Mechanical properties of ASR affected concrete: a critical review

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Abstract: Alkali-silica reaction (ASR) in concrete can induce degradation to its mechanical properties, leading to compromised serviceability and even loss in load carrying capacity of concrete structures. Considering the importance of the problem, extensive studies mostly by means of experimental investigations have been carried out to gain understanding on impacts of ASR on the mechanical properties on both plain and reinforced concrete specimens. This paper presents a state-of-the-art literature review on published research related to mechanical properties of ASR-affected concrete, including mechanisms, influencing factors and evaluation procedures. In order to gain an insight into the effects of ASR on mechanical properties, a database has been established from a large number of experimental data published in open literature. Various empirical models that are commonly used to estimate the mechanical properties through measured ASR expansions are also reviewed and examined for their accuracy using the established database.

Keywords: Alkali-silica reaction, concrete, mechanical properties

1. Introduction

Alkali-silica reaction (ASR) has been identified as one of the major deterioration problems in concrete material and structures. ASR in concrete was first identified and studied by Stanton [1], then this reaction and its effect have been found in several countries worldwide [2]. In term of physical effect on concrete material, ASR causes expansion, cracking and changes in mechanical properties. All these effects consequently contribute to the degradation of serviceability, durability, and load carrying capacity of the concrete structures [3].

The formation and development of micro-cracking are commonly considered as the cause of material properties changes [2-5]. Due to the importance of concrete mechanical properties to structural integrity, serviceability and capacity evaluations, effects of ASR on the mechanical properties have been extensively studied by means of experimental, numerical and analytical studies. The evaluation of the degradation is commonly based on the ASR-induced expansion level. Most of the study agree that ASR causes degradation of each property, i.e. compressive strength, tensile strength and elastic modulus at different extents. According to Institution of Structural Engineers guidance (ISE), elastic modulus, compressive and tensile strength can be reduced up to 65%, 40% and 60% at 0.5% of expansion compared to 28-day properties, respectively [3]. However, based on the experimental investigation in several studies, the reduction of mechanical properties at any given expansion level highly varies from one study to others. Several empirical models have been proposed to estimate the reduction, however, fail to provide an accurate result [16].

This paper aims at providing a critical review of the degradation of concrete mechanical properties due to ASR based on the available experimental investigation and explanatory details on influential factors. In addition, the estimation of mechanical properties reduction based on different empirical models is compared to the available experimental data.

2. Mechanical properties of ASR-affected plain concrete under free expansion

The effects of ASR on mechanical properties of plain concrete under free expansion condition are commonly conducted by means of experimental research subjected to measurements of ASR-induced expansion. Based on the experimental observation, ASR induced degradation in elastic modulus and tensile strength is far more significant compared to compressive strength [6, 7]. However, the reduction extent of each property varies markedly from one to other testings, which depend on several factors. The following part presents more details in different experimental investigations of mechanical properties degradation due to ASR and influential factors.

One of the first and comprehensive guidance for ASR-affected concrete material and structures is from the Institution of Structural Engineers [3]. Based on numerous testing results from laboratory ASR-affected concrete specimens and cores extracted from structures, ISE [3] proposed the lower bounds of mechanical properties reduction of unrestrained concrete as compared to “unaffected” concrete strength at 28 days. The ISE lower bound is commonly adopted as a conservative assessment of ASR effect on concrete mechanical properties and its implication to structural capacity, such as in [8] and [9]. The lower bounds for elastic modulus, compressive and tensile strength are shown in Figure 1. It shows that modulus of elasticity and tensile strength are the most rapidly affected properties, even before significant expansion is attained, while the reduction of compressive strength is significant only at relatively high expansion levels. The degradation rate, however, tends to stabilize at high expansion levels, i.e. higher than 0.5% [10]. Regarding testing specimen, the guidance noted that the reduction of compressive strength once obtained from cylinder and core specimens are at a greater extent than that of the cube specimens.

