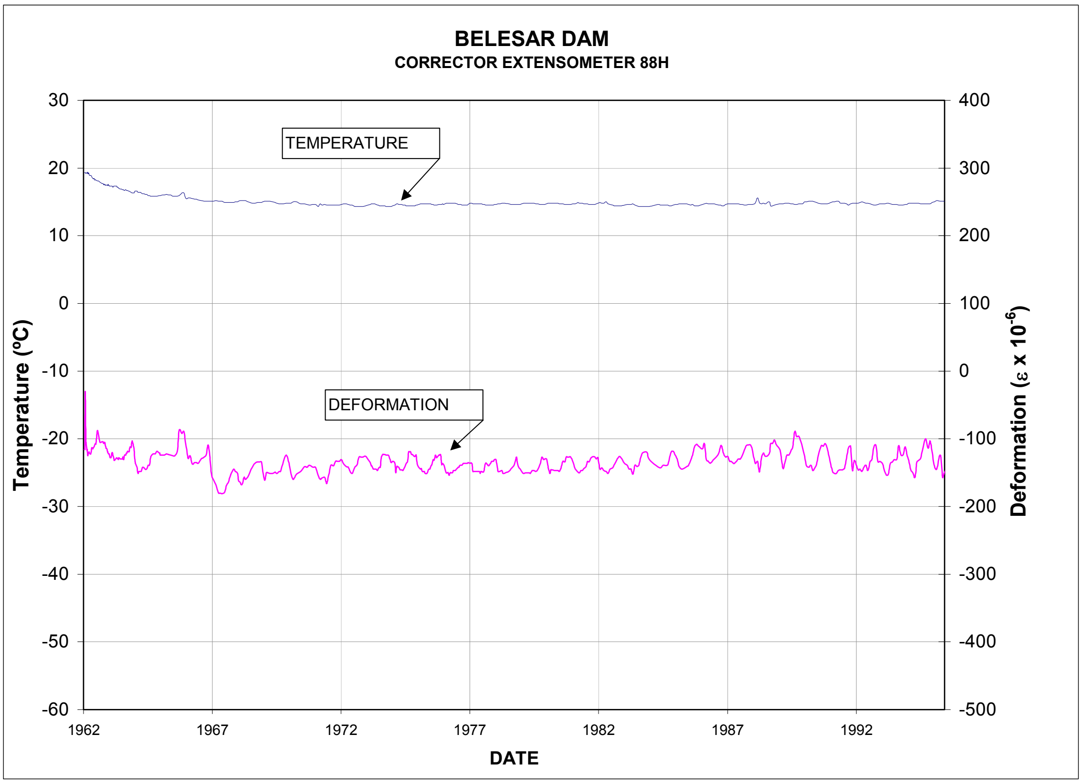
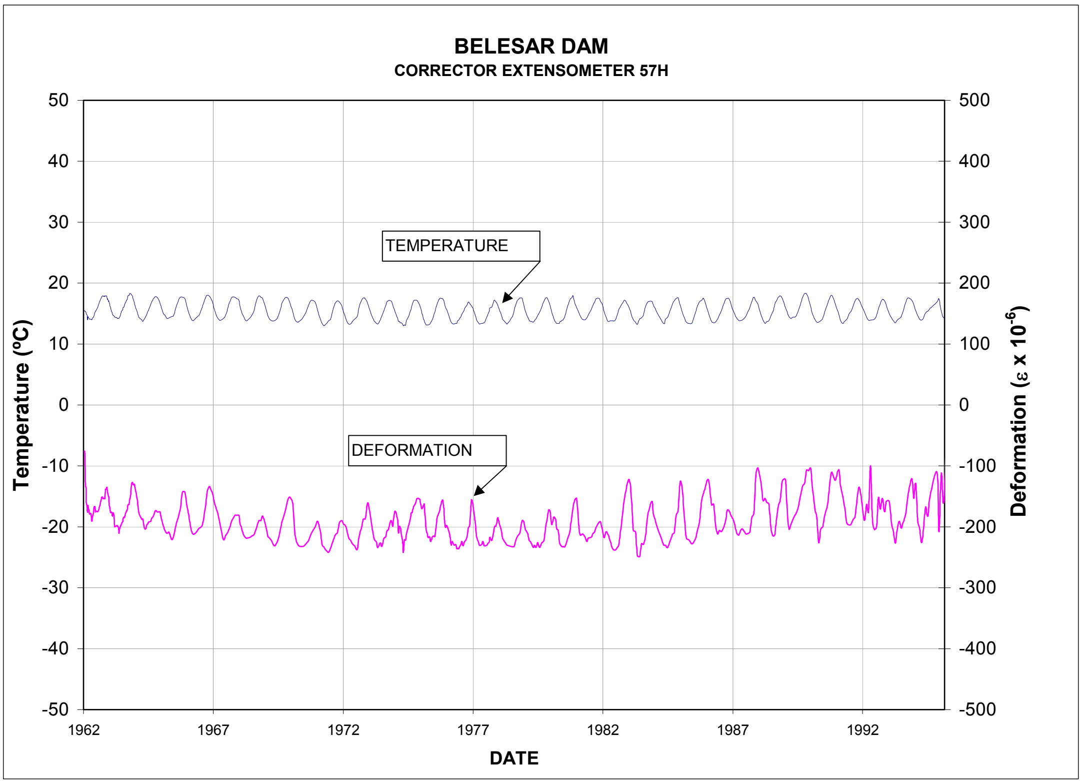
FIGURES

