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The fatigue flexural behavior of fiber reinforced concrete: Effect of the parameters of coarse aggregates

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The effect of the coarse aggregate type on the fatigue flexural behavior of concrete was investigated in this work. Three types of the coarse aggregates were selected from three different careers (CA1, CA2 and CA3). The mechanical parameters of these aggregates were determined (Los Anglos and Micro Deval). Prismatic specimens (70×70×280 mm) for each concrete mixture were made with aggregates of each source. The flexural fatigue tests were conducted on these concrete samples with varying levels of loading of 55 to 80% and the ultimate flexural strength. The test frequency is around 80 Hz and it is automatically determined by pulsing the fatigue machine for a resonance situation (the phase shift is δ=0) between the mass-spring-specimen system. The obtained results show that the aggregates which have the similar parameters (Micro Deval and LA), provide better adhesion with cement paste, and therefore a greater bending strength. The strength evolution at short-term age is typical for specimens based on aggregates with low wear resistance by triturate (a high Micro Deval coefficient). Regarding the fatigue flexural behavior, the concrete specimens based on CA1, which have similar coefficients of Los Angeles and Micro Deval (respectively 18 and 16) present the behavior (load/cycle numbers) close to that of the model prototype of the Wöhler curve. This can be explained by a high homogeneity of the charge distribution during fatigue test compared to other concrete mixtures. Also, it was noted that the relationship between the endurance limit and the coefficient of Los Angeles is inversely proportional: The aggregates which have good strength to fragmentation (low coefficient of LA), as aggregates CA2 case give an endurance limit at around 70% max bending load.

Key words: Coarse aggregate, Los Angeles, Micro Deval, bending test, fatigue testing, endurance limit.

INTRODUCTION

The concrete as a material is considered to be a composite material wherein the aggregates forming the backbone solid and playing the role of reinforcement ensuring the mechanical performance in relation to the various stresses. In this context, many studies focus on the correlation between the proportions, size distribution and mechanical properties of aggregates on the one hand, and the concrete strength on the other hand. In

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Table 1. Relationship between nature, hardness and the application domain of aggregates.

Nature of aggregate	Density	Hardness LA	Hardness MDE	Applications
hard limestone's	2.5 à 2.7	15 à 20	0.4	Building works of art
Sand-lime	2.5 à 2.6	15 à 60	0.3 à 0.4	Road concrete
Clays and shale expanded	0.8 à 1.35	1617.9	10 à 32	Light concrete structure
expanded polystyrene	0.012 à 0.014			Thermal insulating concretes
Fireclay, alumina	2.8	7 on the Mohs scale		Refractory concretes
Silicon carbide	3.1	9 on the Mohs scale		Concrete and mortar wear
Corundum	3.9 à 4.1	9 on the Mohs scale		Concrete and mortar wear

practical cases, the required characteristics for the concrete through the optimization of its formulation to objectives which are generally the class of concrete, density, workability and compactness, according to the graphical approach such as that of Faury or Dreux, or experimental method as the case of the LCPC method (De Larrard and Tondat, 1993; De Larrad, 2000; Gérard, 2010; Mehta, 1986).

On the other hand, it is known that the concrete is designed to be resistant and absorbing the energy of manmade and natural forces such as earthquake (De Larrard and Tondat, 1993; Hashin, 1962; Muttoni, 2003). Among these concretes the fiber reinforced concretes (FRC) which have a high compressive and flexural strength. Many studies have shown that the addition of fibers into concrete significantly improved many of the mechanical properties of concrete notably compressive and flexural strength. The dynamic compressive strength is considered one the main parameters of FRC concrete, which possesses the most important criteria of concrete to resist dynamic loadings of high strain rate. Whatever the concrete formulation methods applied the aggregates which are essential constituents and present permanent elements in the calculations that predict the characteristics of concrete at fresh and hardened state (Mehta, 1986). The choice of such aggregates for concrete is such a technical and economic compromise between nature, price, hardness and field of use as shown in Table 1.