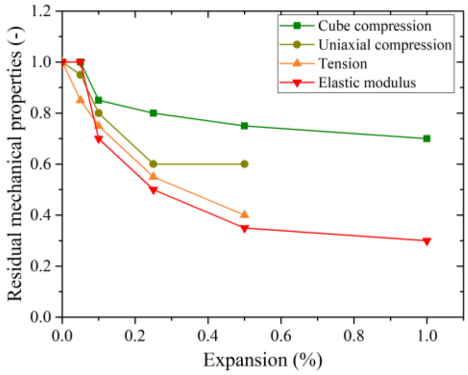
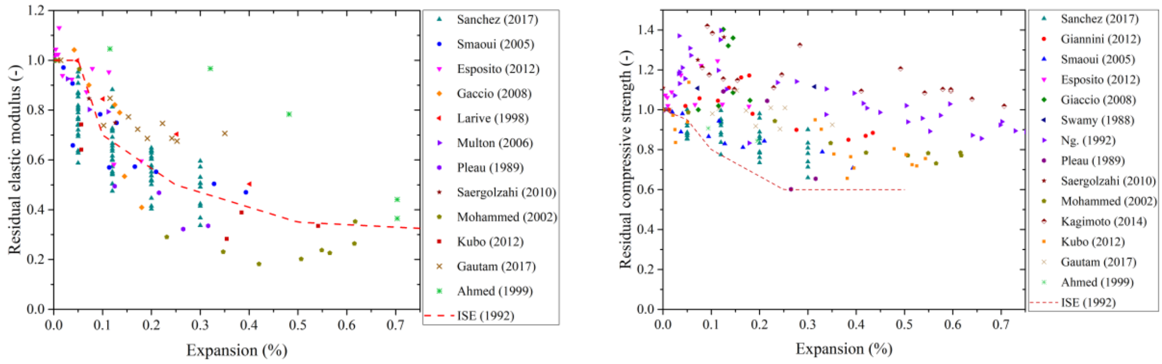


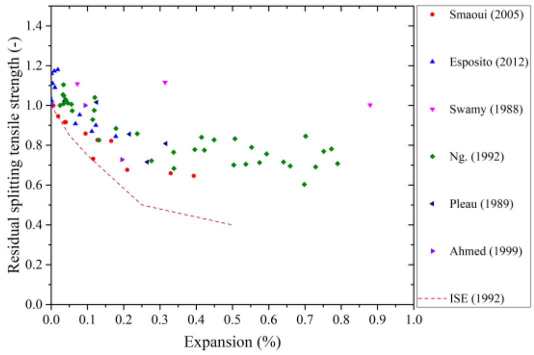
Figure 1. Lower bound residual mechanical properties as percentage of values for unaffected concrete at 28 days [3]

In addition to ISE [3], various experimental studies have been conducted to investigate mechanical properties degradation in relation to measured expansion. While several recommendations or standards have been established to provide evaluation procedures of the reactivity of aggregate to achieve consistent results, there is no specific guidance for testing of ASR effect on concrete mechanical properties. Testing and evaluation procedure of the “degradation” or “reduction” may differ from different studies. For example, the “undamaged strength” of control specimen can be measured at 7 days [11], 28 days [12, 13] of 38^0C curing, or at any curing duration of a low level of expansion [14]. Without experimental testing, this would bring out a major challenge in providing an estimation of the degradation level based on ASR-induced expansion.

To provide an overview on mechanical properties degradation in relation to expansion level, the experimental data from different studies have been collected and plotted with the lower bound from ISE [3], as shown in Figure 2. The strength and stiffness were normalized to the strength/stiffness of unaffected concrete measured at very low levels of expansions of less than 0.03% to represent the residual property. Sanchez et al. showed that the deteriorations of mechanical properties of concrete at this expansion level are negligible [6]. As mentioned previously, the results indicate the negative effect of ASR on material properties and the level of degradation is different from one property to another. Most of these studies agreed that the elastic modulus undergoes a significant reduction compared to splitting tensile strength or compressive strength. Thus, the elastic modulus has been commonly considered as an indicator of ASR-affected concrete deterioration [6, 15-17]. In addition, ASR development causes a remarkable reduction in splitting tensile strength while its effect on compressive strength is much less. In some testing groups, the compressive strength increases with increasing expansion up to 0.1%.