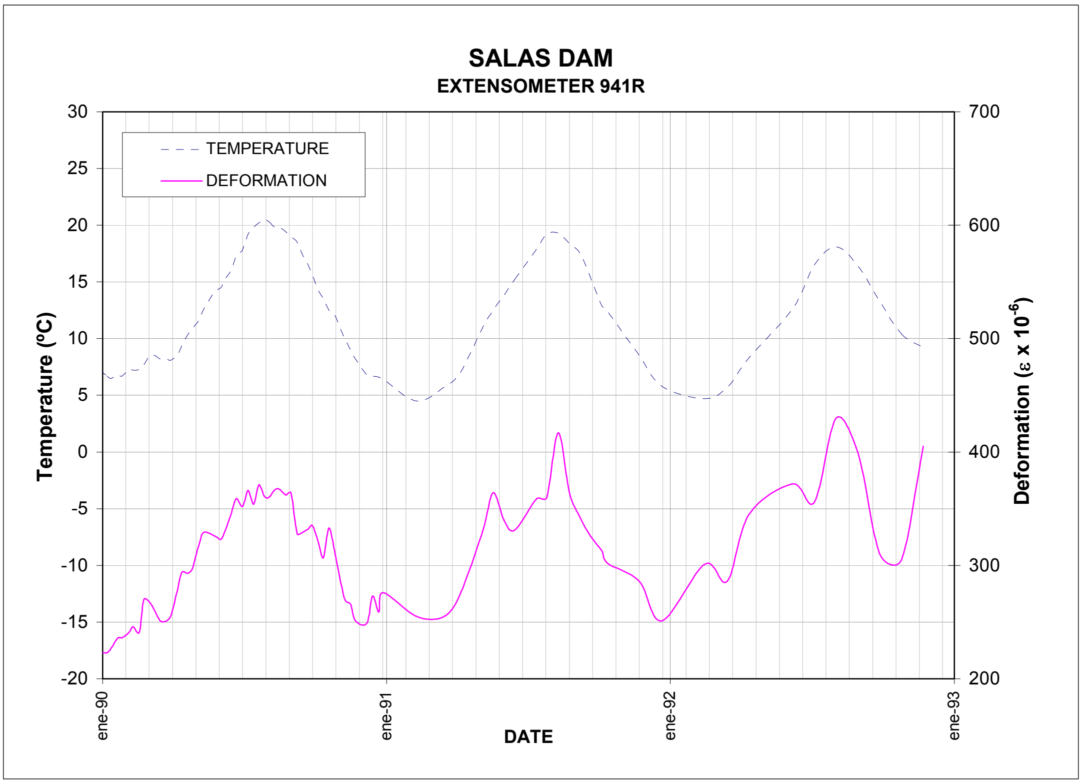

BELESAR DAM
CORRECTOR EXTENSOMETER 36H
Temperature (ºC)
Deformation (ε x 10^-6)
DATE
TEMPERATURE
DEFORMATION
30
20
10
0
-10
-20
-30
-40
-50
-60
400
300
200
100
0
-100
-200
-300
-400
-500
1962
1967
1972
1977
1982
1987
1992

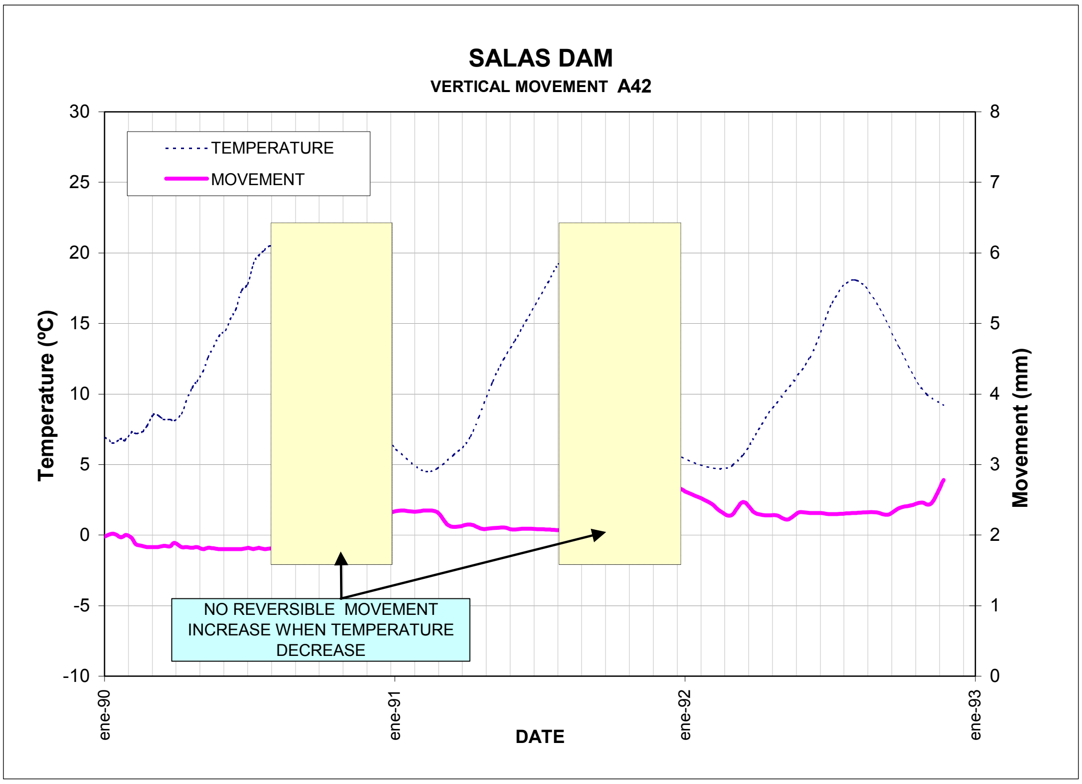

BELESAR DAM
CORRECTOR EXTENSOMETER 65H
Temperature (ºC)
Deformation (ε x 10-6)
DATE
30
20
10
0
-10
-20
-30
-40
-50
-60
400
300
200
100
0
-100
-200
-300
-400
-500
1962
1967
1972
1977
1982
1987
1992
TEMPERATURE
DEFORMATION