According to the standard which defines the categories for each characteristic of aggregates and the fillers used in manufacture of the concretes in conformity with standard NF EN 206-1. The general rules for carrying out checks on aggregate and grouping them by category codes are defined by the standard NF EN 12620 for the various possible uses. The XP P 18-545 standard classes the hardness according to the Los Angeles and Micro Deval as intrinsic aggregate characteristics. These characteristics vary according to their nature and their application field (Table 1).

Los Angeles (LA) indicates the resistance to fragmentation by impact and wears mutual friction during turning of aggregates in a closed drum containing metal balls. The LA coefficient represents the fines proportion produced during the test. The lower value of this coefficient indicates the higher resistance of the coarse aggregates.

The Micro-Deval test (MDE) determines the resistance of the wear of aggregates in the water presence: It consists to reproduce in a cylinder in rotation, wear phenomena by frictions. The MDE coefficient represents the fines proportion produced during the test: The MDE is lower while the abrasion resistance of gravel is higher.

In the real case, the different mechanisms are responsible for the concrete behavior, which are complex and interdependent (Roelfstra et al., 1985). Esse et al. reported that the maximum strength of concrete obtained from high-quality aggregates, does not exceed 1.5 times the strength of the mortar used in the concrete composition (Esse and Grzelak, 1970). Moreover, other studies propose mathematical models where the concrete is considered as biphasic material: One is continuous representing the mortar and the other discontinuous, composed of coarse aggregates (Hashin, 1962; Esse and Grzelak, 1970; Hirsh, 1962; Popovics and Erdey, 1970). These models are used to calculate the elastic modulus of concrete as a function of stress (E_l) of the mortar, coarse aggregate (E_2) and their respective volume portion (V_1) and (V_2) modules, in the following form:

$$E = f\,(E_1, E_2, V_1, V_2) \quad (1)$$

The bending test also called tensile bending to control the concrete quality. It also gives an indication of the tensile strength in bending of the concrete, hence its resistance to cracking. To control the ability to service, some standards such that SIA162/1993 recommends using for concrete exceeding B35/25 quality, tensile strength fct = 2.5 N/mm^2 where: f = 2, $fct = 0.80\ fc$ where fct is the resistance to simple traction and fc the compressive strength of a cubic specimen (Muttoni, 2003; SIA162/1993).

The fatigue loading is generally composed into two categories namely low-cycle and high-cycle loading. Concerning the low-cycle loading involves the application of a few load cycles at high stress levels. However, high cyclic loading is characterized by a large number of

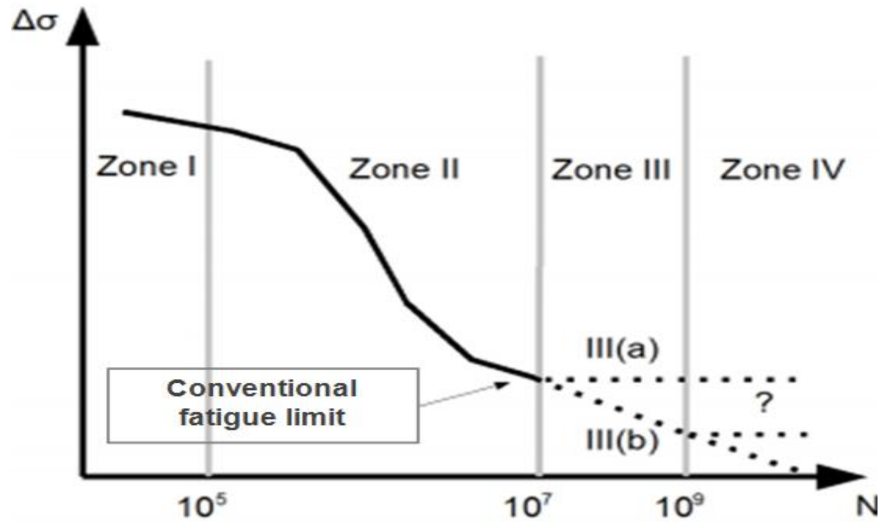

Figure 1. Fatigue curve (S-N) (Lee and Barr, 2004).