(a) Elastic modulus (b) Compressive strength



(c) Splitting tensile strength

Figure 2. Mechanical properties degradation in relation to ASR-induced expansion

In consideration of the proposed lower bounds for material properties reduction from ISE [3], it shows to be a safety margin for evaluation of compressive and splitting tensile strength. However, it is not applicable for the elastic modulus where many experimental testing groups induce a greater reduction than the lower bound. Furthermore, the strength and stiffness of free expansion specimens present a huge variation at any specific level of expansion. For instance, the elastic modulus is twice different at the expansion of 0.1 %, varies from 45 % to 90 % of the 28-day elastic modulus. These variations can be due to differences in several influencing factors, i.e. testing condition (i.e. temperature and humidity), type of reactive aggregate (i.e. size, rock type and reactivity), proportion of reactive aggregate and designed strength of concrete. Details on the effect of these factors are presented as follows.

In most of the previous studies, the degradation of mechanical properties also was at different levels according to different reactive aggregate types and nature which vary in size, rock type and reactivity level [12, 18, 19]. Sanchez et al. found that concrete mixes of reactive sands present earlier reductions of mechanical properties than that of reactive coarse aggregates concrete [20]. Reactive aggregates have been used in several countries worldwide which are different in rock type and their reactivity. In research of Kubo and Nakata [14], the reductions on the modulus of elasticity were greater than the lower bound proposed by ISE [3]. The author explained that typical reactive aggregates found in concrete structures deteriorated by ASR in Japan show rapid expansion and normal Portland cement made in Japan has faster hydration of cement than that of cement made in other countries. On the reactivity of aggregate, it is commonly evaluated through accelerated mortar bar test (AMBT) or concrete prism test (CPT) on standard mix design and aggregate grading based on the measured expansion at specific accelerated conditions and durations [21, 22]. However, for experimental studies in the literature, the utilisation of reactive aggregate for investigation of mechanical properties of ASR-affected concrete subjected to expansion measurements did not follow the same testing standard. Therefore, the effect of reactivity of different aggregate types on mechanical properties degradation is difficult to assess from the available databases.

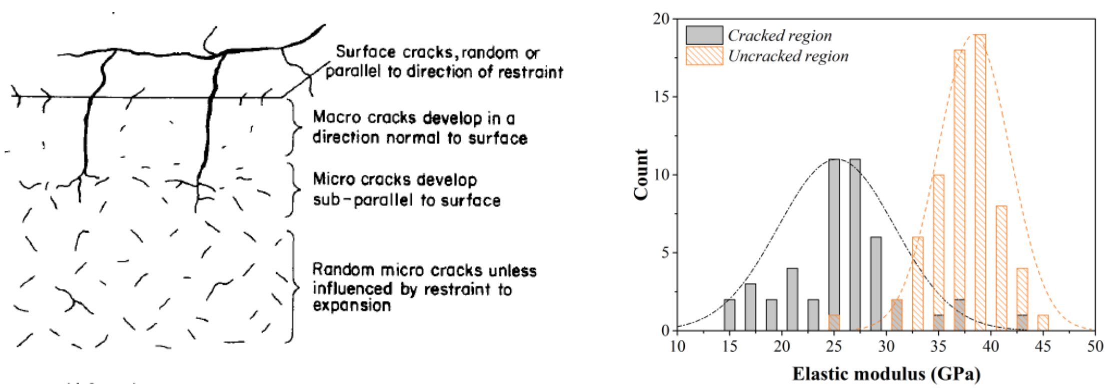
To accelerate the ASR rate in the laboratory testing, additional alkali is commonly added to mixing water of concrete mixes. Total amount of alkali content in a concrete mix is 1.25%, as recommended by many standards [21-23]. However, this number in the previous experimental testings for mechanical properties degradation due to ASR are different from one to others. Many studies indicate that of increasing alkali content in concrete can cause a negative effect to concrete properties [24-26]. Jawed and Skalny [25] suggests that increasing alkali content in the concrete reduce early and ultimate strengths. By investigating the effect of NaOH in reactive concrete, Shayan and Ivanusec [24] concluded that microstructure of concrete with higher alkali content was less dense compared to low alkali content concrete. Experimental study of Smaoui et al. observed that the high alkali concrete presents more reticular and porous microtexture, causing a reduction in strength. The temperature and mix proportion, which have been intensively investigated in relation to concrete properties, are crucial parameters in concrete strength design. The testing condition such as temperature and moisture affect not only the ASR-induced expansion as in ASR accelerated condition but also the strength evolution over time as curing procedure. In addition, mix proportion and designed strength also contribute to the strength and stiffness development of concrete material.

