# Effectiveness of nondestructive tests for assessing AAR-damage in the laboratory

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**Abstract**

A new nondestructive test has been developed for characterizing AAR-damage, based on the particular behavior of AAR cracks submitted to dynamic loading. The swelling gel produced by alkali-silica reaction, which partially or totally fills the cracks, influences the concrete response to external excitation, such as compression waves or vibrations. This paper presents a comparative study of both linear and nonlinear acoustic techniques to assess damage associated with AAR in cores collected from specimens exposed outdoors. Tests were carried out on cores drilled from different concrete blocks exposed at an experimental site located in Austin, Texas. These blocks were cast with one nonreactive aggregate and various reactive aggregates and (an alkali-carbonate reactive dolomitic limestone from Kingston-Canada and three types of reactive aggregates from the U.S.). The cores were drilled from blocks that had reached different expansion levels. The results showed that nonlinear acoustics appeared to be very sensitive to early AAR-damage compared with linear techniques. Results also suggested that nonlinear acoustics may distinguish alkali-silica damage from alkali-carbonate damage.

**KEYWORDS:** nondestructive testing, damage, monitoring, nonlinear acoustics

## 1 INTRODUCTION

The goal is to find out about conditions of the structure as a part of regular maintenance, to have estimation for repairing/rehabilitating the damaged part or to select the best option of repair method. Therefore, a reliable inspection with good judgment is necessary to evaluate probable AAR-damage in terms of amount and extent. To do so, some destructive and non-destructive test methods (DT and NDT, respectively) are used to qualify and/or quantify concrete engineering properties, to detect imperfections, weaknesses and deterioration in existing structures. DTs commonly are expensive and time-consuming, and may provide limited information in some cases. For instance, for detecting propagation and intensity of ASR in a hydraulic structure, several cores should be drilled through the depth in order to have a complete view about ASR damage. Therefore, NDTs have progressively been developed for concrete despite an inherently heterogeneous composition of this material; it is because of benefits of NDTs (rapid, comprehensive, and economic) in comparisons with DTs [1]. For example, Rivard et al. [2] used NDT methods (seismic tomography) for assessing an ASR-affected hydraulic structure. They showed the capabilities of such methods for monitoring concrete structures if they are developed and modified effectively.

Among different methods aiming at detecting cracks in concrete structures, acoustic methods using stress wave propagation have been utilized several times. Acoustic methods are considered into two main categories of linear and nonlinear methods. Linear approaches like ultrasonic pulse velocity or linear resonant frequency are very difficult to judge about the state of microdamage in materials; because linear methods is less sensitive and need materials initial state, e.g. the ultrasonic wave velocity in the sound material.

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Oppositely, the nonlinear technique is more sensitive to microdamage than the linear technique; and this sensitivity ranges from micro to macro [3]. The main advantage of nonlinear acoustic techniques is that this approach not only takes into account linear parameters in the elastic medium but also considers the influence of perturbation of medium on propagation of waves. In this way, theoretically, there is no need to have historic information to evaluate damage in a given concrete member. Moreover, linear methods do not consider perturbation of medium on the waves and, consequently, they are not very sensitive in early detection of damage mechanisms. Nonlinear approaches, e.g. nonlinear attenuation, harmonic generation, resonant frequency shift, slow relaxation dynamics, have been used for characterizing constituent materials like rocks, but they are new approaches in detection of the AAR-damage in cement based materials [4-8].

This paper presents a comparative study between nondestructive measurements of AAR-damage on cores drilled from concrete blocks exposed in outdoor environmental conditions and some destructive measurements. These concrete blocks were fabricated with aggregates from different regions of the US and Canada showing different reactivity degrees. Both linear and nonlinear acoustic techniques were used as the NDT to study AAR development in concrete cores. Both types of AAR (ASR and ACR) were observed in concrete cores. ASR is a complex reaction that alters silica (e.g. microquartz, chalcedony, etc.) and leads to the formation of a swelling gel. Oppositely, ACR is a reaction between the alkali hydroxides of the concrete pore fluid and the dolomite crystals that undergo a dedolomitization process [9]. The results showed a relatively good correlation between NDTs (especially frequency shift, a nonlinear acoustic technique) and DTs.

