# AAR AT PAULO AFONSO HYDROELECTRIC COMPLEX, PART I: INFLUENCE ON THE MECHANICAL AND ELASTIC PROPERTIES OF THE CONCRETE

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**Abstract**

This paper presents some results and discussions about experimental research developed at the University of São Paulo, studying a case of concrete affected by alkali-aggregate reaction (AAR) in five power plants of the Paulo Afonso Hydroelectric System, belonging to CHESF, Brazil. Concrete cores drilled from the power intake and spillway of Paulo Afonso IV plant were tested. Some mechanical and elastic properties of the concrete were evaluated and correlated, such as: compressive strength, tensile strength, elasticity modulus and Poisson ratio. The tests results showed that the compressive strength was not significantly reduced due to concrete expansion caused by AAR. However, the tensile strength was reduced and the elasticity modulus presented around 30% reduction in cores extracted from regions where high humidity was available.

**Keywords**: alkali-aggregate reaction – concrete expansion - mechanical properties – hydropower plants.

## 1 INTRODUCTION

Paulo Afonso Hydroelectric Complex comprises five plants – Paulo Afonso I, Paulo Afonso II, Paulo Afonso III, Paulo Afonso IV (PA I, PA II, PA III and PA IV) and Moxotó. The first AAR symptoms were observed at the end of the 70s, in Paulo Afonso II (PA II), when the concrete of the generators walls presented several cracks.

At the beginning of the 80s, some small concrete pillars that supported cable trays were crushed, at PA II powerhouse due to the concrete expansion e. At that time, no suspicion was arisen about AAR in the PA II concrete structure. However, in 1984, when the occurrence of AAR was confirmed in Moxotó plant [1], which was built with the same aggregates used in the concrete of PA I, PA II, PA III and PA IV, it was realized that all the hydropower plants in the Complex would develop the reaction, and that the concrete cracking and crushing observed in PA II were related to AAR [2].

Some concrete cores were extracted from PA I, PA II, PA III, PA IV and Moxotó plants for petrographic analyses in order to confirm the presence of AAR. The report prepared by Richard Mielenz [3] from USA and by Brazilian Cement Association ABCP [4] stated that AAR was presented in the concrete and diagnosed strained quartz as the main reactive mineral.

Once AAR was confirmed in the concrete of Paulo Afonso Complex plants, CHESF decided to monitor the evolution of AAR, and to investigate the concrete structures. The investigation program included development of mathematical models to simulate the evolution of the concrete expansion and to verify the effectiveness of possible repair and control procedures, for instance, installing monitoring instrumentation, to evaluate the actual rate of the concrete expansion and, carrie out some laboratory tests to determine physical, chemical, mechanical, and elastic properties of concrete samples.

There are several papers published ([5], [6], [7], [8]) about the results of some of the investigation campaigns on the AAR affected concrete of Paulo Afonso Complex plants. This paper presents recent results of some mechanical and elastic properties tests on extracted cores from the

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intake and the spillway of PA IV hydropower plant. Another paper in this conference presents the results of how AAR concrete influences creep [9].

## 2 MATERIALS AND METHODS

### 2.1 General

The cores were drilled from the concrete structures of the intake and spillway of PA IV hydropower plant, by rotative diamond drilling equipment and water cooled, with 200 mm diameter. The concrete cores were immediately wrapped in a PVC film after removal from the plant structures. In such conditions, they were placed in wooden boxes and shipped to the laboratory, for the tests series.

The location of the boreholes was as follows:

- Intake - Cores TA 1 to 3, on the top of blocks 3, 5 and 8 (el. 254.25 m), respectively, with 2 m in vertical depth.
  Cores TA 4, 5 and 7, on el. 230.25 m of the intake blocks 3, 5 and 8, respectively, with 2 m in the transverse depth from downstream face.
  Cores TA 8 to 10, on el. 226.00 m of the intake blocks 3, 5 and 8, respectively, with 2 m in the longitudinal depth on the concrete anchor block of the penstocks.
- Spillway - Cores VE 1 to 3, on el. 241.20 m of piers 1, 4 and 6, respectively, with 2 m in vertical depth.
  Cores VE 4 to 6, on el. 242.50 m of piers 1, 4 and 6, respectively, with 2 m in transverse depth from downstream face.

