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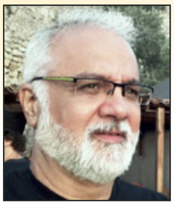
Evaluation of mechanical damage in concrete subjected to uniaxial compression and tensile by diametrical compression with longitudinal and transverse ultrasonic waves

Avaliação do dano mecânico em concreto submetido à compressão uniaxial e à tração por compressão diametral com ondas ultrassônicas longitudinais e transversais



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Abstract

In the research program both longitudinal and transverse ultrasonic waves were applied to concrete specimens under uniaxial compression and tensile diametrical compression. A total of 45 concrete specimens with five (5) different mixes were loaded until failure. While load was being applied – in compression and split tension – ultrasonic pulses were recorded and velocities calculated for both shear and pressure waves. The results indicate that longitudinal or transverse ultrasonic waves can be applied in the evaluation of diffuse damage (microcracking in uniaxial compression) or concentrated damage (tensile microcracking by diametrical compression) imposed on the concrete mechanically through the application of loads.

Keywords: concrete, ultrasonic testing, transverse and longitudinal wave velocities, uniaxial compression, split tension.

Resumo

O trabalho discute o padrão de comportamento de ondas ultrassônicas longitudinais (*compression waves*) e transversais (*shear waves*) em concretos de variadas resistências submetidos a compressão axial e diametral. Foram ensaiados 45 corpos de prova confeccionados de concretos com variadas resistências a compressão. Os corpos de provas foram submetidos ao ensaio de compressão simples e tração por compressão diametral em máquina servo-controlada e, durante os ensaios, foram realizadas leituras de ondas de ultrassom longitudinais e transversais. Os resultados obtidos mostram que há alterações na velocidade de propagação de ondas, longitudinais e transversais, com o incremento do nível de tensão que é aplicado ao corpo de prova. Adicionalmente, foi possível observar que esta alteração de velocidade ultrassônica ocorre para nível de tensão próximo à tensão de ruptura. Os resultados obtidos indicam que ondas ultrassônicas longitudinais ou transversais podem ser aplicadas na avaliação do dano difuso (microfissuração na compressão uniaxial) ou dano concentrado (microfissuração de tração na compressão diametral) imposto ao concreto mecanicamente, através da aplicação de cargas.

Palavras-chave: concreto, ultrassom, velocidade das ondas transversais e longitudinais, compressão uniaxial, compressão diametral.

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1. Introduction

The need to investigate the structural behavior of concrete of different strengths, growing risk of the environment's aggressiveness, aging of structures, understanding behavior of structures throughout their working life, requirements and performance criteria of structures, all contribute to the growing demand for easy-to-apply rapid and reliable test procedures, which are able to provide qualitative and quantitative information on the performance of concrete in conditions of use.

Many innovative research studies have been undertaken at a national and international level to characterize the materials, evaluating qualitatively structural concrete properties using ultrasonic testing [1].

Researchers have looked to correlate the strength and deformation properties of the concrete by non-destructive testing (NDT) in order to analyze the material in real situations of use, but various factors influence this correlation, such as, for example, water-cement ratio, type of aggregate and thickening.

The cracking and degradation process of the elastic properties of concrete subjected to unconfined compression tests by emitting longitudinal and transverse ultrasonic pulses has led to a drop in amplitude with a heavier load level which the concrete element undergoes [2]. This finding could be a valuable tool for evaluating the degree of damage to the investigated element. An important observation of the study was that there was some increase in measured amplitude to low compressive stress levels for longitudinal waves. In the case of transverse waves, a steady drop in this amplitude was found for all stress levels studied. When evaluating the change in ultrasonic pulse velocity as a measure of the damage to structural concretes subjected to unconfined compression, a sudden drop in the pulse velocity was noted from an 85% stress level of the tensile strength. In another study, the authors used the technique to successfully estimate the opening of cracks at different levels of stress [3]. Moreover, the ultrasonic test can also be used to evaluate the profile of thermal damage to concrete structures exposed to high temperatures [4] [5].