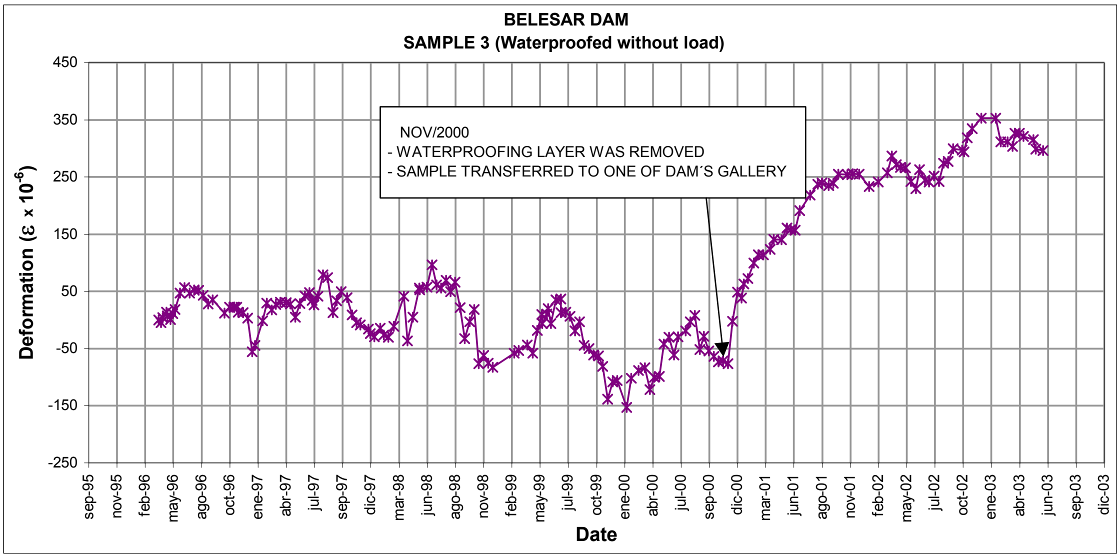


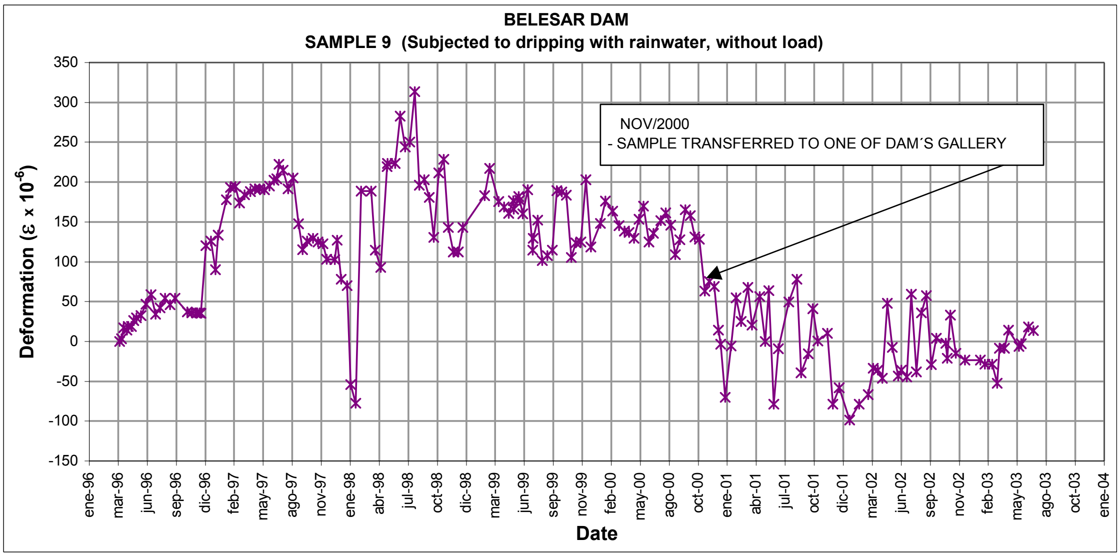
BELESAR DAM
CORRECTOR EXTENSOMETER 88H
TEMPERATURE
DEFORMATION
Temperature (ºC)
Deformation (ε x 10-6)
30
20
10
0
-10
-20
-30
-40
-50
-60
400
300
200
100
0
-100
-200
-300
-400
-500
1962
1967
1972
1977
1982
1987
1992
DATE

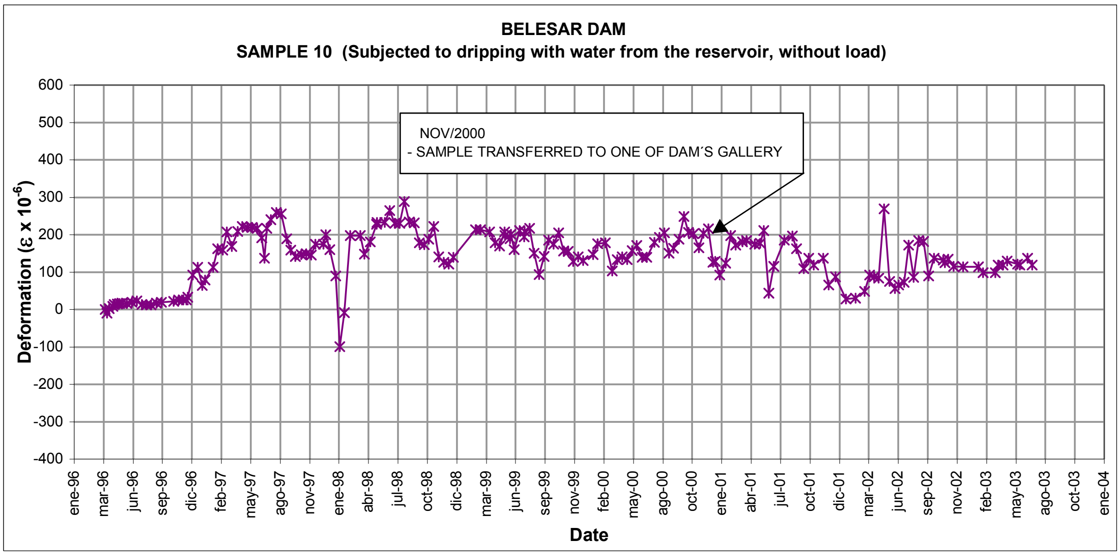

BELESAR DAM
CORRECTOR EXTENSOMETER 57H
TEMPERATURE
DEFORMATION
Temperature (ºC)
Deformation (ε x 10-6)
50
40
30
20
10
0
-10
-20
-30
-40
-50
500
400
300
200
100
0
-100
-200
-300
-400
-500
1962
1967
1972
1977
1982
1987
1992
DATE

