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Effect of coarse aggregate size and matrix quality on ITZ and failure behavior of concrete under uniaxial compression

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Abstract

Effects of coarse aggregate size and water/cement (w/c) ratio of the matrix on the formation of interfacial transition zone (ITZ) and subsequently on the failure process of concrete under uniaxial compression were studied. For this purpose, a series of experiments were designed and carried out on mortars with two different w/c ratios containing single spherical steel aggregates of different sizes. The ITZ properties and the failure process of concrete were investigated through tensile strength tests both before and after compressive preloading, stress–axial strain, stress–volumetric strain and stress–lateral strain measurements. It was observed that ITZ becomes critical for larger aggregates and lower w/c ratio mortar matrices. The negative effect of smooth surface texture of the aggregate and the large difference between aggregate and matrix moduli of elasticity on the properties of ITZ is of paramount importance for low w/c ratio composites. The effect of reduced bond properties of ITZ relative to its matrix was reflected in the lower critical stress levels for the low w/c ratio composites with larger aggregates.

Keywords: Aggregate; w/c ratio; Interfacial transition zone; Failure behavior

1. Introduction

Concrete is a three phase composite structure at a microscopic scale. A mortar matrix, aggregate and the interfacial transition zone (ITZ) between the two. The ITZ is typically 10–50 μm thick. Its morphology, composition, density and other features differ from those of the matrix [1–4]. The structure of ITZ is influenced by the properties of the individual constituents (coarse aggregate, cement, and admixtures) and the w/c ratio of the mix. ITZ, which is normally regarded as the weakest link in concrete, plays a key role on the mechanical behavior of concrete even though it is disproportionately smaller than the other two constitutive components [5–8].

The properties (size, shape, surface texture, mineralogy, etc.) of the aggregates have an important influence on the properties of ITZ. Numerous studies have been carried out to assess the influence of aggregates with different shapes (rounded or irregular) and different surface textures (smooth or rough) on the ITZ properties [2–6]. In general, mechanical interlocking strengthens with rough surface texture and with irregular aggregate shape. Consequently, bond strength increases. Rounded and smooth surface aggregates result in lower bonding with the matrix. Depending on the aggregate type, the bond may also be strengthened or weakened through chemical reactions between the cement matrix and the aggregate [2,4,6]. The influences of the type of aggregate on the overall mechanical properties of the concrete composite have been previously reported [7,9–11]. It was concluded that the stiffer and stronger the aggregate the higher the elastic modulus of the concrete [9,10]. The compressive strength of concrete is mainly controlled by the quality of mortar and surface characteristics of aggregates (i.e., bond properties) more than the aggregate type [9–11]. The influence of the type of aggregate, however, becomes important as the quality of the mortar is improved. As concluded by Aitcin and Mehta [9], using a coarse aggregate with proper texture and mineralogy in high strength concrete, may improve the compressive strength of concrete. Zimbelman [2] and

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Özturan and Çeçen [11] evaluated the dependence of the tensile strength of concrete on the quality of the matrix and the ITZ. It is concluded that quality of the ITZ plays an important role on the tensile strength of concrete particularly for higher matrix quality.

The quality of the matrix and the ITZ are highly influenced by the w/c ratio of the concrete. It is a well-known fact that increasing w/c ratio increases the porosity of the matrix as well as that of ITZ [2,8,12]. The pore structure around the aggregates is different from that in the matrix. Higher water content and less dense packing of cement grains close to the aggregate surface increase ITZ porosity [1,3,8]. Even though its effect on the thickness of ITZ is not adequately addressed in the literature, there is a general agreement that decrease in w/c ratio reduces the thickness of this critical region to some extent [2,8]. It was observed that the thickness of the ITZ was also dependent on the aggregate size [1].

In addition to the factors stated above, the initial defects, which may be present even before the application of any load may result in the weakness of the ITZ [13–16]. The main causes of the initial microcracks are the differences between the moduli of elasticity of the aggregate and the matrix [17,18] and the differential shrinkage of the two materials [14–16]. Difference between the elastic moduli and pronounced differential shrinkage at early stages increase the stress concentrations in the ITZ. Such effects are the causes of the low tensile strength of concrete [14,15].