cycles at lower stress levels (Cachim et al., 2000; Lee and Barr, 2002). The flexural strength under cyclic loads (fatigue) is a key criterion for evaluating the mass concrete intended for road applications. These tests consist in subjecting prismatic samples to bending loads lower than the rupture and determine the number of loading cycles that the concrete can support. The loading levels typically vary between 50 and 80% of the flexural strength at the time of the test, with a number of cycles up to one million according to ASTM standard. At present, the concept of fatigue limit is related to the hypothesis of the existence of a horizontal asymptote of the curve from SN 106 or 107 cycles. It is thus considered that any sample not broken at 107 cycles lasts infinite life and very high. Generally, the possible forms of the SN curve are shown in Figure 1, showing four zones (Bathias and Pineau, 2008):

Zone I: corresponds to the oligocyclic fatigue also known as LCF (Low Cycle Fatigue) that is defined with a small number of cycles (about 105cycles). It is characterized by testing in high stress amplitudes

Zone II or Zone of limited endurance which is generally between 105 and 107 cycles. This is the fatigue area many cycles (HCF). It is noted that in this area a lower loading involves a greater number of cycles to failure (Nf).

Zone III shows the fatigue having very large number of cycles (for the number of higher than 107 cycles). It relates generally to the field tests on the requesting machine piezoelectric samples to very high frequencies, in the case III (a), the curve tends to a limit defined as horizontal asymptote of conventional strain (Papadopoulos and Panoskaltsis, 1996). In the case III (b) where it continues to monitor fractures caused by mechanisms of initiation surface or samples at an inclusion, in the case of steel (Blanche, 2012).

Zone IV shows a case corresponding to a material that continues to damage, even at lower stresses, whereas the other two cases show that the material has reached a stress below which microstructural mechanisms are perfectly reversible or their irreversibility would be negligible (Mughrabi, 2006).

According to carried researches on the mechanical behavior of materials, the fatigue failure will take place under the effect of repetitive or cyclic load, or the maximum value of the load is substantially smaller than the safety load estimated (the static load). In the concrete case, these changes are mainly related with the progressive growth of internal micro cracks, which result in an increase of irrecoverable strain which manifest at the level changes in the material’s mechanical properties (Sun et al., 1999; Shang and Song, 2006; Hasan et al., 2008; Li et al., 2011; Shi et al., 1993; Lee and Barr, 2004; ACI 215R-74, 1997). However, it was noted by Mudock and Kesler that fatigue failure in concrete is due to progressive deterioration of the bond between the coarse aggregate and the matrix cementitious. These authors have found that the section reduction of the specimen leads to its failure due to fracture of matrix (Murdock and Kesler, 1958).

Many studies have already been carried out on the effect of the nature and type of aggregate on the mechanical performance of concrete (Malesev et al., 2010; Tavakoli and Soroushian, 1996; Corinaldesi and Moriconi, 2010; Thomas et al., 2013; Corinaldesi, 2011; Zaetang et al., 2013). The physical properties and mechanical performance of the recycled aggregate concrete have been compared to those concrete made with natural aggregates. Other works have been realized on the recycled aggregate-based concretes with the fly

Table 2. Characteristics of used aggregates.

Parameter	Class of aggregates	CA1	CA2	CA3
Specific gravity (Kg/m^3)	8/15	2650	2680	2670
	15/25	2640	2670	2660
Apparent density (kg/m^3)	8/15	1475	1445	1490
	15/25	1436	1555	1490
Absorption (%)	8/15	1.66	1.33	3,66
	15/25	2	01	2,33
Porosity (%)	8/15	4.41	3.57	9,75
	15/25	5.28	2.67	6,23
Water content (%)	8/15	0.93	0.75	0,5
	15/25	0.49	1.52	0,5
Los Angeles (%)		28,86	8.52	18
Micro-Deval in water presence (%)		21,6	15	16