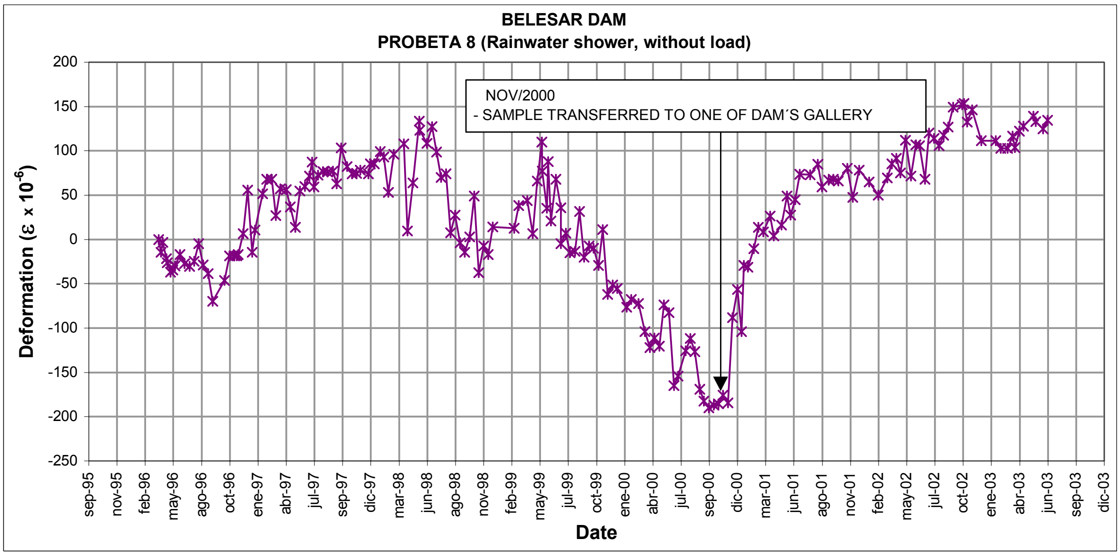

SALAS DAM
EXTENSOMETER 941R
TEMPERATURE
DEFORMATION
Temperature (ºC)
Deformation (ε x 10^{-6})
30
25
20
15
10
5
0
-5
-10
-15
-20
700
600
500
400
300
200
ene-90
ene-91
ene-92
ene-93
DATE

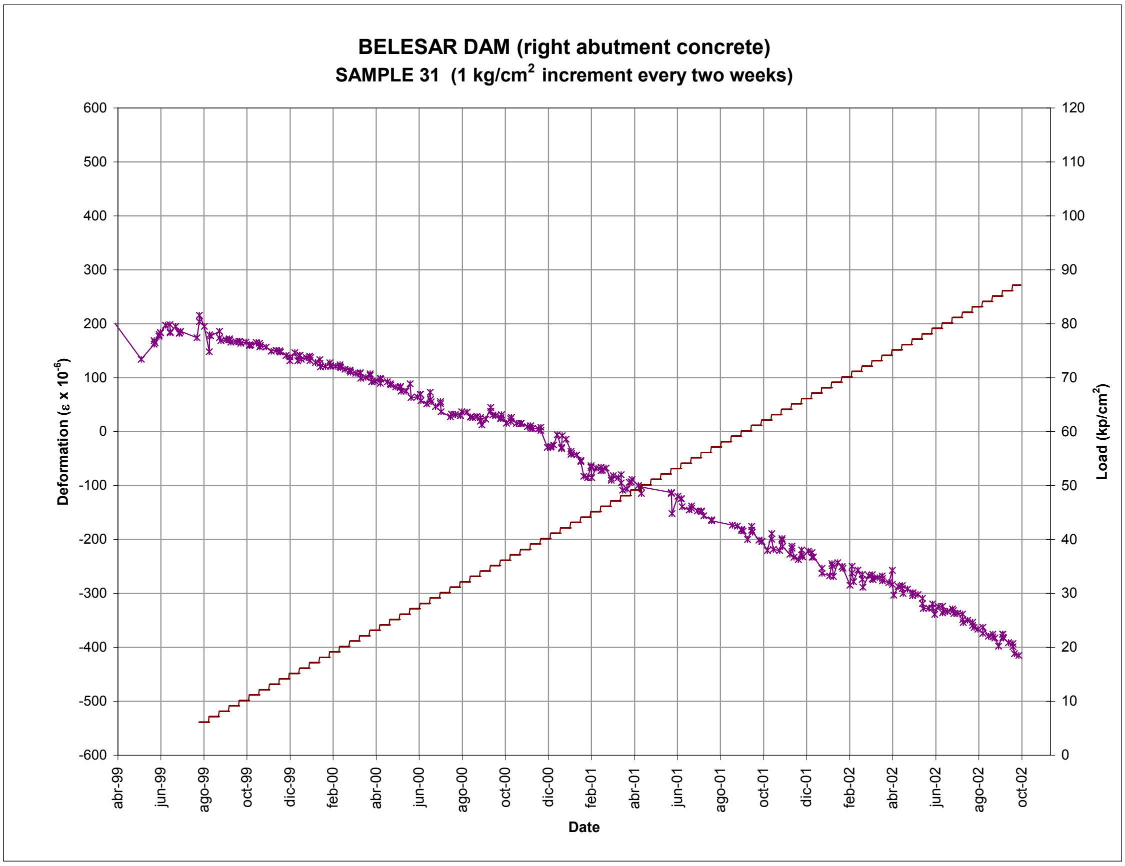

SALAS DAM
VERTICAL MOVEMENT A42
TEMPERATURE
MOVEMENT
Temperature (ºC)
Movement (mm)
NO REVERSIBLE MOVEMENT INCREASE WHEN TEMPERATURE DECREASE
DATE
ene-90
ene-91
ene-92
ene-93


BELESAR DAM
SAMPLE 3 (Waterproofed without load)
NOV/2000
- WATERPROOFING LAYER WAS REMOVED
- SAMPLE TRANSFERRED TO ONE OF DAM´S GALLERY
Deformation (ε x 10^-6)
Date