## 2 PREPARATION INVESTIGATION OF CONCRETE BLOCKS AND CORES

Concrete blocks, nominally 400 × 400 × 700 mm in size, were made at the University of Texas at Austin, US using different types of reactive aggregates. For each type of aggregate, four blocks were made and were then placed on the outdoor exposure site. Nonreactive (Carbonate limestone), moderately reactive (Quartzite) and highly reactive aggregates (Siliceous and Dolomitic limestone, Greywacke and Chert as coarse aggregates and Cherty sand in one of the mix designs as a fine reactive aggregate) from different locations of the US and one from Ontario, Canada were used to fabricate the blocks. This paper presents the results for highly reactive aggregates only (Table 1). To accelerate the rate of the reaction, a control high-alkali ASTM Type I portland cements as well as NaOH solution (boosted to 1.25% $Na_2O_{eq}$) were used in all the concrete mixtures. The nominal cementitious materials content for all concrete mixtures was 420 ± 10 kg/m$^3$ with the water-to-cement ratio of about 0.45 (instead of 0.42 as stated by the standard) .

Changes in lengths of the concrete blocks were monitored by manual method of Demec measurement and development of ASR was monitored by both linear and nonlinear acoustics methods). At selected expansion levels, i.e. approximately 0.05%; 0.10%; 0.20% and 0.30%, cores were drilled from each block and subjected to a series of NDTs (both linear and nonlinear acoustic tests). To assess the progress of ASR-damage, two linear acoustic tests of ultrasonic pulse velocity (UPV) according to ASTM C 597-97 [10] and linear resonant frequency according to ASTM C 215-02 [11], as well as nonlinear resonant frequency were carried out on the concrete cores. Linear acoustics refers to propagation of mechanical waves of low amplitudes. These waves are very weak to induce enough deformations and consequently modify the elastic properties of materials. Linear acoustics, current NDT methods used in the field, are capable only of discriminating high states of damage. When microdefects due to AAR undergo loading, they begin to interact rapidly and larger cracks will coalesce and form rapidly; after this stage, any of the linear acoustic methods can reliably detect deteriorations [12]. At this stage, defects are usually large and significant and therefore, it is often too late and costly to repair the structure. For instance, pulse velocity method is a linear acoustic method. Pulse velocity is calculated from the travel time of the compressional wave propagated in a medium.

As mentioned above, the fundamental transverse and longitudinal resonant frequencies are used to calculate dynamic modulus of elasticity ($E_d$). By formulation in ASTM C 215-02 standard [11], both $E_{d-L}$ and $E_{d-T}$ can be calculated for concrete cores and then the average value ($E_{d-average}$) is considered for comparison. Sargolzahi et al. [6] studied the effect of ASR-damage on the dynamic modulus of elasticity. According to this work the dynamic modulus showed no significant sensitivity to ASR expansion. After 5 months of exposure in damp environment at 38°C, this value decreased by about 6%. Then, a slight decrease was observed and finally minimum values were reached after 17 months, a total decrease of about 17%. This value remained approximately constant from 17 months, representing despite ongoing expansion in the specimens.

Unlike the linear technique, there is no standard methodology for nonlinear resonant frequency shift method, but there is a good experience for using the test for monitoring ASR-damage [6-8 & 13]. In this method, the sample is driven from low amplitude to high amplitude signal while the amplitude dependence of sample resonant frequency is tracked. Damage increase leads to the increase of the nonlinear behavior that is manifested by an increase in the sample resonant frequency shift. Accordingly, higher states of damage associated with ASR yield higher shift in nonlinear resonant frequency. No results have been found regarding ACR.