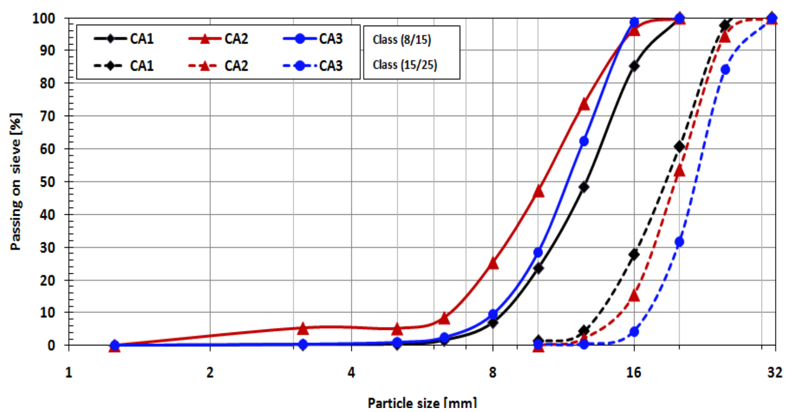

Figure 2. Particle size distribution of coarse aggregates.

ash presence in a binder mixture (Lima et al., 2013; Abo-El-Enein, 2014). These studies have shown that the improvement of physical properties can be conducted to significant improvement of mechanical performances of concrete material.

Although a few studies have been dealing the effect of the parameters of coarse aggregates on the flexural fatigue resistance of concrete, there are still insufficient experimental data about to the fatigue behavior of concrete realized with different types of coarse aggregates. For this, the present study focuses on the parameters effect of coarse aggregates on the flexural fatigue behavior of concrete.

EXPERIMENTAL STUDY

Materials used

The cement used was a Portland cement (CEMII 42.5) with specific gravity of 3.15. The chemical and mineralogical composition is given in Table 1. The natural sand (0/5 mm) is used as a fine aggregate. Three coarse aggregate types of class (8/15 and 15/25) were also used from three different careers (CA1, CA2 and CA3). Table 2 gives the physical and mechanical characteristics of these aggregates. Also, Figure 2 gives the grain-size distribution of the studied aggregates. According to this grain-size distribution, it is clear that the aggregates have practically the same size and fraction for the two class cases (8-15 and 15-25).

Concrete mixtures

In order to see the effect of nature and the aggregate parameters on the concrete behavior at fatigue stresses, a serial of concrete mixtures were established using the Dreux Gorisse method. The formulation calculations are performed to achieve minimal resistance Rn = 35 MPa of concrete with a workability around Af = 10 cm for a granular coefficient G = 0.5. After mixing concrete, the workability test was carried out on each mixture using the Abrams cone test according to EN norm (EN 12350-2: Testing fresh concrete - Part 2: Slump test).

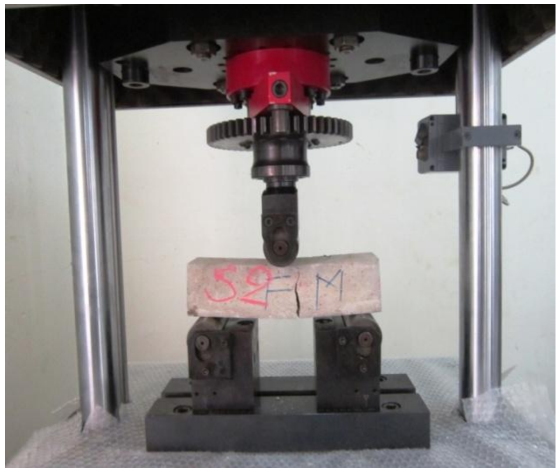

Figure 3. Fatigue testing machine.

To conduct this work, a prismatic (70×70×280 mm^3) and cylindrical (320ϕ160 mm^2) concrete samples were manufactured for each mixture. One day after casting, samples were stored in water under 21±1°C, and various tests and measurements were carried. The prismatic (70×70×280 mm^3) samples were used for flexural test and fatigue test. The cylindrical samples of concretes were used for compressive test.