BELESAR DAM
SAMPLE 9 (Subjected to dripping with rainwater, without load)
NOV/2000
- SAMPLE TRANSFERRED TO ONE OF DAM´S GALLERY
Deformation (ε x 10^-6)
Date


BELESAR DAM
SAMPLE 10 (Subjected to dripping with water from the reservoir, without load)
NOV/2000
- SAMPLE TRANSFERRED TO ONE OF DAM´S GALLERY
Deformation (ε x 10-6)
Date


BELESAR DAM
PROBETA 8 (Rainwater shower, without load)
NOV/2000
- SAMPLE TRANSFERRED TO ONE OF DAM´S GALLERY
Deformation (ε x 10-6)
Date


BELESAR DAM (right abutment concrete)
SAMPLE 31 (1 kg/cm2 increment every two weeks)
Deformation (ε x 10-6)
Load (kp/cm2)
Date
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
120
110
100
90
80
70
60
50
40
30
20
10
0
abr-99
jun-99
ago-99
oct-99
dic-99
feb-00
abr-00
jun-00
ago-00
oct-00
dic-00
feb-01
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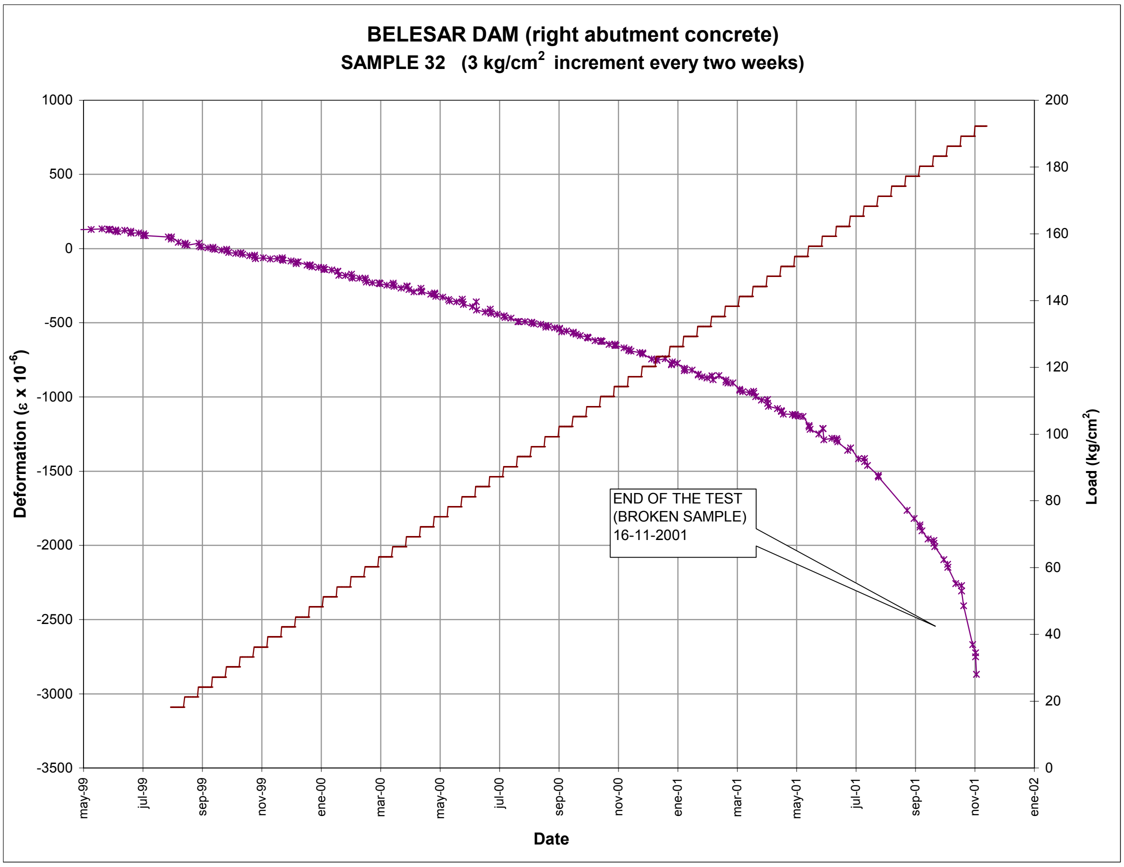
jun-02
ago-02
oct-02


BELESAR DAM (right abutment concrete)
SAMPLE 32 (3 kg/cm2 increment every two weeks)
Deformation (ε x 10-6)
Load (kg/cm2)
Date
END OF THE TEST
(BROKEN SAMPLE)
16-11-2001
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
200
180
160
140
120
100
80
60
40
20
0
may-99
jul-99
sep-99
nov-99
ene-00
mar-00
may-00
jul-00
sep-00
nov-00
ene-01
mar-01
may-01
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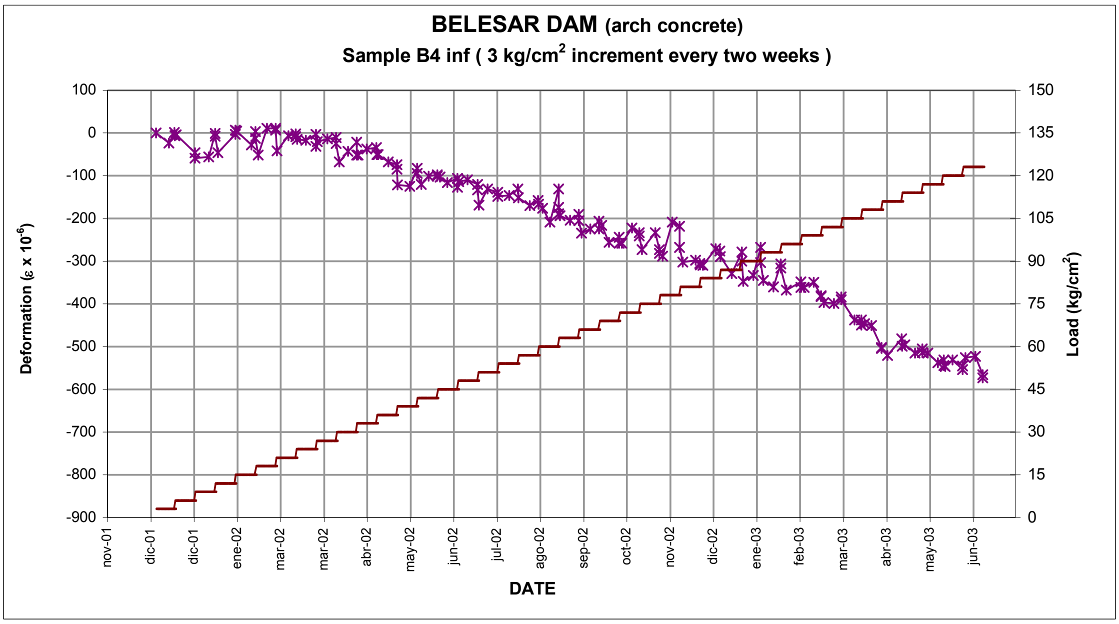
sep-01
nov-01
ene-02