## 3 RESULTS AND DISCUSSION

### 3.1 Ultrasonic pulse velocity and linear resonant frequency

Ultrasonic pulse velocity is related to concrete quality and it can be used to assess damage related to ASR. However this method appears to be less sensitive to ASR damage [6]. Figure 1 shows the correlation between expansion of the concrete blocks and ultrasonic pulse velocity of cores extracted from them. The pulse velocity smoothly decreased with ASR expansion. Similar results were observed for the relation between the block expansion and the dynamic Young modulus (Figure 2). With pulse velocity test, previous experience by Sargolzahi et al. [6] showed a decrease of only 7% in pulse velocity on lab specimens that had reached a high level of expansion of 0.13%. It can be inferred that this test was no sensitive to growth of ASR cracks in the early stage. Van Hauwaert et al. [12] also studied crack growth in mechanical test on concrete cubes reinforced by steel fibers and they could not find any change in UPV before the crack reached a width of 100μm. In this study, the UPV are over 4000 m/s$^2$ on the cores (except one case). Despite the high expansion of the concrete blocks, the velocities are compatible with fairly high quality concrete. Indeed, the pulse velocity has negligible sensitivity to microdefects in concrete and normally begins to change when large fractures and cracks are forming. According to Figure 2, there is no clear relation is between degree of expansion and the dynamic Young modulus, but for reliable comparison, knowing the initial values would be very important because the values extracted by linear methods are mostly comparative values.

### 3.2 Nonlinear resonant frequency

The concrete cylinder is excited with a pure sine wave by increase excitation voltage. For each voltage, a frequency sweep was performed to find the specimen resonant frequency. The signal was produced by a low frequency generator Agilent 33250A. The signal is amplified in order to drive the piezoelectric actuator that excited one end of the specimen. At the other end, an ICP accelerometer detected the signal after its propagation through the specimen. The signal detected by the accelerometer is conditioned before being converted to digital signal by the computer.

Figure 3 shows the amplitude dependence of resonant frequency for one of the cores drilled from one of the concrete blocks. According to the equation 1, there is a linear relationship between deformation ($\Delta\varepsilon$) and resonant frequency shift ($\Delta f$).

$$\alpha \Delta \varepsilon \approx \frac{\Delta f}{f_0} \qquad \text{Eq.1}$$

Nonlinear parameter $\alpha$ is calculated by plotting the frequency shift as a function of fundamental mode strain amplitude Figure 4 shows an example of the curve of resonant frequency shift vs. strain (deformation) for concrete cores fabricated with reactive aggregates. A similar method was used to calculate the nonlinear parameter for different aggregates with various degrees of reactivity. Figure 5 shows the nonlinear parameter for the cores incorporating different reactive aggregates compared with non reactive concrete. As expected, nonlinearity is much higher in reactive concrete than in nonreactive concrete. The nonlinear parameter increased with the global expansion of the concrete blocks; except for block J (reactive sand) where $\alpha$ shows variations that were not in accordance with expansion. No explanation could have been provided for this behavior. It might be related to the particular nature of this highly reactive sand.

Interesting results are observed from concrete cores incorporating dolomitic limestone Kingston aggregate (K), which is damaged by Alkali Carbonate Reaction (ACR). This aggregate was introduced as a highly sensitive aggregate for ACR by Fournier and Bérubé [9].The petrographic analysis show cracks but no gel was observed, and therefore its nonlinear behavior, is clearly more important. That can be explained by the fact that ASR gel, due to its viscosity reduces the opening of the cracks, and consequently reduces the nonlinear behavior [5]. Concrete damaged by ACR presents empty cracks that make easy their opening/closing and nonlinearity behavior is therefore more significant.

In order to verify the effectiveness of the nonlinear resonant frequency shift, the results were compared with the results of petrographic examination (Damage Rating Index or DRI), carried out by Université Laval on the same concrete cores [14]. The DRI has turned out to be relevant and effective for the quantification of the internal deterioration caused by ASR. It consists in a petrographic examination performed on a polished concrete section with a stereomicroscope in order to identify and count defects associated with ASR [15]. Figure 6 shows the relation between DRI of the cores and the expansion of the concrete blocks and good correlation was observed between DRI on the cores and expansion of the concrete blocks. This is an exemption for the blocks P2, P3 and P4 because no significant changes were observed in DRI although expansions were relatively significant. This correlation is not limited to DRI-Expansion. Figure 7 shows that DRI generally increases with the nonlinear parameter. However, concrete cores from the blocks J1, J3, P2, P3 and P4 which shows the reverse relation; whereas the nonlinearity of the other cores grows with increasing the DRI. No explanations can be provided for now. The comparative study between the destructive tests and nonlinear acoustic method shows the reliability of the nonlinear acoustic method for detecting ASR-damage, where linear methods show no clear variations.