The concrete specimens are made and controlled according to ASTM C 597-1980 standard. The tests are carried out using the ultrasonic pulse velocity testing (UPV testing). This system consists of several functional units which are pulser/receiver, transducer and display devices as schematically described in ASTM C597-97 (The UPV testing - ASTM C597-97) (ASTM C597-97, 1993).

Nondestructive evaluation of concrete by ultrasound is a technique commonly used in research (Breysse, 2012) shows that the choice of a given model type has no material consequence, since all models lead roughly to the same quality of the evaluation, the error of each model is much smaller than that due to the measurement uncertainties.

The bending tests are performed on a frame bending Toni technique, with a force sensor and at 100 KN load and the computer driven through testXpert software version 7.0. The test protocol is established according to NF EN 12390.

Compression tests are performed on the two parts obtained by bending test bed through a maximum compressive strength of 3000 kN. The test speed is 10 mm/min. Bending tests are conducted at 28 days of curing age.

Fatigue test

The main objective of this part of work is to see the influence of the aggregates properties on the fatigue behavior of the concrete prepared at various levels of fatigue stress on prismatic specimens (280×70×70 mm). The test protocol involves applying level solicitations 50, 60, 70 and 80% of the maximum bending strength with a 0.6 ratio between the max load and the min load.

Fatigue tests were performed on an electromechanical machine (vibraphone; Figure 1) for fatigue testing high frequency (30-300 Hz) by the application of alternative sinusoidal loads using the principle of resonance with a variable amplitude and mean load, allowing obtaining the S/N curve any saving energy.

Fatigue testing machines apply cyclic loads to test specimens. Fatigue testing is a dynamic testing mode and can be used to simulate how a component/material will behave/fail under real life loading/stress conditions. They can incorporate tensile, compressive, bending and/or torsion stresses and are often applied to springs, suspension components and biomedical implants.

RESULTS AND DISCUSSION

Workability of studied concretes

The obtained results of concrete workability are given in Figure 3. According to these results and the Figure 4, all concrete mixtures have workability acceptable for concrete construction. Also, it was noted that all concretes studied have the same workability even concrete implementation, which gives us virtually no effect of the aggregates types on workability.

Strength of studied concretes

Non-destructive testing

After the non-destructive testing on prismatic samples of the studied concrete by ultrasonic waves, the speed obtained is used to calculate the compressive strength using the following Equation (7) (Table 3):

$$R_C=0.08177.e^{(0.00147.Vt)} \quad (2)$$

Average speeds used for all concrete specimens with aggregates made up of different careers are above 4200 m/s, this value is an indication of good quality concrete according to ACI 228.2R-98 (American Concrete Institute Report ACI 228.2R-98, 1998).

Destructive testing

The studied concretes were also tested in destructive

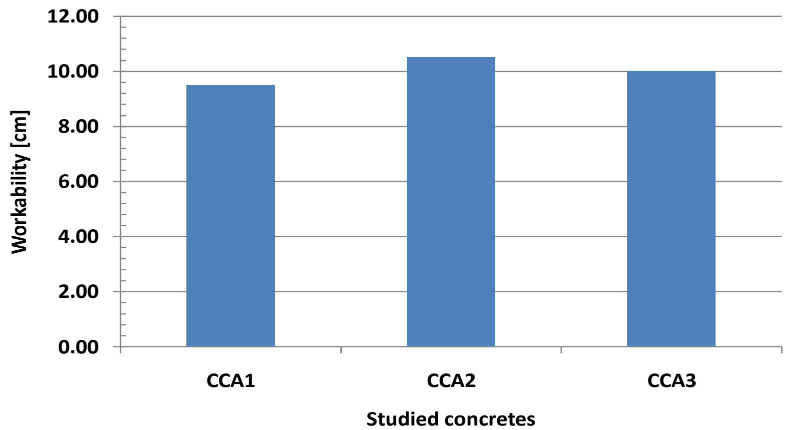

Figure 4. Workability evolutions of studied concretes based on aggregate types.