BELESAR DAM (arch concrete)
Sample B4 inf (3 kg/cm2 increment every two weeks)
Deformation (ε x 10-6)
Load (kg/cm2)
DATE
100
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
150
135
120
105
90
75
60
45
30
15
0
nov-01
dic-01
dic-01
ene-02
mar-02
mar-02
abr-02
may-02
jun-02
jul-02
ago-02
sep-02
oct-02
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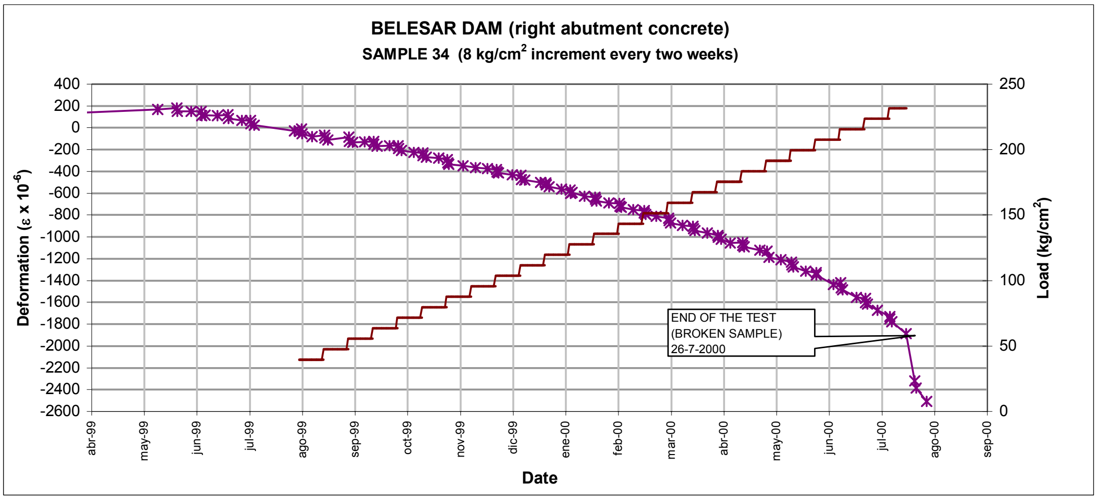
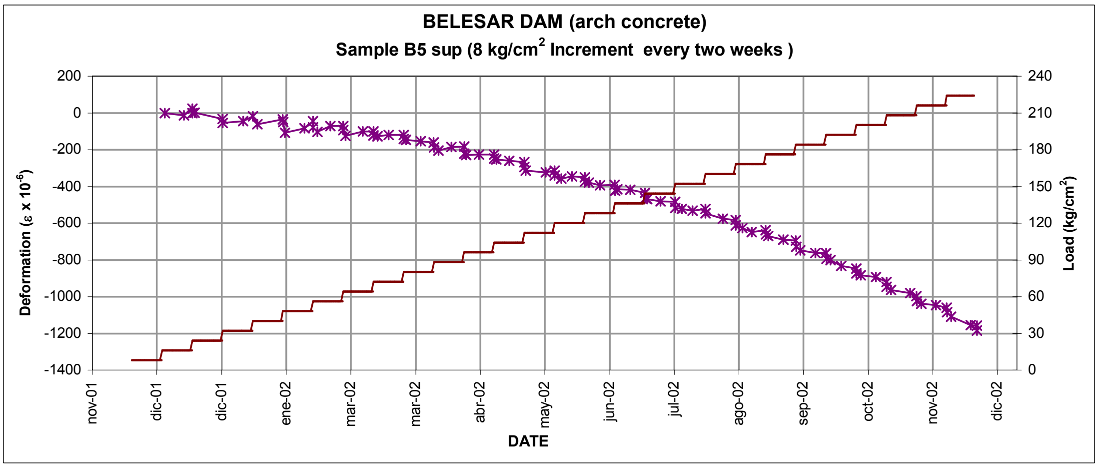
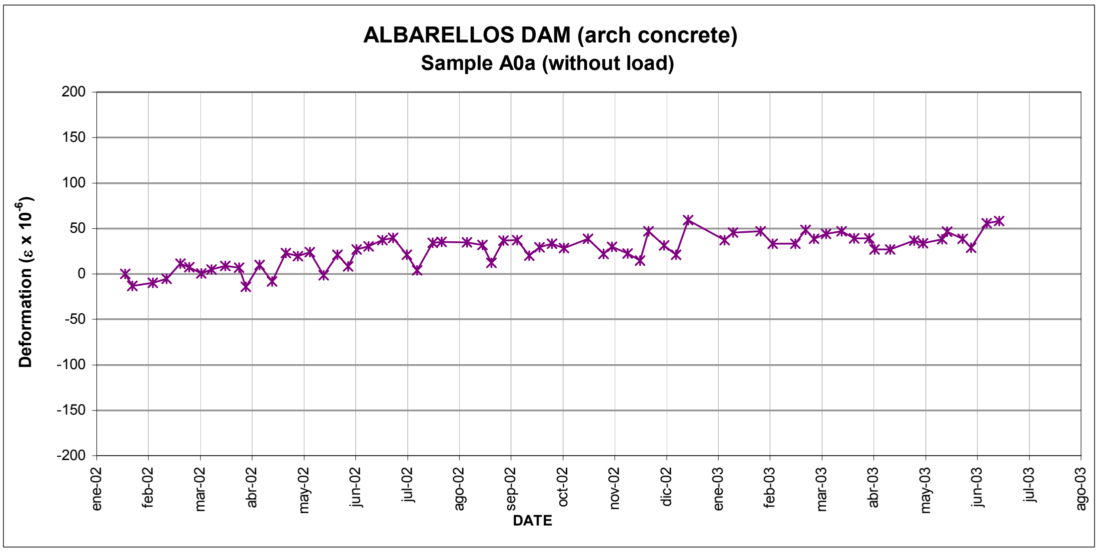
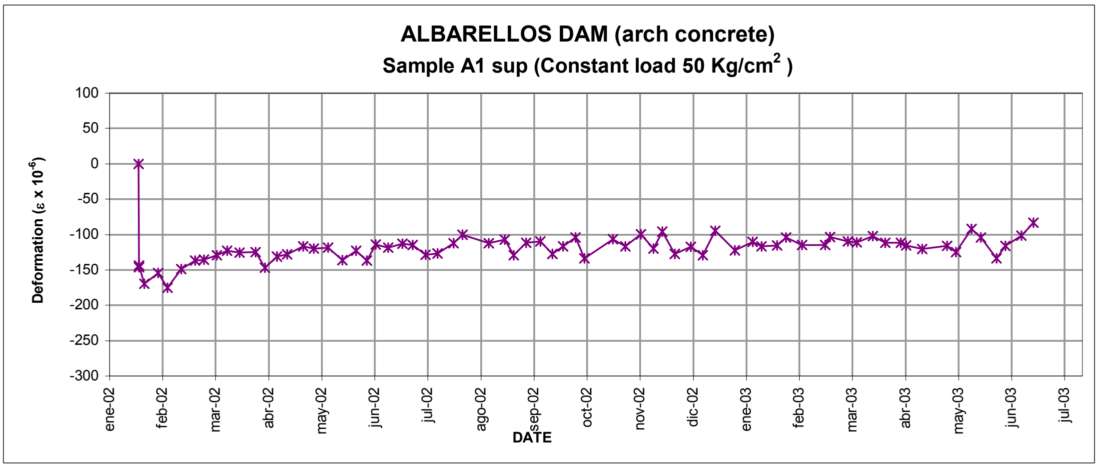
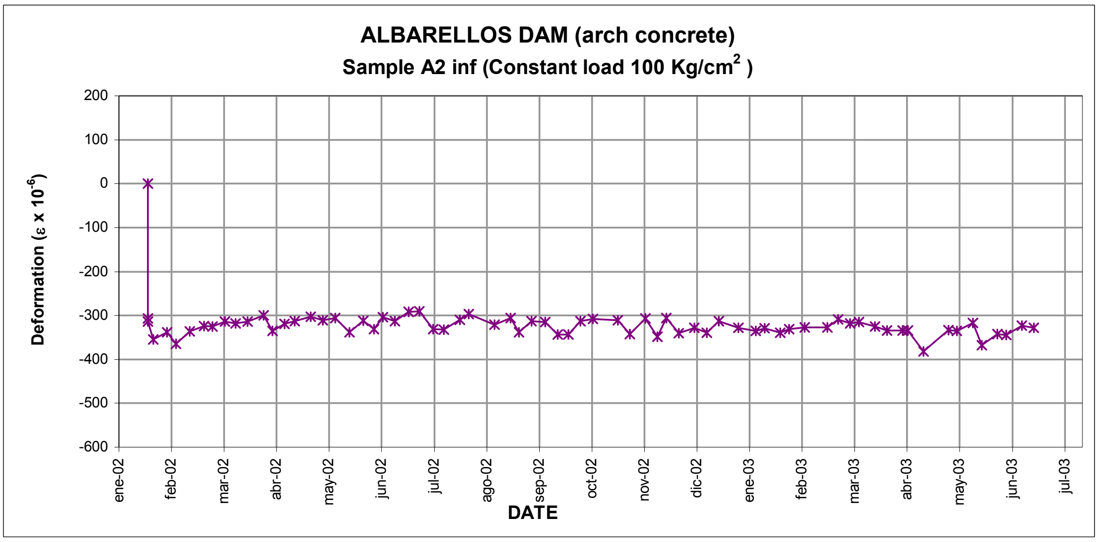
feb-03
mar-03
abr-03
may-03
jun-03