## 4 CONCLUSION

As defined previously, concrete is a nonlinear material (due to microdefects and heterogeneities) and because of microcracks caused by AAR, concrete increasingly behaves in a nonlinear way. In this research, ultrasonic pulse velocity method and dynamic Young modulus, as two linear methods, as well as nonlinear resonant frequency shift method were used to assess the propagation of ASR-damage. To do this, cores were drilled from the concrete blocks. The study showed that linear methods were less sensitive to propagation ASR; much more in initial stages of the reaction. Oppositely, the nonlinear method like nonlinear resonant frequency shift method was more sensitive to ASR-damage, especially in the initial stages of the reaction. The results showed that for the similar expansion level damage caused by ACR exhibit higher nonlinearity than that caused by ASR. These differences in its nonlinear behaviour might be a way to distinguish ACR damage from ASR damage. For instance, two types of cracking (due to ASR and due to ACR) were observed by the petrographic examination; whereas these were detected quantitatively by the nonlinear method, not qualitatively. Finally, it should be considered that nonlinear techniques are generally capable to detect damages in early age, although their sensitivities in some cases have limited their applications for monitoring defects in concrete structures.


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Table 1: Aggregates used in the test program

| **Aggregates** | **Rock type** | **Expansion in concrete blocks** |
|---|---|---|
| Jobe – Texas, (J) | Cherty sand | 0.04% - 0.28% |
| Massachusetts, (M) | Greywacke | 0.05% - 0.10% |
| Kingston – Ontario (Alkali carbonate reactive - ACR), (K) | Dolomitic limestone | 0.05% - 0.30% |
| Placitas – New Mexico, (P) | Gravel (chert; mixed volcanics) | 0.04% - 0.20% |
| Nonreactive aggregate | Limestone | - |

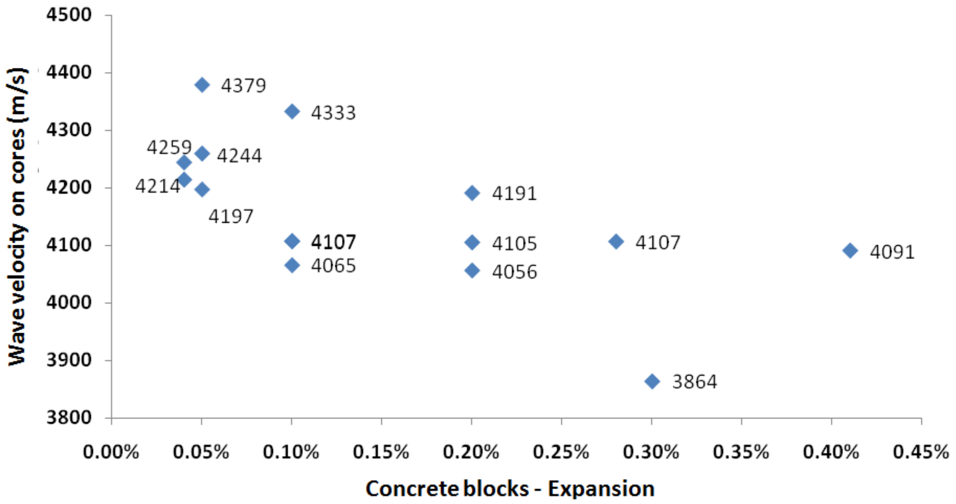


FIGURE 1: Correlation between ultrasonic pulse velocities measured on the cores and expansion of the concrete blocks and (all mixtures).