So far, many researchers have investigated the propagation of cracks in concrete under uniaxial compression [13,16,19–22]. It was concluded that; very fine cracks exist at the interface even before any load is applied [13,16]. With increasing load, these microcracks remain stable up to about 30% of the compressive strength (σ_c) [13] and then they start to grow in length, width and number. The propagation of microcracks within the ITZ corresponds to 50% of the σ_c [19] and the coalescence of bond and mortar cracks and their rapid propagation corresponds to (70–90)% of the σ_c [13,19,20,22]. At the beginning of this stage, bond and mortar cracks coalesce as single or several cracks and propagate in the direction of the applied load [16,20,21]. Upon further increase in the load at this stage, rapid and continuous crack propagation, which accelerates the failure of the material, is initiated. The formation of rapid and continuous crack patterns correlates well with the fact that at this critical point, volume of the concrete under increasing load, rather than continuing to contract begins to expand [16,19]. Similarly the rapid increase in Poisson's ratio indicates the rapid and continuous crack growth through matrix up to fracture [16].

In the present study, the effects of the size of a very rigid, nonporous aggregate with a smooth surface texture on the formation of ITZ and on the mechanical performance of concrete composites were studied experimentally using indirect methods. For this purpose single spherical steel aggregates of different sizes were used in two mortars of different compressive strengths. Although the single aggregate model is not representative of real concrete, the use of single aggregates having simple geometry may lead to get at least an idea on the properties and effect of ITZ on the crack performance [16].

2. Experimental procedures

Two control mortar mixes of 25 MPa (low strength, LS) and 47 MPa (high strength, HS) compressive strength at 28 days were prepared. Then, single spherical steel aggregates were inserted into the center of the 100 mm cube specimens right after the molds were filled with mortar. It was verified after split tension tests that the aggregates were actually at the center of the specimens. The mix proportions of the mortars are given in Table 1. Diameters of the single aggregates used were 9, 12, 19, 25 and 32 mm. Ordinary Portland cement, natural river sand of 4 mm maximum size, and tap water were used to prepare the mortars. All specimens cast in 100 mm steel moulds kept under ambient conditions for 24 h, covered with wet cloth. Then the molds were stripped and the specimens were cured in water until testing.

The microcrack initiation and propagation were analyzed by interpreting the 28 days compressive (σ_c) and tensile (σ_t) strengths, tensile strength loss (TSL), relation between compressive stress and longitudinal, lateral, and volumetric strains, and change in Poisson's ratio with stress.

In TSL analyses, specimens were loaded up to 40%, 60%, and 80% of the σ_c then subjected to split tension test. Tension tests were performed in such a way that the plane of tensile fracture was in the direction of the previous compressive loading. To obtain the stress–longitudinal, lateral, and volumetric strain relations, the specimens were tested at a constant deformation rate of 1.5×10^{-3} mm/s.

3. Test results and discussion

The process of microcrack initiation and propagation and the eventual failure of concrete in the single aggre-

Table 1
Mix proportions and strength of the control mortar matrices

Ingredients (kg/m^3)	LS	HS
Sand	1905	1905
Cement	525	525
Water	420	220
Superplasticizer	–	37
28-D strength (MPa)		
Compressive	25	47
Tensile	1.9	3.1

gate model can be explained by knowing the intricate relationship between the three phases of concrete and their interaction under loading. The effect of spherical steel aggregate, which is highly stiff and strong with smooth surface texture, plays an important role in the formation of interfacial transition zone structure and subsequently the failure process of the mortar.