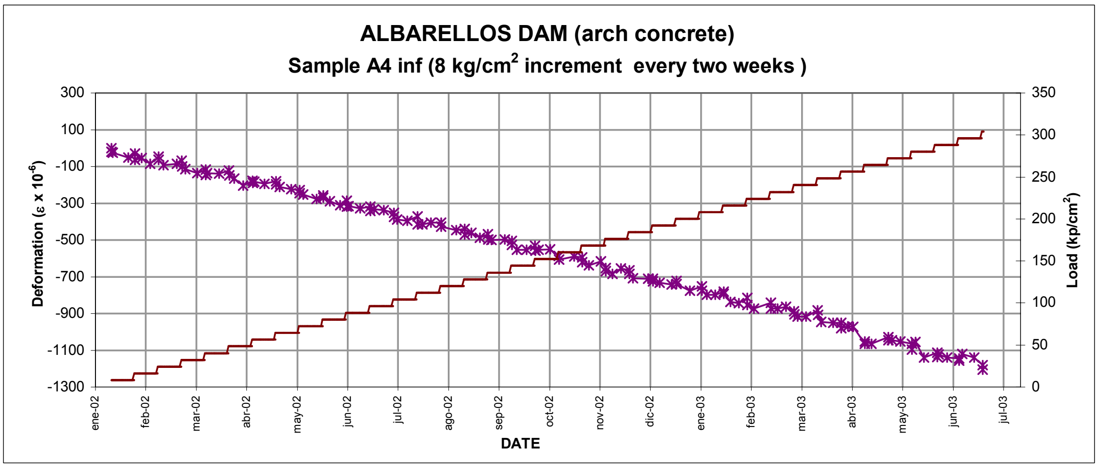

BELESAR DAM (right abutment concrete)
SAMPLE 34 (8 kg/cm2 increment every two weeks)
Deformation (ε x 10-6)
Load (kg/cm2)
Date
END OF THE TEST
(BROKEN SAMPLE)
26-7-2000
abr-99
may-99
jun-99
jul-99
ago-99
sep-99
oct-99
nov-99
dic-99
ene-00
feb-00
mar-00
abr-00
may-00
jun-00
jul-00
ago-00
sep-00