Due to the extensive differences of these influencing factors in experimental testing from the literature, it is difficult to compare and evaluate the degradation of mechanical properties due to ASR by considering only the expansion. In addition to expansion, the effects of different influencing factors on mechanical properties of ASR-affected concrete need to be further intensively studied to get a fundamental understanding.

3. Mechanical properties of concrete in confined elements and structures

ASR mechanism and its effect on concrete mechanical properties in confined elements and structures are far more complicated compared to free expansion small specimens. The confinement can be from external, loading or internal restraint from reinforcement (Noël et al., 2018). Concrete elements expand and crack more in the unrestrained direction, but less along the reinforcement and principal compressive stresses directions [3]. Indeed, as presented in ISE guidance [3] and Gautam et al. [13], the ASR induced expansion significantly reduce when increasing reinforcement ratio and compressive stress. In addition, cracking is more obvious on the surface compared to the internal zone that is more confined, as shown in Figure 3(a). In addition to confinement effect, the development of ASR in a concrete structure differ from one region to others because they expose to different environmental conditions. For instance, structure's regions that expose to highly moisture condition experience ASR earlier and faster than others do. The reduction of mechanical properties due to ASR is commonly governed by the expansion level as presented before. The strongly dependence of ASR expansion and cracking development on the confinement and exposure condition, therefore, significantly affect mechanical properties degradation.

ISE guidance [3] suggests that the residual strengths and stiffness in actual structures are commonly higher than values obtained from core specimens as the proposed lower bounds because restraints and confinements tend to reduce ASR-induced damage in the concrete. Its degradation, thus, should be modified from the lower bounds. However, a detailed procedure or suggestion for the modification was not addressed in this guidance for practical applications. In term of ASR effect, in the structural context under the different effect of restraints and confinement, the core test results depend on many other factors such as the direction of extracting core, structural components or parts of the components. Different parts in a structure may experience different level of ASR due to exposure condition, therefore, consequence of ASR on mechanical properties also different. For instance, Crouch and Wood [27] extracted 117 cores from an ASR-affected structure and tested for elastic modulus, including more than half of all cores from *nominally uncracked* zones and the remainder from *nominally cracked* regions. Figure 3(b) shows the measured elastic modulus from two regions and their probabilistic distribution. The results revealed 36% difference between the mean of the elastic modulus of the *nominally uncracked* and *nominally cracked* specimens. Furthermore, the elastic modulus of the cracked cores varied in a higher range compared to that of uncracked cores. For the probabilistic viewpoint, the coefficient of variation of elastic modulus of cracked cores was up to 22%, which is higher than that of uncracked cores of 10% and also higher than the proposed value from the probability model code of 15% [28]. A similar observation can be found in [29] and [30]. The results from these studies indicate that the mechanical properties of concrete cores remarkably depend on the position and direction of extracting which are different in environmental and confinement conditions. First, the exposure condition such as moisture and temperature, which varies between different zones and members of a structure, causes different levels of ASR deterioration. For example, in regions expose to high moisture, the ASR occurs earlier and faster than other regions. Second, the confinement of concrete components could help to reduce ASR-induced expansion and cracking in confined directions, however, increase in other directions. It induces anisotropic phenomenon of the ASR-induced damage in concrete.



(a) Cracking development [31] (b) Elastic modulus reduction from core specimens [27]

Figure 3. Development of cracking and elastic modulus reduction due to ASR in RC structures

4. Empirical models for estimation of mechanical properties

To evaluate the capacity of concrete structures, concrete material properties are the key input parameters. For ASR-affected concrete structures, the estimation of mechanical properties degradation due to ASR is thus crucial. Three common used approaches in current practice include (1) obtaining from experimental testing (on cores or the cylinder samples) [9, 32, 33], (2) adopting the lower bound proposed by ISE [8, 9], and (3) using existing empirical models [34-36]. The first approach is commonly preferred to present the strength and stress-strain behaviour of the concrete. Unfortunately, the data on the material properties are not always available. The second approach thus can be used for a conservative evaluation. However, from the collected data set, the elastic modulus varies from lower to higher than the proposed lower bounds from ISE [3]. Therefore, the second approach with lower bounds of the degradation can lead to overestimating the capacity of the affected structures. These first two approaches were previously presented in details. For the third approach, several empirical models have been proposed to evaluate concrete mechanical properties in relation to ASR free expansion level. The following part presents more details of these models and their accuracy in comparison to the available experimental database.