This study addresses the method of ultrasonic wave propagation used to understand the propagation pattern of longitudinal and transverse waves in concrete of different compression strengths, undergoing unconfined compression and diametrical compression tests. The completed study gains in knowledge about specimen testing, inasmuch as transverse waves (shear waves) were used instead of only longitudinal waves (compression waves), as normally occurs in ultrasonic wave tests on concrete. Furthermore, the research also considered the fact that the concrete was loaded, under unconfined compression and diametrical compression, when exposed to ultrasonic waves, thus allowing the capture of the ultrasonic wave propagation profile with the stress level applied to the specimen, both for longitudinal and transverse waves.

1.1 Importance of the research

There is an ever increasing urgent need to obtain information about the behavior of structures throughout their working life, and especially to meet recent requirements in the NBR 15575 performance regulations published in Brazil in 2013, and by the middle of that year their use has already become mandatory, with stricter requirements especially for reinforce concrete structures [6].

The ultrasonic wave testing proves to be a valuable ally of builders and designers of reinforced concrete buildings, since it helps to obtain qualitative information about the structures in conditions of use without the need for destructive interventions [7].

The use of the longitudinal and transverse ultrasonic wave propagation to access qualitative information of concrete with varying compressive strengths is perfectly consistent with the current Brazilian standards for design and execution of today's concrete structures that, in 2014, incorporated a possible design with concretes stronger than 50 MPa, a situation that was not considered in earlier versions of Brazilian standards. Today construction projects with concretes of high compressive strength can be designed and implemented, which certainly behave differently from concretes with moderate strength [8], [9].

In order to assess the efficiency of the ultrasonic pulse methods in detecting a process of internal cracking in concrete elements, studies evaluate the velocities and amplitudes of the ultrasonic signal perpendicular and parallel to the cracking plane. The results indicated that both the velocity and amplitude of the signal provided valuable data on the extent of the cracking process, even though velocity has proven to be a more sensitive parameter [10]. The velocity of the ultrasonic pulse depends on the stress level in the concrete up to 70% for tensile strength [1].

In an analysis of the conditions of the conservation state of the concrete in the columns in a Rio Grande do Sul case study, an investigation was carried out on a group of columns in use, in which there was a suspected drop in compressive strength in the test batch of the tested concrete specimen. The investigation's solution to the problem was to use the ultrasonic pulse velocity test (UPV), in which it was possible to verify the efficiency of this test in solving this problem. The UPV test can be considered one of the most promising tests for evaluating concrete structures [5]. The study shows that UPV tests are sensitive to variations in homogeneity and density, thus providing important data for making decisions about conditions of concrete structures. UPV testing could also contribute to the quality control of the concrete structures in conditions of use [11].

2. Materials and experimental program

A total of 45 cylindrical specimens (D = 10 cm and h = 20 cm) were prepared and subjected to increasing levels of unconfined compression and tensile diametrical compression until failure while, at the same time, longitudinal and transverse pulses with single-crystal transducers were transmitted and captured. Five (5) concrete mixes were prepared, nine samples for each mix (three samples to obtain the reference compressive strength, three samples for the ultrasonic pulse velocity test with axial compression, and three samples for the ultrasonic pulse velocity test with tensile diametrical compression).

The cement used in the experimental program was Portland Cement Clinker PC II F 31, with filler. This cement has a compressive strength class of 32 MPa, consisting of 90%-94% clinker and 10%-6% lime filler, pursuant to standard ABNT NBR 11578:1991. The reason why this cement was chosen was because its addition

Table 1
Technical data of admixtures used in the study

Description	Reference values		
	Sikament PF 175	**MasterGlenium 304**	**MasterSet R 283**
Chemical base	Sulfonate salts & carbohydrates in water medium	Synthetic polymers & special admixtures	Sulfonate salts & special admixtures
Aspect	Brown liquid	White & yellowish liquid	Light brown liquid
Density	1.19 ± 0.02 kg/ liter	1.06 – 1.10	1.085 – 1.125
pH	5.5 ± 1.0	8.5 – 10.5	7.0
Solids (%)	–	24.0 – 28.0	22.0 – 26.0

is inert, with no chemical reaction, in order to minimize interferences in the longitudinal and transverse wave propagation velocity inside the prepared test samples. Large and small aggregates of 19 mm crushed stone and course sand, respectively, were used. The materials were characterized in a technological laboratory for civil construction materials.