3.1. Tensile and compressive strength measurements

The influence of the presence of an aggregate on compressive (σ_c) and tensile (σ_t) strengths of mortars can be observed in Figs. 1 and 2. Each test result is an average of at least three specimens. Due to the differences between the Poisson's ratios of the matrix and the aggregate, the matrix material above and below the particle is confined, i.e., a state of triaxial compression develops above and below the aggregate particle as described by Perry and Gillot [5] and Miloshi et al. [16]. Since the strength of concrete increases under such a triaxial confinement, higher σ_c was observed (Fig. 1) for both low strength (LSC) and high strength (HSC) composites than the control specimens. The experimental results presented in Fig. 1 also indicate that increasing single aggregate size increases the σ_c only slightly. However, this effect is more pronounced in HSC due to a relatively better compatibility between the mortar matrix and aggregate phases as compared to LSC.

The effect of the aggregate size and w/c ratio on ITZ strength can be seen in Fig. 2 where σ_t measurements are presented. The presence of a single aggregate reduces the σ_t as its size increases. The maximum σ_t differences between the control specimens and specimens containing single steel aggregates were about 6% and 14%, for LSC and HSC, respectively. It is also noted that, the reduction in the σ_t with increasing aggregate size is higher in HSC. Thus, it can be stated that the additional tensile strains introduced with an aggregate inclusion is higher in HSC and results in more reduction in σ_t. This may be attributed to the fact that ITZ in HSC is structurally much more different than the matrix when compared with that in LSC.

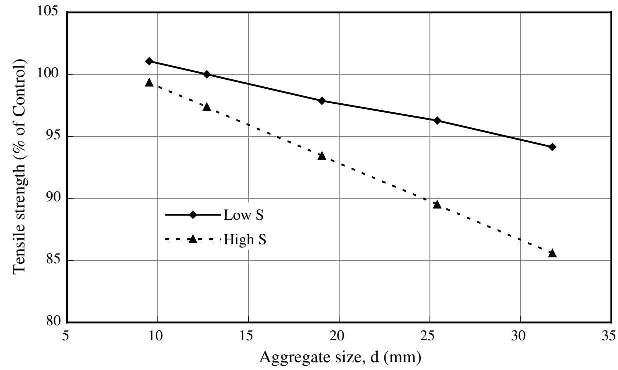

Fig. 2. Effect of aggregate size on tensile strength of LSC and HSC.

The observed decrease in the σ_t with increasing aggregate size both in LSC and HSC indicates a decrease in bond strength. This is due to increased aggregate volume relative to the total composite volume that causes the large difference between the elastic moduli of the two phases to become more pronounced thus, creating an increased stress concentration and more microcracks in the vicinity of the aggregate. Also the negative effect of a smooth surface texture on bond strength is highlighted due to the increased surface area of the aggregate. The smooth surface texture and large elastic modulus of the aggregate results in higher reduction in σ_t in composites with lower w/c ratio ($w/c = 0.42$).

Another important parameter of ITZ is its thickness and the concentration of microcracks and voids relative to its thickness. Because of the lower w/c ratio in HSC, the ITZ is expected to be narrower [2,8]. The σ_t values (Fig. 2) indicated that the structural difference of ITZ and the matrix is more in HSC. This leads to more condensed stress concentrations and microcracks in the narrower ITZ of HSC. Therefore, for larger steel aggregate inclusions (which are rigid, nonporous and smooth) and lower w/c ratios, ITZ becomes critical.

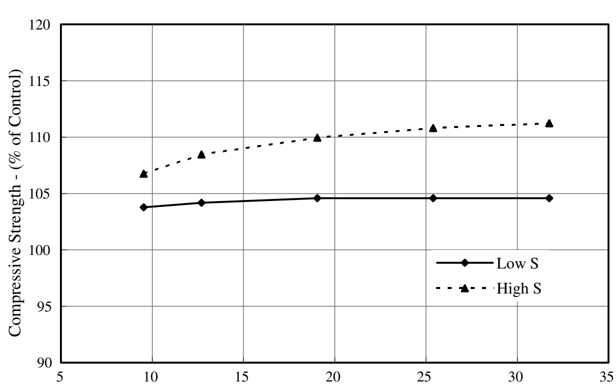

Fig. 1. Effect of aggregate size on compressive strength of LSC and HSC.