In Saouma and Perotti [37], time-dependent nonlinear models were proposed for time-dependent degradation of mechanical properties, described as follows:

$$E(t,\theta) = E_{c0} \times [1 - (1-\beta_E) \times \xi(t,\theta)] \quad (1)$$

$$f_t(t,\theta) = f_{t0} \times \left[1 - \left(1-\beta_f\right) \times \xi(t,\theta)\right] \quad (2)$$

Where, $\xi(t,\theta)$ is the kinetics law for reaction extent which is time and temperature (θ) -dependent, f_{t0} is the original tensile strength, and β_E and β_f are the corresponding residual fractional values when ASR-induced expansion tends to laboratory-determined (or predicted) maximum free volumetric expansion. This model is able to take into consideration of temperature effect on the expansion rate and consequently on mechanical properties degradation rate. This model has been adopted in [35] and [36] for modelling structural behaviour of bridge deck and shear wall structures, respectively.

Esposito et al. [16] proposed a continuous piecewise linear function and fitted with a more comprehensive available data set on mechanical properties of the ASR-affected concrete collected from the literature using a weighted least-squares fitting process. The formula for the residual strength/stiffness is shown as follows.

$$\beta_P = \frac{P}{P^{ref}} = \begin{cases} q_1 + m_1\varepsilon & if\ \varepsilon \leq 0.05\% \\ q_m + m_m\varepsilon & if\ 0.05\% < \varepsilon \leq 0.1\% \\ q_h + m_h\varepsilon & if\ 0.1\% < \varepsilon \leq 0.5\% \\ q_e + m_e\varepsilon & if\ \varepsilon > 0.5\% \end{cases} \quad (3)$$

In which, P_{ref} is the estimated mechanical properties at the reference expansion of 0.05%; q and m are linear coefficients for each level of expansion: $q_m = q_l + 0.05 \times (m_l - m_m)$; $q_h = q_m + 0.1 \times (m_m - m_h)$; $q_e = q_h + 0.5 \times (m_h - m_e)$. This model was compared to the Saouma and Perotti's model, and presents more accurate in estimation of the degradation level.

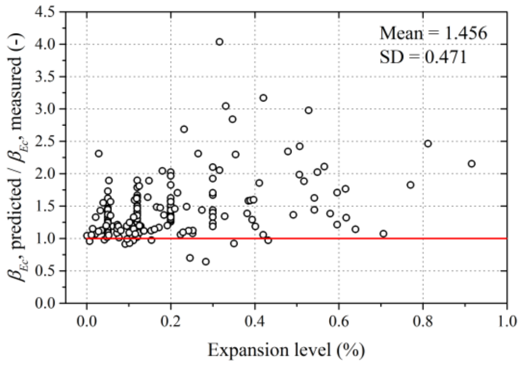
Recently, Kawabata et al. [34] and Martin et al. [38] adopted the chemical damage rule proposed by Seignol et al. [39], then fitted to a certain set of collected data from the literature. The degradation laws were subsequently applied to evaluate the damage of ASR-affected concrete material and structures in both experimental and numerical studies.

$$E_c = E_{c0} \times (1-d) \quad (4)$$

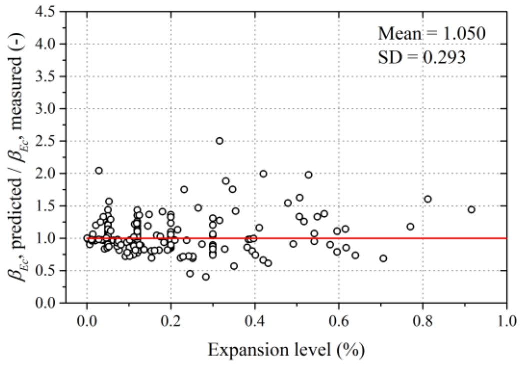
$$d = d_{max}\left(1 - \exp\left(-\omega \times \langle \varepsilon_\chi - \varepsilon_0 \rangle^+\right)\right) \quad (5)$$

Where, E_{c0} is the undamaged modulus, d represents the ASR-induced damage; ε is the expansion level, ε_0 is the chemical expansion above which cement paste starts cracking, d_{max} and ω are the maximum damage and rate of damage evolution, respectively. The model from Kawabata's model was utilised in Kawabata et al. [34] for macroscopic chemo-mechanical modelling of ASR-affected concrete under stress.