### 2.2 Concrete Composition and Mixture Proportion

Petrographic analyses indicated that the coarse aggregate had a predominant rock lithology of pink porphyritic granite, followed by protocataclasites derived from fragile strains in granite rocks. Moreover, it was observed with less intensity, rocks with dark colors formed by amphibole, biotite, and plagioclase. The minerals considered with reactive potential from the point of view of AAR, were quartz with undulatory extinction and microcrystalline quartz.

The petrographic analyses indicated that the fine aggregate is natural sand, with angular roundness grains, and the main mineralogies are quartz and feldspar.

The concrete used in PA IV plant were produced with Ordinary Portland cement, without any mineral admixture or addition, and with a total $Na_2O$ equivalent alkali content of 1.0%. The concrete mixture proportion of the structural concrete used in the intake had a coarse aggregate with maximum dimension of 38mm, cement content of 273 kg/m$^3$, w/c ratio of 0.50 and average compressive strength at 28 days of 22.5 MPa. The concrete mix of the spillway had a coarse aggregate with maximum dimension of 38mm, 273 kg/m$^3$ of cement, w/c ratio of 0.52 and average compressive strength at 28 days of 24.9 MPa.

### 2.3 Methods for assessment and analysis

The tests carried out, among others, were: compressive strength, splitting tensile strength, elasticity modulus and Poisson ratio. The testing procedures were based on standards NBR 5739 [10], NBR 7222 [11], NBR 8522 [12] and ASTM C 469 [13], respectively, for each of the tests listed above. These testing procedures are similar to ASTM C39 [14], ASTM C496 [15] and ASTM C 469 [13], respectively.

The tests were performed on drilled cylindrical cores measuring 150 mm x 300 mm, extracted from the intake and spillway structures. The cores were sawn and had their tops rectified. The samples were stored in a wet chamber at 23°C and 95% of relative humidity, until the test date.

The load applied on the cores from the intake and spillway for the elasticity modulus and Poisson ratio test was 8 MPa and 12 MPa, respectively. Strains were measured with LVDT extensometer attached to the cores with elastic rings which compresses the ends of the extensometer against the concrete and being able to read from 0.0 to 2.5 mm and having a resolution of 0.001 mm. The Poisson ratio was determined through readings of strains by means of a micrometer with precision of 0.001 mm.

## 3 RESULTS

Figure 1 shows graphs comparing values for compressive strength, splitting tensile strength, elasticity modulus and Poisson ratio of the concrete in the intake and spillway structures of PA IV, each value (bar) representing the average results for a hole. Some of the results were published in [2] and [8]. Table 2 shows the individual and average values of compressive strength. Table 3 shows the individual and average values of tensile strength and Table 4 shows the individual and average values of elasticity modulus and Poisson ratio for each hole.

## 4 DISCUSSION

### 4.1 Compressive Strength

In order to check the influence of the AAR in the compressive strength, the results of the cores drilled from the 28 year old structure, were compared with the average compressive strength at 28 days, of samples casted and tested during the construction. The later had their results extrapolated to 28 years using a correlation for the growth of strength. This equation was proposed by Helene [16]. Equation (1) describes the expression of the correlation used, which is a function not only of time and type of cement, but also of the w/c ratio. This correlation can be extended for the prediction of concrete growth.

$$\text{Log}\,(f_{ccj}/f_{ccm28}) = k_9 + k_{10} \text{ x } 1/t^{1/2} \quad (1)$$

Where:
$f_{ccj}$ = concrete strength at j days age, using a type of cement and w/c ratio.
$f_{ccm28}$ = average compressive strength of the concrete at 28 days , using a type of cement and w/c ratio.
$k_9$ e $k_{10}$ = coefficients that are function of the type of cement and the w/c ratio used.