3.2. Microcrack development

3.2.1. Tensile strength loss measurement

The loss in σ_t, as a result of previously applied compressive stress, is referred to as 'damage' [22]. In this investigation, the first method of assessing the development of microcracks is through the TSL measurements. Microcracking has been observed directly by an appreciable loss of tensile resistance in the direction normal to the microcracks. Fig. 3 presents the relationship between damage and aggregate size for LSC and HSC after applying 40%, 60%, and 80% of the σ_c. Higher damage was obtained in LSC at all compressive stress levels. For a

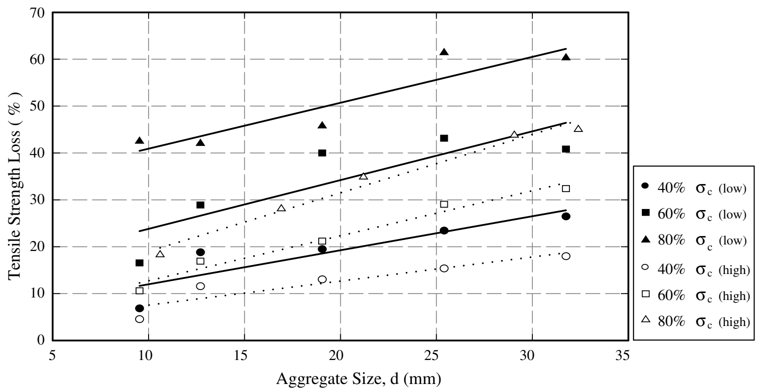

Fig. 3. Effect of aggregate size on TSL of LSC and HSC.

specific compressive stress, as the aggregate size increases TSL also increases. Maximum TSL of about 60% and 45% were observed for LSC and HSC, respectively at 80% of the σ_c. The increase in TSL with increasing aggregate size in both types of composites indicates that increase in ITZ area is influential in damage process. However, the lower overall damage observed in HSC shows that the matrix is at least as important as ITZ during the damage process. The lower damage in HSC is due to the decreased w/c ratio, which leads to a matrix with reduced pore content and cracks therefore resulting in higher σ_t resistance. Furthermore, the increased quality of the mortar matrix surrounding the aggregate results in the confinement of cracks and forces them to accumulate mostly in the ITZ up to an initial stress level (σ_i) corresponding to the onset of crack propagation.

3.2.2. Stress–strain relations

Microcracking under increasing compressive loading was identified from the slopes of the stress–strain curves, also (Figs. 4 and 5). In addition, volumetric strains and Poisson's ratios were used to determine the effect of aggregate size on the critical stress level (σ_{cr}) at which rapid and continuous crack propagation starts.

Microcracking studies [13,16,19,20] have revealed that cracks frequently initiate at the interface and extension of bond cracks initiates the nonlinear response of concrete. Cracks through the mortar occur extensively at the latter stage, which results in the formation of rapid and continuous crack paths prior to ultimate stress.

In HSC, the initial stress levels (σ_i) decreases with increasing aggregate size while it is nearly constant in LSC containing the same size aggregates. As can be observed from Fig. 4, end of linearity in LSC is around 70% of the ultimate and that of HSC (Fig. 5) is 75–85% of the ultimate. This indicates that the bond strength effect in LSC is diminished, however it is still effective in HSC. Results obtained from TSL analysis correlate well with the results obtained from stress–strain analyses in that TSL in LSC are higher than that in HSC. More damage occurred in LSC results with lower level of linearity when compared with HSC for which early loading causes less damage.

Upon further increase in the load, the propagation of ITZ cracks through the matrix starts. Due to the smooth surface texture and high elastic modulus of the aggregate, the matrix material tends to flow around the aggregate. Depending on the flow of the matrix around