Table 3. Compressive strength from longitudinal velocity ultrasound.

Variable	V_t moyenne (mm/s)	Strength (MPa)
CA1	4413.33	53.71
CA2	4341.33	48.32
CA3	4263.33	43.08

Table 4. Flexural and compressive strength of studied concretes at 28 days.

Aggregates used	CCA1	CCA2	CCA3
Flexural strength (MPa)	7.79	6.84	6.51
Compressive strength (MPa)	43	46	37

testing by measurement of the flexural and compressive strength of all concrete specimens after 28 days of curing age. The obtained results are given in Table 4.

The results show that strength can be influenced by the aggregates properties that have a direct impact on the properties of concrete. However, the Figure 5 shows the relationship between the parameters of aggregates namely: Micro-Deval and Los Angeles on the mechanical bending and compression resistance. This figure shows that the resistance to compression deflection is inversely proportional to the parameters of aggregates; this relationship is the case for highly flax Los Angeles.

Fatigue test

The fatigue machine is controlled by computer through the testXpert (12.1) software that can give different settings fatigue test: Resonant frequency and these variations, changes in static and dynamic loads, report "r" and the number of cycle. At the beginning of the test, the machine applies a scanning frequency until the resonant frequency of the test piece, in this case the phase shift between the mass-spring system and the specimen is zero, and Table 4 illustrates the results obtained on different types of specimens.

The results can be commented through two parameters: The cycle number and the resonance frequency; the second parameter is proportionally related to the compactness of the material (Table 5). The specimens based on CA2 aggregates exhibit resonance frequency 90 Hz, respectively, followed by those of CA1 and CA3. From this parameter, may have concluded that CA2 aggregates have a higher stiffness compared to other, this is confirmed by the results of characterization of aggregates (Los Angeles and Micro Deval).

Figure 6 give the fatigue results of all studied concretes. This figure presents the applied loading level

Figure 5. Workability test of studied concrete.

Table 5. Results of fatigue testing of concrete samples.

Aggregate types	Loading level (%)	Static force (KN)	Dynamic force (KN)	Cycle numbers	F_{max} (HZ)	Observation at test end
CCA1	80	5.51	1.38	2,000	83.5	Rupture
	70	4.83	1.21	6,462	82.63	Rupture
	60	4.16	1.07	94,804	83.77	Rupture
	55	3.75	0.95	7,499,968	83.84	Sans rupture
CCA2	80	4.83	1.21	1534	89.84	Rupture
	70	4.23	1.05	10,002,341	90.64	Sans rupture
CCA3	80	4.6	1.15	100	79.56	Rupture
	70	4.02	1.00	119,271	76.32	Rupture
	60	3.45	0.86	822,079	80.71	Rupture
	55	3.16	0.79	7,838,769	82.33	Sans rupture

as a function the cycle numbers. It is clearly that the curve fatigue has the same trend as that described in the literature. Indeed, it was observed that a concave portion and a linear portion representing the reduction of the stress with increasing of number of cycles applied. The CA2 aggregate-based concrete has a best fatigue behavior compared to other concrete mixtures. Indeed, the CA2 aggregate-based concrete can support about 70% of maximum load during 1milion of the cycle. For CA2 aggregate-based concrete, the endurance limit is around this level of stress comparatively to the CA1 and CA3 aggregate-based concretes which have a limit is estimated to be around 55% of max loading. The curves obtained in the case of test-based CA3 aggregates are similar to the theoretical model of Wöhler. This means that the load distribution during the test in this case is more homogeneous than in the other cases. Taking into account the mixture homogeneity, the concrete strength and the main characteristics of aggregates such as (Micro-Deval and L.A), the fatigue flexural behavior of concrete with CA1 aggregates appears much better than other concretes (Figure 7).