Although, other correlation equations exist for the growth of strength along time, as the one proposed by CEB [17], it was adopted the equation proposed by Helene [16] because the cements used to obtain this correlation were from Brazilian cement industry on the 70s and 80s, and some of them had similar characteristics to the ones used in PA IV.

For the intake concrete, the cement characteristics were Ordinary Portland cement CP 32 and w/c ratio of 0.50, so the growth of compressive strength at 28 years is 41%. As the average of compressive strength at 28 days was 22.5 MPa, using the correlation proposed by Helene [16], at 28 years the concrete would have a compressive strength of 31.6 MPa. Doing the same analyses for the structural concrete of the spillway, there is a growth of 42%, and the concrete would have a compressive strength of 40.6 MPa at 28 years.

The average of the results of compressive strength for PA IV are close to the values provided by the equation (1), suggesting that the AAR had a small effect on the compressive strength of the concrete, although the universe studied is not significant statistically. Table 1 shows the average of compressive strength of the samples from PA IV, as well as the compressive strength predicted for the concrete by the equation (1).

The places where the samples were drilled , was visually investigated for AAR symptoms. There was no advanced level of deterioration on the concrete structure due to AAR. This might justify the fact that there isn't an important reduction of compressive strength.

Some authors published different behavior for compressive strength in concrete with AAR. It depends, among other factors, on the concrete expansion. Castro et al. [18] compared some mechanical and elastic properties of a concrete with AAR from Furnas 32 years old hydropower plant, with a concrete made at the laboratory with the same mixture, but without AAR, and observed that the compressive strength was reduced due to the AAR. Studies developed by Smaoui et al. [19] on mechanical properties of concrete mixed at the laboratory, with different reactive aggregates, submitted to treatment to accelerate the development of AAR , shows that the compressive strength reduces 16% when comparing the values of the samples with 0.1% of expansion and the ones without expansion. Hasparyk [20] developed studies in samples drilled from the foundation gallery in the spillway of Furnas plant. She classified, according to visual inspection the concrete in three levels of deterioration, showing that the compressive strength increases on the concrete classified as medium deterioration, and decreases for the concretes classified as more deteriorated and as less deteriorated, indicating the influence of the deterioration level in the compressive strength values.

### 4. 2 Splitting Tensile Strength

Figure 3 shows the correlation between splitting tensile and compressive strength. Each point of the graph corresponds to the average values of a particular hole, in a given power plant. Figure 3 shows also the results of previous investigations, published in [8]. The statistic universe investigated is not significant and can only indicate a trend of behavior.

The NBR 6118 Brazilian standard [21], correlates splitting tensile and compressive strength by the equation showed on Figure 3. It can be observed that the values obtained with the concrete samples are lower than the theoretical curve.

The concrete samples affected by AAR investigated do not have an important drop in compressive strength, so the loss observed on Figure 3 is related to the loss in splitting tensile strength. This fact shows that the splitting tensile strength is more affected by the AAR.

Other results about the influence of AAR on the splitting tensile strength of concretes were published by other authors, like Smaoui et al. [19] that show a reduction of 24% on the splitting tensile strength in concretes with an expansion of 0.1%, as compared with the same concrete without expansion. The authors comment the cracking influence on the samples surface in the tensile strength, showing that the deterioration level of the concrete and the cracking distribution influences the mechanical properties. The cracking and expansion levels, in fact, may justify different behavior on the tensile strength of concretes affected by AAR.

### 4.3 Elasticity Modulus and Poisson Ratio

Figure 3 shows test results and the correlation between compressive strength and elasticity modulus according to the equation proposed by the NBR6118 Brazilian Standard [21], similar to ACI 318 [22]. Each point of the graphic corresponds to the average values of a particular hole, in a given powerplant.