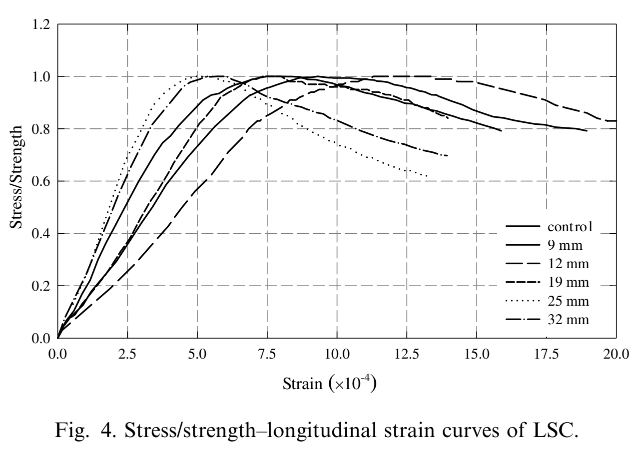

Fig. 4. Stress/strength–longitudinal strain curves of LSC.

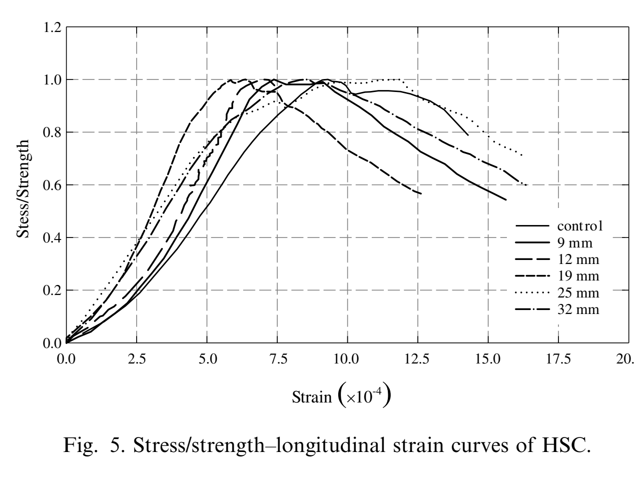

Fig. 5. Stress/strength–longitudinal strain curves of HSC.

the aggregate, lateral splitting tensile stresses are created contributing to the propagation of ITZ cracks through the matrix. The critical ITZ structure in HSC including large aggregates promotes the flow of the matrix leading to an increase in lateral tensile stresses. The additional stress required for the concrete composites to reach the σ_{cr} from σ_i depends on the amount of the created lateral stresses along with the material properties (w/c ratio, aggregate size) of individual constituents.

The σ_{cr} of LSC are around the ultimate and show no significant difference with increasing aggregate size while those of HSC are lower than the ultimate and decrease with increasing aggregate size. Considering the slope changes in Figs. 4 and 5, rapid crack propagation in HSC containing large aggregates starts at around 75% of the ultimate and increases to 85–90% for smaller aggregates, whereas in LSC it is higher at around 95% for all aggregate sizes. The σ_{cr} is reduced considerably in HSC with larger aggregates (Fig. 5). This verifies that the damage process is controlled by the matrix in LSC whereas ITZ is more critical in HSC in the damage process beyond the initial stress level σ_i.

It is worth mentioning that with reduced w/c ratio a more brittle and homogeneous matrix is achieved. This results with a lower ability of redistributing stress and lower energy absorption capacity. Therefore, a less extensive microcrack pattern of the matrix together with the condensed microcracking in the narrow ITZ contributes to a comparatively sudden failure.

The above claim about the stress levels for the onset of rapid and continuous crack propagation is well supported by the rapid changes in Poisson's ratio and volumetric strain given in Figs. 6–9. From Figs. 6 and 8, where the volumetric strain and Poisson's ratio curves for LSC are presented, it is obvious that the critical stress level is just below the ultimate stress (around 95% of the ultimate) and does not show significant difference with increasing aggregate size. In contrast, for HSC it is observed from Figs. 7 and 9 that the σ_{cr} for progressive and unstable crack formation decreased with increasing aggregate size from approximately 90–75% of the ultimate for 9 and 32 mm sized aggregates, respectively.