Conclusion

This study focuses on the research of the influence of aggregates parameters on the mechanical properties of concrete under static and dynamic state. The obtained results show that the aggregates which have parameters and the Los Angeles and micro Deval similar as the case of coarse aggregates 3 (CA3), provide better adhesion with the cement paste, and therefore a greater mechanical strength to bending. As against, the compressive strength and Los Angeles coefficient are inversely proportional: aggregates that have a high

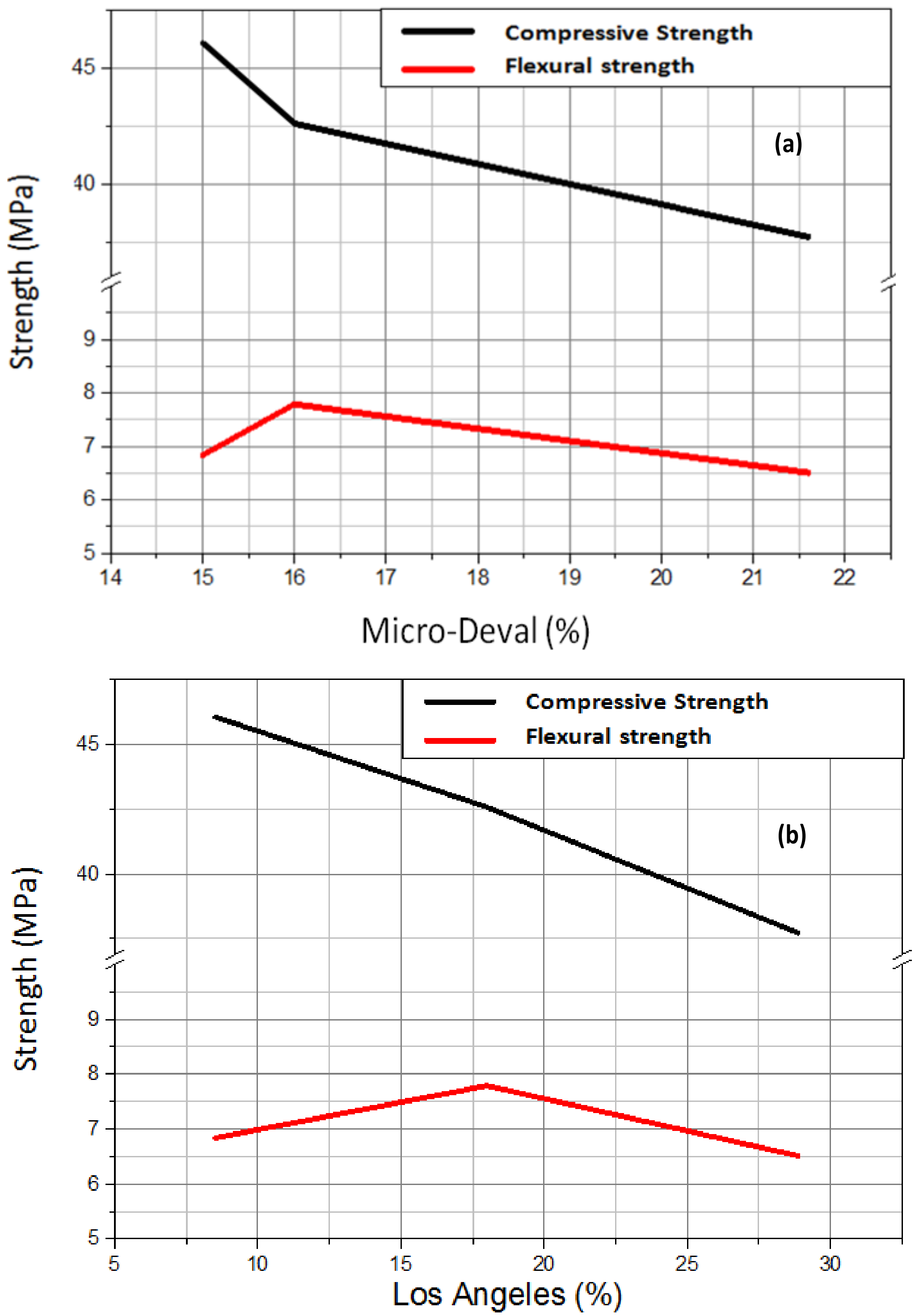

Figure 6. Parameters effecting on the mechanical strengths (flexural and compressive strength) (a) Micro- Deval; (b) Los Angeles.

resistance to fragmentation (a low LA coefficient), provide better a compressive strength of concrete.