It is possible to notice that the concrete of the spillway and the vertical holes of the intake, which were extracted from high humidity areas, present the same behavior as the concrete structures of PA I, PA II and PA III, affected by AAR and previously investigated [8]. A decrease of 30% on the elasticity modulus of the concrete was observed. For the concrete of the longitudinal and transverse holes of the intake, located in a dryer part of the structure, a similar behavior to the one proposed by the equation of the standard NBR 6118 [21], can be observed suggesting lower influence of AAR in this property. According to studies by Hasparyk [19], by modeling data from AAR affected concretes, it was verified a reduction about 46% in the elasticity modulus in 35 years of deterioration.

Figure 1 shows that the Poisson ratio values for the concrete affected by AAR are similar to those obtained in sound concrete and published in the literature that ranges from 0.15 to 0.22 [23], suggesting that this property has not been significantly affected.

## 5 CONCLUSIONS

The main conclusions of this paper are:

- Alkali-aggregate reaction is heterogeneous: different cores of the same concrete affected by AAR can present totally different values when tested in laboratory; visual inspections can show completely different patterns of the same concrete that is affected by AAR. Observing visually the places investigated in this study, many features of AAR were noticed, for example, pores filled with white materials, dark rims surrounding aggregate and cracking on the aggregate. Just some centimeters apart, none of these features were detected.
- The average results of compressive strengths are close to the expected values for 28 years provided by the equation (1), suggesting that the compressive strength of the concrete was not significantly reduced due to AAR, although the reduced number of studied samples is not enough to allow a firm conclusion.
- The average results of splitting tensile strength are lower than the equation proposed by the NBR 6118 Brazilian Standard [21], indicating that the concrete expansion affect this property.
- Finally, the elasticity modulus test results showed two patterns: concrete of the spillway and the vertical holes of the intake, which were extracted from areas with high humidity, presents a reduction of 30% on the elasticity modulus of the concrete. For the concrete of the longitudinal and transverse holes of the intake, located in a dryer part of the structure, was observed a behavior similar to the one predicted by using the NBR 6118 [21] model, suggesting a lower influence of AAR in this property.

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TABLE 1: Paulo Afonso hydropower plants features.

| Power Plant | Starting year | | Generating units | |
|---|---|---|---|---|
| | Construction | Exploration | Quantity | MW/unit |
| PAI | 1949 | 1954 | 03 | 60 |
| PAIIa | 1955 | 1961 | 03 | 75 |
| PAIIb | 1961 | 1967 | 03 | 85 |
| PAIII | 1967 | 1971 | 04 | 216 |
| PAIV | 1972 | 1979 | 06 | 410 |
| Moxoto | 1971 | 1977 | 04 | 110 |

TABLE 2: Compressive strength test results and predicted values.

| Core / Hole | Depth (m) | Compressive strength (MPa) | | |
|---|---|---|---|---|
| | | Individual | Average | Estimated by eq. (1) |
| TA1 (vertical) | 0-0.4 | 33.2 | 35.5 | 31.6 |
| | 0.4-0.8 | 39.2 | | |
| | 0.8-1.2 | 34.1 | | |
| TA3 (vertical) | 0-0.4 | 42.1 | 39.6 | |
| | 0-0.4 | 37.0 | | |
| TA4 (horizontal - transverse) | 0-0.4 | 31.7 | 31.8 | 31.6 |
| | 0.4-0.8 | 31.8 | | |
| TA7 (horizontal - transverse) | 0-0.4 | 29.2 | 29.6 | |
| | 0.4-0.8 | 29.9 | | |
| TA8 (horizontal - longitudinal) | 0.6-1.0 | 34.9 | 36.9 | 31.6 |
| | 1.0-1.4 | 38.9 | | |
| TA10 (horizontal - longitudinal) | 0.3-0.7 | 25.2 | 26.7 | |
| | 0.7-1.1 | 27.2 | | |
| | 1.1-1.4 | 27.7 | | |
| VE1 (vertical) | 0.8-1.2 | 44.4 | 42.8 | 40.6 |
| | 1.5-2.0 | 41.1 | | |
| VE3 (vertical) | 0.3-0.7 | 37.0 | 37.0 | |
| VE4 (horizontal - transverse) | 0.3-0.6 | 42.7 | 41.6 | |
| | 0.6-1.0 | 40.5 | | |
| VE6 (horizontal - transverse) | 0.4-0.8 | 36.7 | 36.7 | |