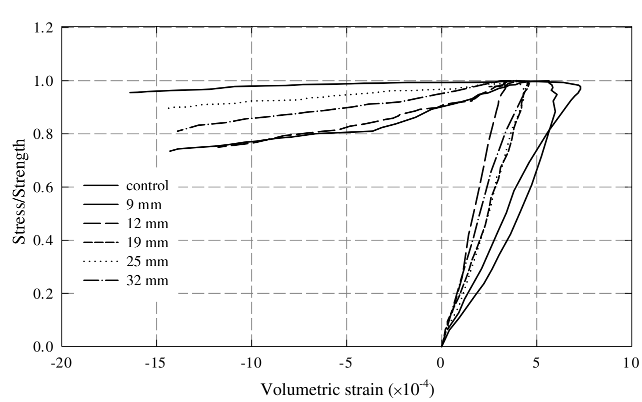

Fig. 6. Stress/strength–volumetric strain curves of LSC.

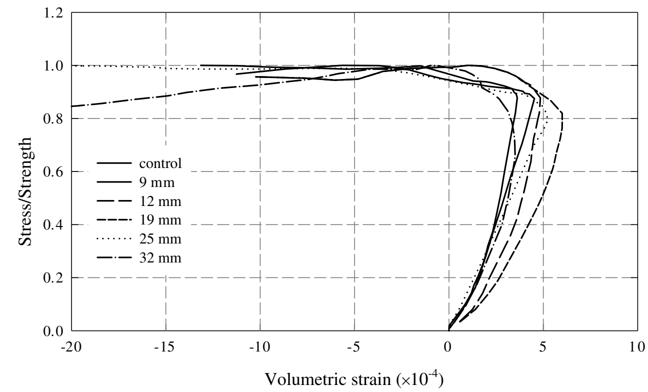

Fig. 7. Stress/strength–volumetric strain curves of HSC.

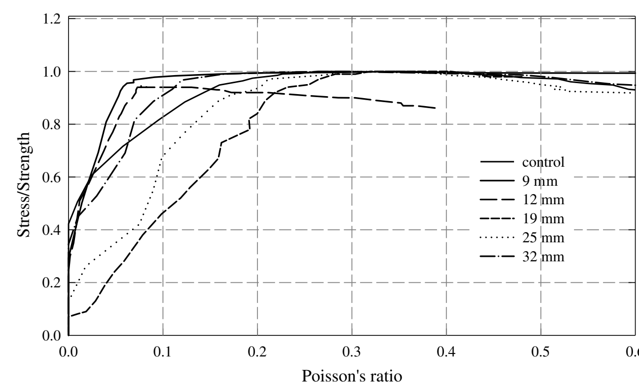

Fig. 8. Stress/strength–Poisson's ratio curves of LSC.

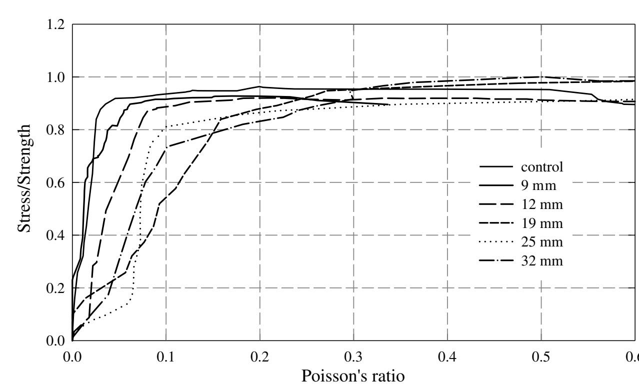

Fig. 9. Stress/strength–Poisson's ratio curves of HSC.

4. Conclusions

1. With larger aggregates, low w/c ratio matrices result in more critical ITZs with a more condensed microcrack in a narrower region. This indicates that the adverse effect of the rigid aggregate becomes more

pronounced with increased matrix quality and aggregate size.

2. The interfacial bond was observed to be the determining factor for the tensile strength and played little role on the compressive strength. The tensile strength decreases as the aggregate size increases. The rate of tensile strength reduction with increasing single aggregate size becomes higher in HSC.
3. In HSC the stress levels corresponding to the onset of crack propagation decrease with increasing aggregate size while it was nearly constant in LSC containing the same size aggregates. The critical stress at which rapid and continuous crack propagation starts is around the ultimate and showed no significant difference with increasing aggregate size in LSC whereas its lower in HSC and decrease with increasing aggregate size.
4. The role of ITZ and matrix on the damage process depend on the w/c of the mixture. In high w/c mixtures ITZ effect is more pronounced up to the onset of crack propagation (σ_i) whereas it is important at rapid crack propagation in low w/c mixtures.