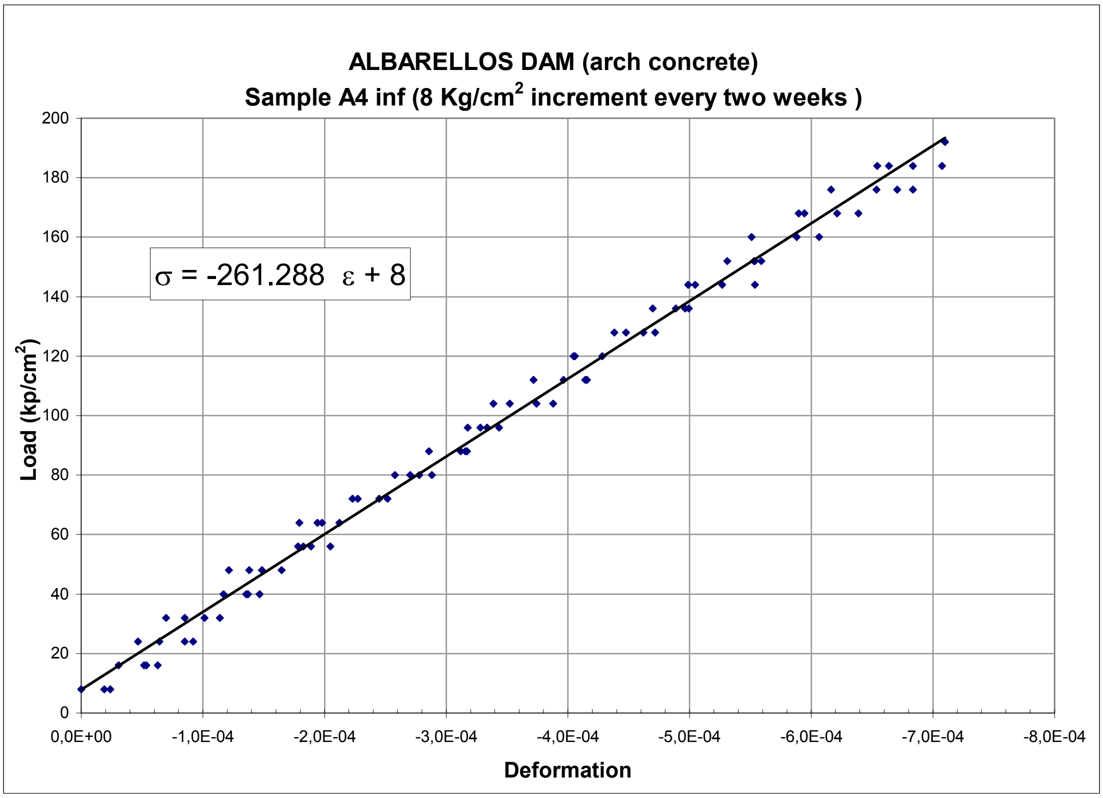

BELESAR DAM (arch concrete)
Sample B5 sup (8 kg/cm2 Increment every two weeks)
Deformation (ε x 10-6)
Load (kg/cm2)
DATE
nov-01
dic-01
dic-01
ene-02
mar-02
mar-02
abr-02
may-02
jun-02
jul-02
ago-02
sep-02
oct-02
nov-02
dic-02


ALBARELLOS DAM (arch concrete)
Sample A0a (without load)
Deformation (ε x 10-6)
200
150
100
50
0
-50
-100
-150
-200
ene-02
feb-02
mar-02
abr-02
may-02
jun-02
jul-02
ago-02
sep-02
oct-02
nov-02
dic-02
ene-03
feb-03
mar-03
abr-03
may-03
jun-03
jul-03
ago-03
DATE


ALBARELLOS DAM (arch concrete)
Sample A1 sup (Constant load 50 Kg/cm2)
Deformation (ε x 10-6)
100
50
0
-50
-100
-150
-200
-250
-300
ene-02
feb-02
mar-02
abr-02
may-02
jun-02
jul-02
ago-02
sep-02
oct-02
nov-02
dic-02
ene-03
feb-03
mar-03
abr-03
may-03
jun-03
jul-03
DATE


ALBARELLOS DAM (arch concrete)
Sample A2 inf (Constant load 100 Kg/cm2)
Deformation (ε x 10-6)
200
100
0
-100
-200
-300
-400
-500
-600
ene-02
feb-02
mar-02
abr-02
may-02
jun-02
jul-02
ago-02
sep-02
oct-02
nov-02
dic-02
ene-03
feb-03
mar-03
abr-03
may-03
jun-03
jul-03
DATE


ALBARELLOS DAM (arch concrete)
Sample A4 inf (8 kg/cm2 increment every two weeks)
Deformation (ε x 10-6)
300
100
-100
-300
-500
-700
-900
-1100
-1300
Load (kp/cm2)
350
300
250
200
150
100
50
0
ene-02
feb-02
mar-02
abr-02
may-02
jun-02
jul-02
ago-02
sep-02
oct-02
nov-02
dic-02
ene-03
feb-03
mar-03
abr-03
may-03
jun-03
jul-03
DATE


ALBARELLOS DAM (arch concrete)
Sample A4 inf (8 Kg/cm2 increment every two weeks)
σ = -261.288 ε + 8
Load (kp/cm2)
0
20
40
60
80
100
120
140
160
180
200
0,0E+00
-1,0E-04
-2,0E-04
-3,0E-04
-4,0E-04
-5,0E-04
-6,0E-04
-7,0E-04
-8,0E-04
Deformation