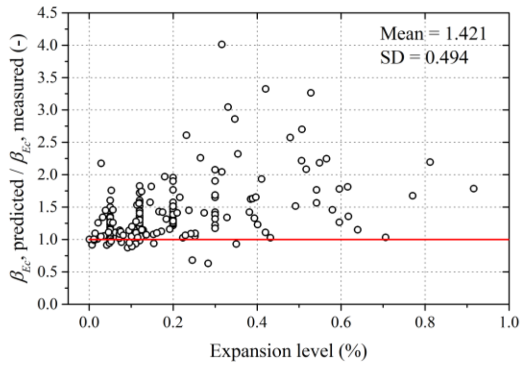
All these empirical models aimed at providing an accurate estimation of the mechanical properties degradation based on ASR-induced expansion and further evaluation of the consequence on structural behaviour and capacity. To evaluate the accuracy of these models, this study conducted a comparative study on estimation from these models according to the available database as previously presented. The elastic modulus is selected for the calculation and comparison. The ratio between predicted and measured residual elastic modulus (β_{Ec}) of all collected experimental ASR affected concrete samples are plotted with the expansion level in Figure 4.



(a) Esposito et al. model [16]



(b) Kawabata et al. model [34]



(c) Martin et al. model [38]

Figure 4. Comparison of predicted residual elastic modulus from the empirical models to measure data in relation to expansion level

The data points are expected to be along the equality line for an accurate estimation. The data points above the equality line in this figure mean that the predicted normalised elastic modulus are lower than the measured one, indicates the underestimation of the elastic modulus reduction due to ASR. In this context, it is apparent that the estimations based on Martin et al. [38] and Esposito et al. [16] present higher residual elastic modulus compared to measured data, as shown in Figs. 6(a) and (c). These two empirical models give the residual elastic modulus approximately more than 40% higher than the measured value. This estimation may lead to underestimation of deterioration due to ASR. In addition, it is observed that three empirical models provide a better estimation of the elastic modulus reduction at low expansion level of less than 0.2%, and then increase estimation error as the expansion level increases. However, the ratio of predicted to measured elastic modulus reduction obtained from three empirical models still vary in a wide range with high standard deviation. In Fig. 4, the estimated data points are highly scattered from the equality line where the standard deviation is up to almost 50%.

Due to significant reduction in the elastic modulus and tensile strength compared to that of compressive strength, the calculation of these two properties based on compressive strength as proposed correlation formulas in design codes become inefficient. Experimental results from Hiroi, Yamamoto [29] indicated that the elastic modulus/compressive strength ratio was much lower than analytical values calculated based on Japanese design standard. Similar observation was presented in study of Deschenes, Bayrak [40] where experimental results were compared to the relationship proposed in ACI 318 design code. Different studies also proposed the correlation among the mechanical properties of ASR-affected concrete, however, it is based on only a single experimental data set from those studies.

5. Conclusion and recommendations

The development of alkali-silica reaction in concrete has been identified as one of the main causes of mechanical properties degradation for ASR affected concrete structures. According to experimental results from the literature, ASR induces more significant degradation to elastic modulus and tensile strength than to compressive strength. The experimental results from the database also indicate that there are significant variations on the degradation level of ASR affected concrete at the same level of expansion. Several influential factors have been identified to be responsible for the development of ASR and consequently strength reduction. These factors have not been considered and investigated in the evaluation of the ASR degradation. In addition, it was found that the lower bounds proposed by ISE (1992), which has been widely adopted in current practice for evaluation of structural implication of ASR, may be applicable for compressive and tensile strength but not suitable for elastic modulus. Several empirical models have been proposed for mechanical properties estimation based on the ASR induced expansion. These models, however, failed to capture the vast variation of the mechanical property reduction of ASR affected concrete at a given level of expansion. The effects of these influencing factors on mechanical properties of ASR-affected concrete need to be further investigated to gain fundamental understanding and provide better estimation model for mechanical properties degradation. In the structure context, mechanical properties of a core specimen depend on many factors when extracted from a field structure, such as the extraction process, direction in relation to principal direction, and the location of the extraction. All these factors need to be taken into considerations for extracting core samples as well as evaluation of the results from mechanical properties testing.

6. Acknowledgments

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