References

[1] Monteiro PJM, Maso JC, Ollivier JP. The aggregate-mortar interface. Cement Concrete Res 1985;15:953–8.

[2] Zimbelman R. A contribution to the problem of cement-aggregate bond. Cement Concrete Res 1985;15:801–8.

[3] Scrivener KL, Nemati KM. The percolation of pore space in the cement paste/aggregate interfacial zone of concrete. Cement Concrete Res 1996;26(1):35–40.

[4] Tasong WA, Lynsdale CJ, Cripps JC. Aggregate-cement paste interface. Part I. Influence of aggregate geochemistry. Cement Concrete Res 1999;29:1019–25.

[5] Perry C, Gillot JE. The influence of mortar-aggregate bond strength on the behavior of concrete in uniaxial compression. Cement Concrete Res 1977;7:553–64.

[6] Prokopski G, Halbiniak J. Interfacial transition zone in cementitious materials. Cement Concrete Res 2000;30:579–83.

[7] Ramesh G, Sotelino ED, Chen WF. Effect of transition zone on elastic moduli of concrete materials. Cement Concrete Res 1996;26(4):611–22.

[8] Simenow P, Ahmad S. Effect of transition zone on the elastic behavior of cement-based composites. Cement Concrete Res 1995;25(1):165–76.

[9] Aitcin PC, Mehta PK. Effect of coarse-aggregate characteristics on mechanical properties of high-strength concrete. ACI Mater J 1990;87(2):103–7.

[10] Zhou FP, Lydon FD, Barr BIG. Effect of coarse aggregate on elastic modulus and compressive strength of high performance concrete. Cement Concrete Res 1995;25(1):177–86.

[11] Özturan T, Çeçen C. Effect of coarse aggregate type on mechanical properties of concretes with different strengths. Cement Concrete Res 1997;27(2):165–70.

[12] Prokopsi G, Langier B. Effect of w/c ratio and silica fume addition on the fracture toughness and morphology of fractured surfaces of gravel concretes. Cement Concrete Res 2000;30:1427–14330.

[13] Hsu TTC, Slate FO, Sturman GM, Winter G. Microcracking of plain concrete and the shape of the stress–strain curve. ACI Mater J 1963;60(2):209–24.

[14] Acker P, Boulay C, Rossi P. On the importance of initial stresses in concrete and of the resulting mechanical effects. Cement Concrete Res 1987;17:755–64.

[15] Igarashi S, Bentur A, Kovler K. Autogeneous shrinkage and induced restraining stresses in high-strength concretes. Cement Concrete Res 2000;30:1701–7.

[16] Milashi H, Sasaki T, Izumi M. Failure process of concrete: crack initiation and propagation. ICM 3, Cambridge, England, vol. 3, 1979. p. 97–107.

[17] Van Mier JGM. Fracture processes of concrete. CRC; 1997. p. 52.

[18] Tasdemir MA, Tasdemir C, Akyuz S, Jefferson AD, Lydon FD. Evaluation of strains at peak stresses in concrete: a three-phase composite model approach. Cement Concrete Res 1998;20:301–18.

[19] Shah SP, Chandra S. Critical stress, volume change and microcracking of concrete. ACI Mater J 1968;65(9):770–81.

[20] Shah SP, Sankar R. Internal cracking and strain softening response of concrete under uniaxial compression. ACI Mater J 1987;84(3):200–12.

[21] Maji AK, Shah SP. Application of acoustic emission and laser helography to study microstructure in concrete, in nondestructive testing. ACI Mater J 1988;SP-112:83–109.

[22] Liniers AD. Microcracking of concrete under compression and its influence on tensile strength. Mater Struct 1987;20:111–6.