The relationship between the compressive strength and the coefficient is inversely proportional Micro Deval: aggregates that have a good wear resistance by triturate (a low MD coefficient) as the case coarse aggregates 2 (CA2), provide a better compressive strength of concrete. Taking into account the compressive strength concrete

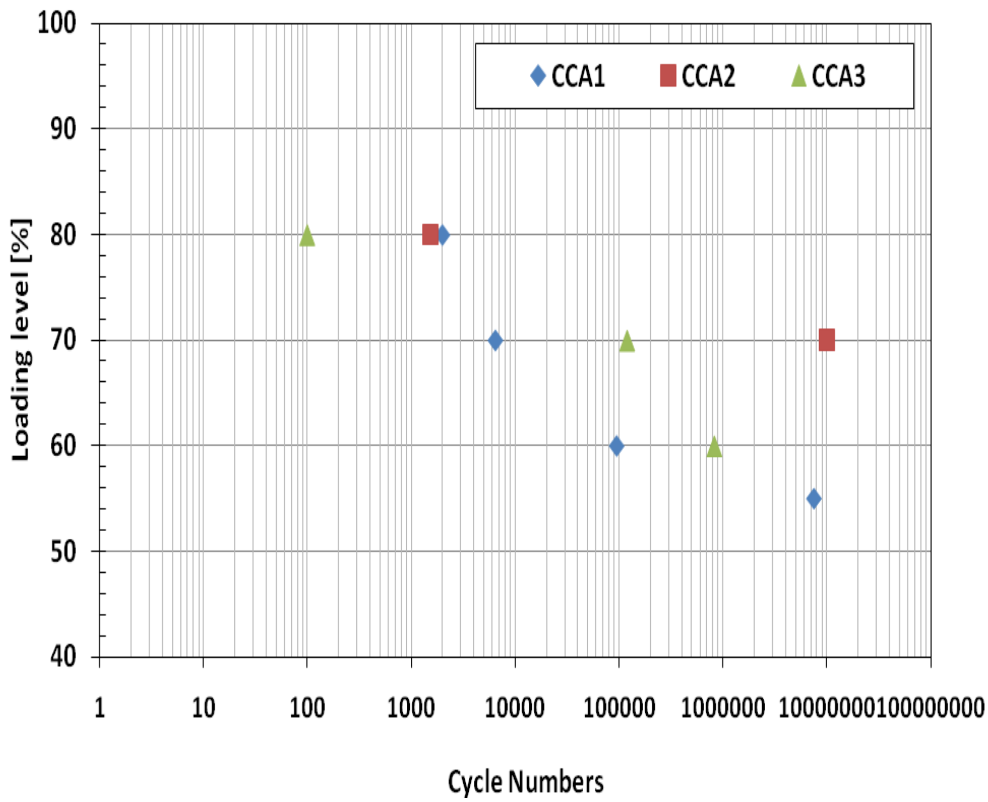

Figure 7. Cycle numbers obtained in the level of the applied load.

and the main characteristics of aggregates such as (Micro-Deval and L.A), the fatigue flexural behavior of concrete with CA1 aggregates appears much better than other concretes.

Dynamic flexural behavior of concrete based on CA3 aggregates, which have a similar Los Angeles and Micro Deval coefficients (respectively 18 and 16), has a force/Cycle numbers with a speed close to the model curve of Wöhler, which indicates a high homogeneity of the charge distribution in the test compared to other concrete varieties.

The relationship between the endurance limit and the coefficient of Los Angeles is inversely proportional: The aggregates which have good resistance to fragmentation (a low LA coefficient) as the case of CA2 aggregates provided an endurance limit at around 70% max load bending.

Conflict of Interest

The authors have not declared any conflict of interest.

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