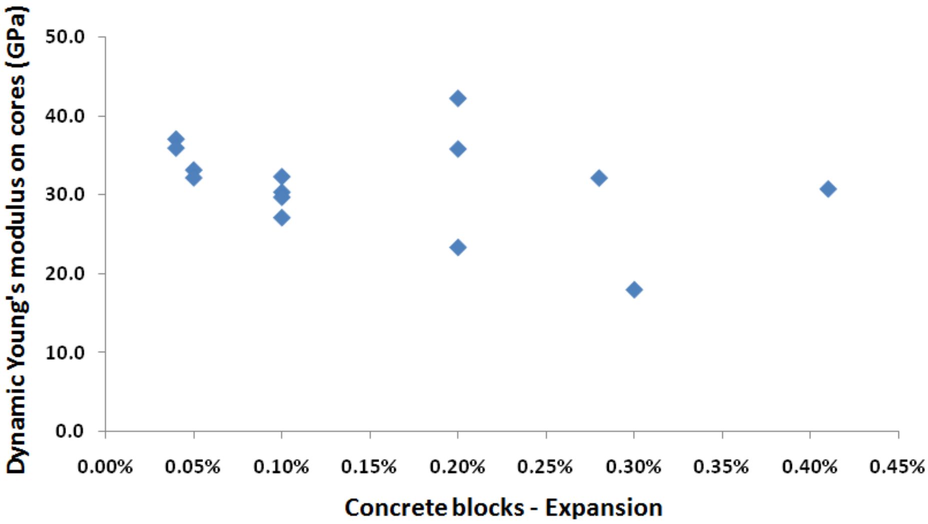


FIGURE 2: Relation between dynamic modulus of elasticity measured on cores and expansion of the concrete blocks (all mixtures)