TABLE 3 – Splitting tensile strength test results.

| Core / Hole | Depth (m) | Splitting tensile strength (MPa) | |
|---|---|---|---|
| | | Individual | Average |
| TA3 (vertical) | 0-0.4 | 3.3 | 2.8 |
| | 0-0.5 | 2.9 | |
| | 0.5-0.8 | 2.2 | |
| TA7 (horizontal - transverse) | 1.2-1.7 | 2.7 | 2.7 |
| TA8 (horizontal - longitudinal) | 0-0.3 | 2.4 | 2.7 |
| | 0.3-0.6 | 2.9 | |
| VE1 (vertical) | 0-0.4 | 3.7 | 3.5 |
| | 0.4-0.8 | 3.3 | |
| VE3 (vertical) | 0-0.4 | 3.0 | 2.9 |
| | 0.4-0.8 | 2.8 | |
| | 0.7-1.1 | 2.5 | |
| | 0.7-1.1 | 3.2 | |
| VE4 (horizontal - transverse) | 1.0-1.4 | 2.5 | 2.5 |
| VE6 (horizontal - transverse) | 1.7-2.1 | 2.4 | 2.4 |

TABLE 4 – Elasticity Modulus and Poisson ratio test results.

| Core / Hole | Depth (m) | Elasticity Modulus (GPa) | | Poisson ratio | |
|---|---|---|---|---|---|
| | | Individual | Average | Individual | Average |
| TA1 (vertical) | 0-0.4 | 23.0 | 22.8 | 0.20 | 0.19 |
| | 0.4-0.8 | 20.9 | | 0.18 | |
| | 0.8-1.2 | 24.4 | | 0.20 | |
| TA3 (vertical) | 0-0.4 | 25.4 | 21.9 | 0.18 | 0.18 |
| | 0.4-0.8 | 18.4 | | 0.17 | |
| TA4 (horizontal - transverse) | 0-0.4 | 24.1 | 25.7 | 0.18 | 0.17 |
| | 0.4-0.8 | 27.4 | | 0.16 | |
| TA7 (horizontal - transverse) | 0-0.4 | 30.7 | 29.2 | 0.18 | 0.18 |
| | 0.4-0.8 | 27.7 | | 0.17 | |
| TA8 (horizontal - longitudinal) | 0.6-1.0 | 29.0 | 30.1 | 0.22 | 0.22 |
| | 1.0-1.4 | 31.2 | | 0.21 | |
| TA10 (horizontal - longitudinal) | 0.3-0.7 | 23.6 | 26.4 | 0.17 | 0.19 |
| | 0.7-1.1 | 27.9 | | 0.20 | |
| | 1.1-1.4 | 27.7 | | 0.19 | |
| VE1 (vertical) | 0.8-1.2 | 23.0 | 24.9 | 0.21 | 0.21 |
| | 1.5-2.0 | 26.8 | | 0.21 | |
| VE3 (vertical) | 0.3-0.7 | 18.6 | 18.6 | 0.18 | 0.18 |
| VE4 (horizontal - transverse) | 0.2-0.6 | 24.4 | 24.2 | 0.18 | 0.18 |
| | 0.6-1.0 | 24.0 | | 0.17 | |
| VE6 (horizontal - transverse) | 0.4-0.8 | 20.0 | 20.0 | 0.21 | 0.21 |