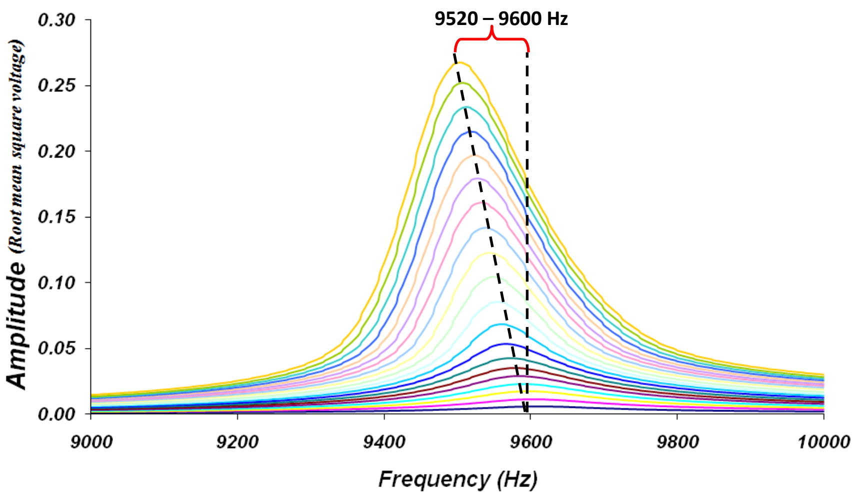


FIGURE 3: A diagram of frequency-amplitude for core J1-1

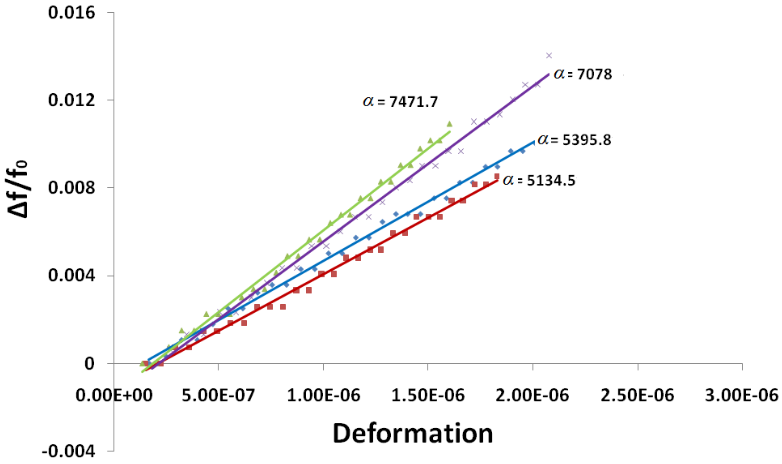


FIGURE 4: An example of the curve of resonant frequency shift – deformation for concrete cores made with cherty sand Jobe. The expansion of the concrete block was 0.28%. The unit of the deformation is (m/m).

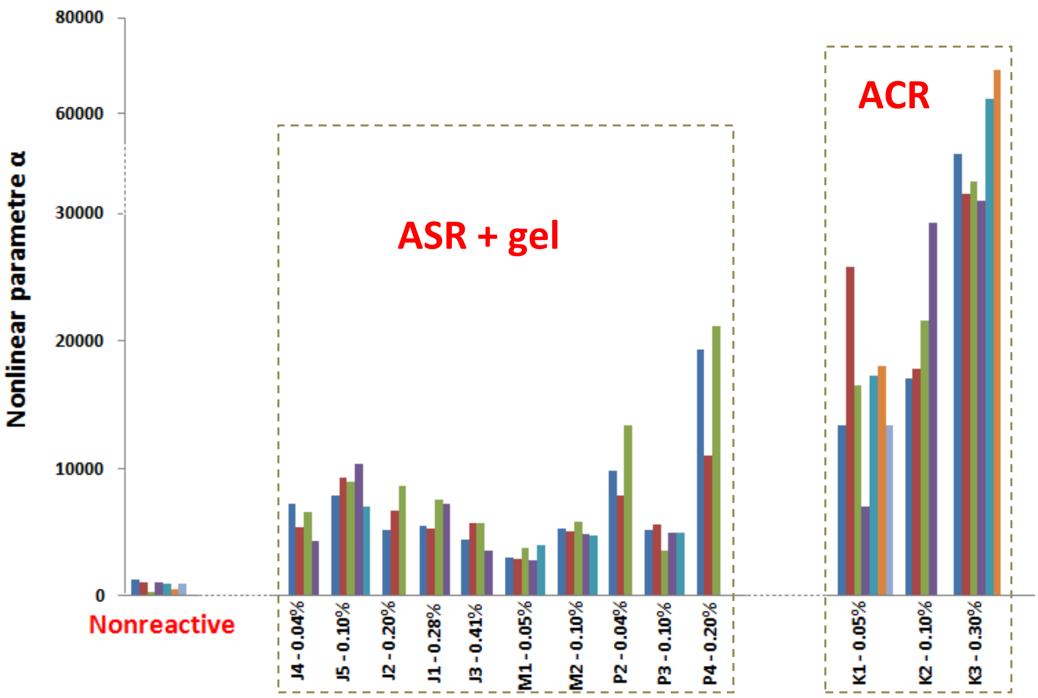


FIGURE 5: Frequency shift (nonlinear parameter α) for different aggregates with various degrees of reactivity. Expansion generally increases with expansion for every type of aggregate.