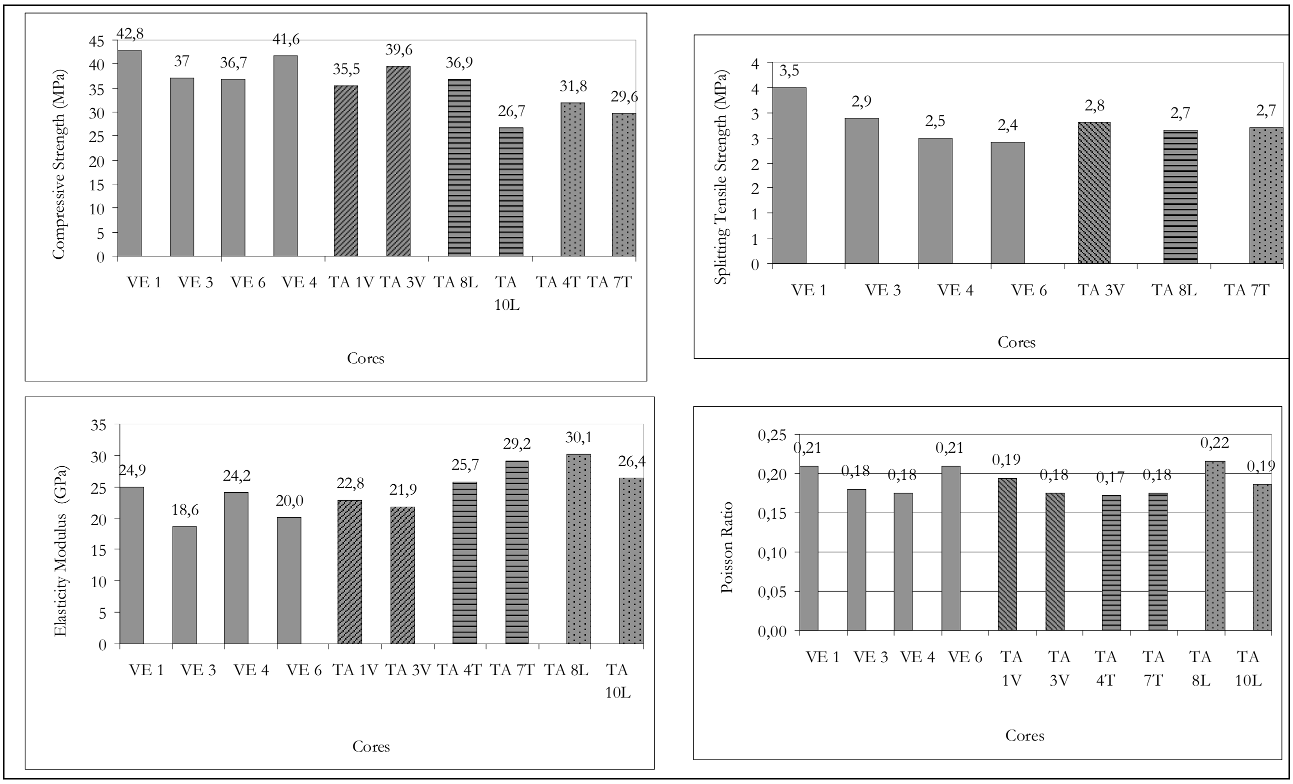


Figure 1: Average test results for compressive strength, splitting tensile strength, elasticity modulus and Poisson ratio.