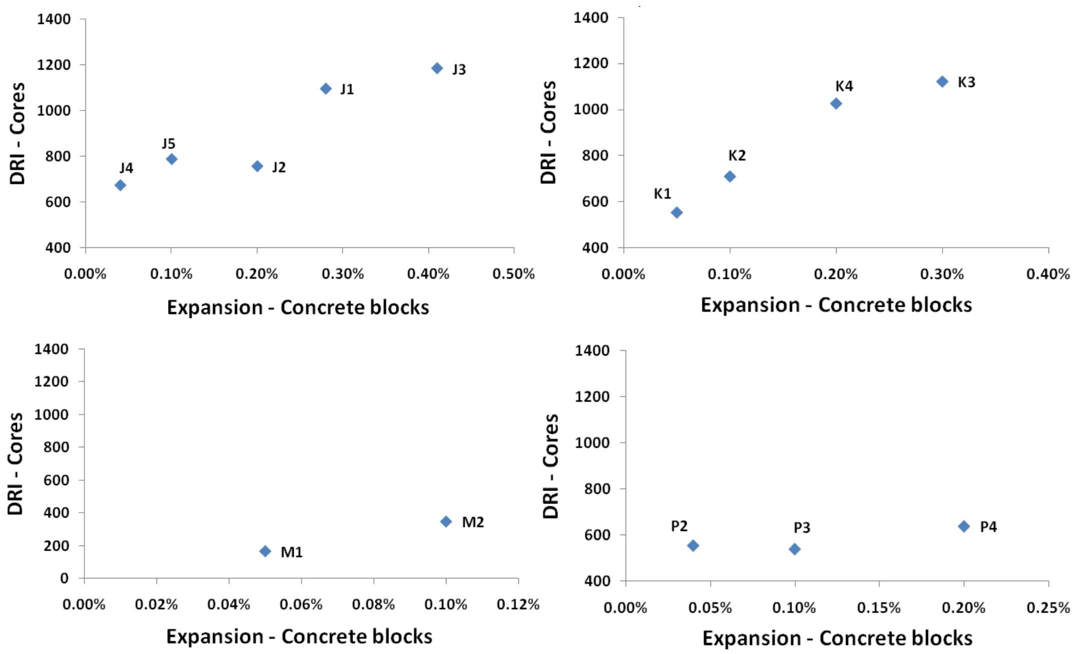

FIGURE 6: Relation between DRI of the cores and the expansion of the concrete blocks.

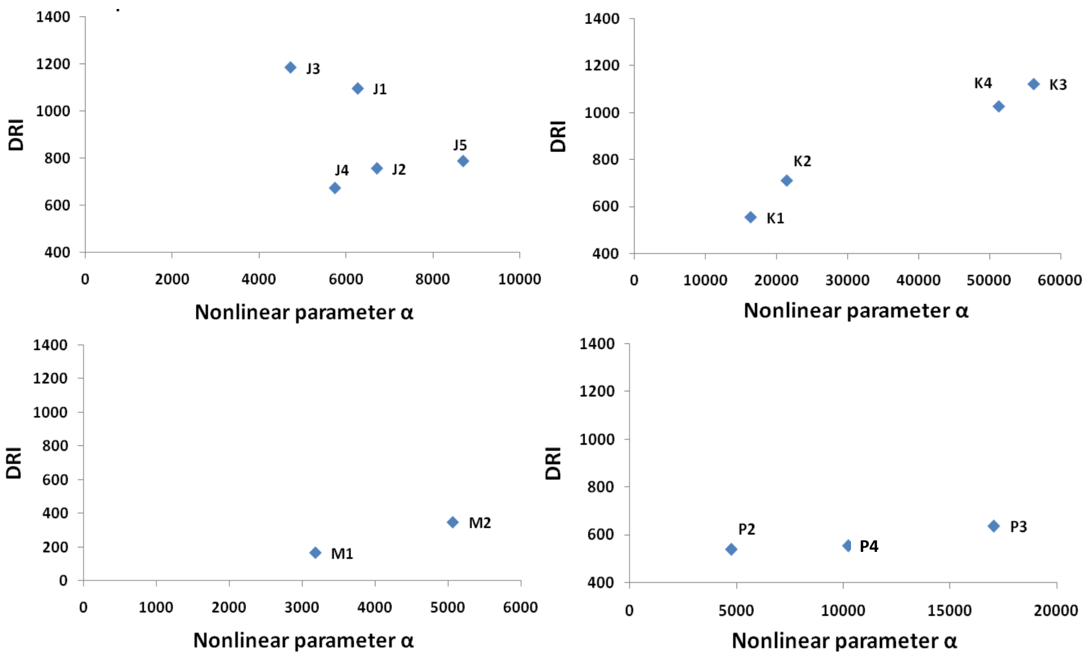

FIGURE 7: Comparison of DRI values and nonlinear parameter α