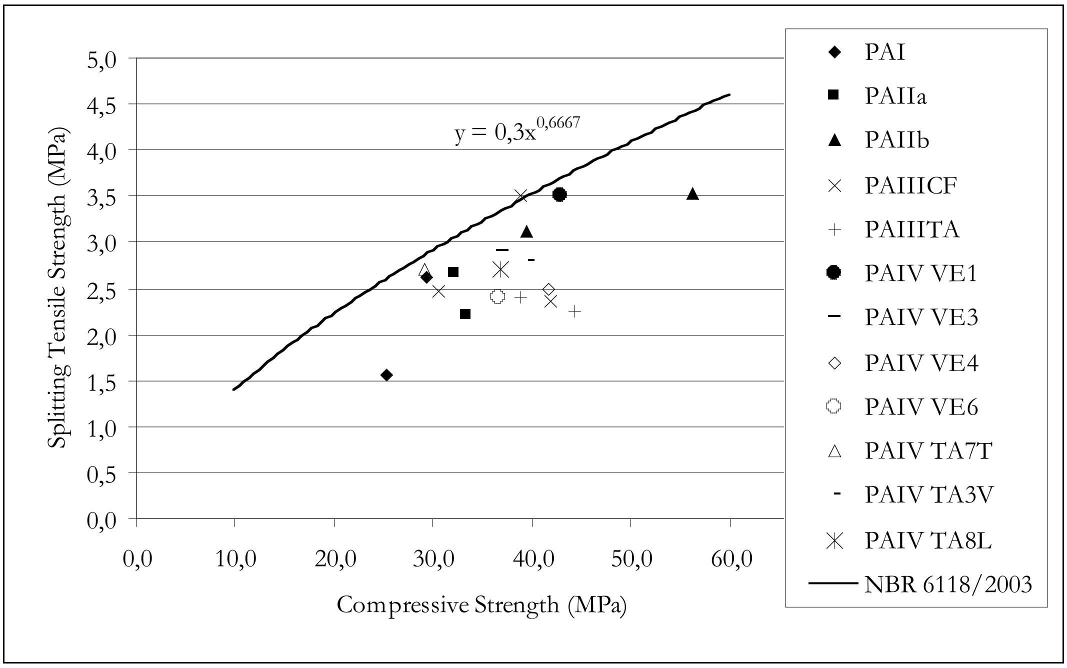


Figure 2: Compressive strength and splitting tensile strength comparison.

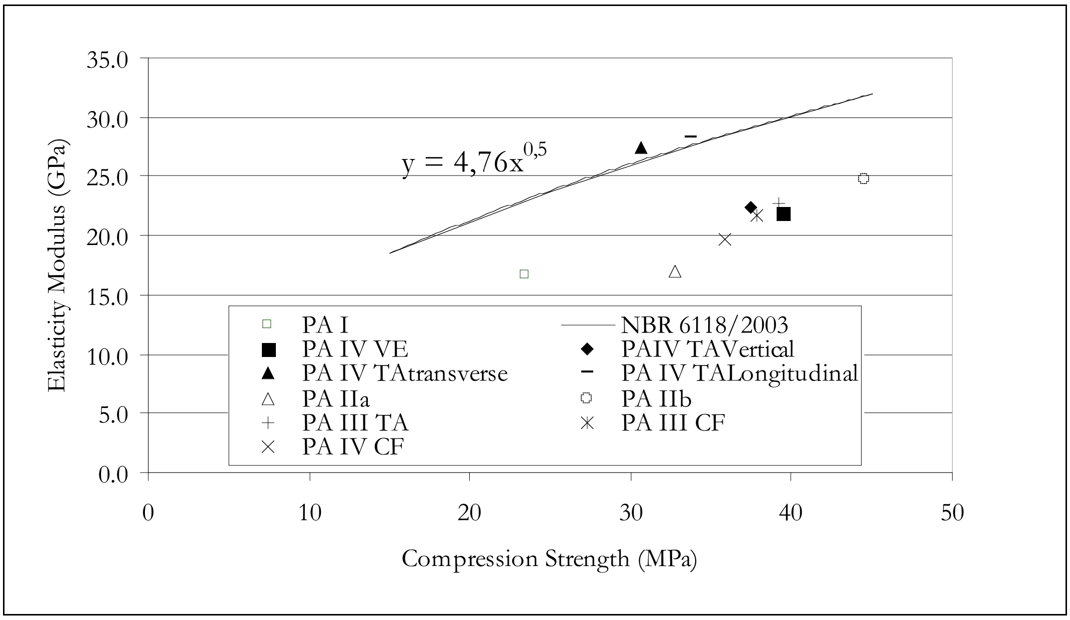

Figure 3: Compressive strength and Elasticity Modulus comparison.