When making the concrete mixes in the study, three types of admixture were used (Table 1), a plasticizer, superplasticiser and setting retardant. The plasticizer admixture and superplasticiser were used in the mixes in which it was harder to obtain suitable workability, due to the high dry material content. The setting retardant was used in the mixes in which, with the use of the superplasticiser, they would start setting very quickly, hindering the molding of the specimens. Table 2 summarizes the compositions of the mixes used in preparing the concrete (mixes A, B, C, E and F).

After unmolding, the samples were wet-cured for 28 days. Before undertaking the destructive and non-destructive tests, the specimens underwent grinding at the top and bottom. Lateral cuts to the specimen were made so that the transducers could be attached during ultrasonic testing (Figure 1). After grinding a new area approximately 73.34 cm² in size was obtained for the specimens, so that the distance between the parallel surfaces created by the grinding is 9.66 cm. All tests were performed in the construction materials technological testing laboratory (Letmacc) at the Agua Fria Senai Technical School, Recife, Pernambuco, Brazil.

2.1 Ultrasonic pulse velocity test (UPV)

The Pundit ultrasonic instrument was used for UPV testing. Longitudinal and transverse transducers, both with a 500 KHz frequency, were used and all transducers are produced by Panametrics. Every specimen underwent unloaded UPV testing. The transducers were positioned so that the waves were read from direct transmission, which is the most efficient way to transmit the ultrasonic wave in continuous media [12].

2.2.1 UPV test with unconfined compression loading

This test required the following items of equipment: notebook, UPV equipment, longitudinal and transverse transducers with a frequency of 500 KHz; servo-hydraulic universal press and concrete testing microprocessor with maximum capacity of 2,000 kN; couplings suitable for the type of ultrasonic wave; PVC mold to attach the transducers (Figure 2) and a switching element.

The longitudinal and transverse transducers were attached to the

Figure 1
Grinding of specimens to attach transducers

Table 2
Mixes to make the concretes (kg/m³)

Mix	Portland cement	Active silica	Total water	Large aggregate	Fine mesh aggregate	Total	W/C ratio
A	667		193	973	571	2404	0.290
B	597		140	1090	650	2477	0.235
C	495	131	120	1120	620	2486	0.192
E	500		275	785	1005	2565	0.550
F	500		275	355	1430	2560	0.550

Source: Mehta & Monteiro (2014); modified by author

Figure 2
PVC mold for attaching transducers

specimen, supported in a PVC mold and fixed by an elastic band. The loading velocity used for this test varied during the process. The load application velocity was 2 MPa/minute and the last 30% the velocity was 0.5 MPa/minute, to a stress level of approximately 70% or less of the last tension applied to the specimen. This procedure was adopted to obtain as many points as possible in the readings of the longitudinal and transverse ultrasonic waves throughout the test of each specimen. In order to obtain an estimate of the last stress for each concrete mix studied, three specimens failed under unconfined compression to estimate the compressive strength of each mix. These values were used as a benchmark for the loaded UPV test, detailed below.

2.1.2 UPV test with loading in split tension

The UPV test with longitudinal and transverse wave propagation was carried out in conjunction with the tensile diametrical compression test, on 15 cylindrical specimens, and three samples for each mix were prepared.

The standard provides the diagram and fittings required for the tensile diametrical compression test, but in order to enable the coupling of the transducers for the ultrasonic test, it was necessary to create a mold to fix the units to the concrete element, while they were being loaded. To attach the longitudinal and transverse transducers to the specimens during the diametrical compression test, it was necessary to use a steel mold for this purpose, as shown in Figure 3. The mold consists of four coupling points of the transducers, two on each side placed parallel, and attached to the tested elements using four rubber bands.

When carrying out the destructive test (diametrical compression and unconfined compression) and non-destructive test (UPV), pauses were made to take a reading of the longitudinal and transverse wave. The pauses were made every 3 MPa until reaching 70% of the last stress and the remaining 30% showed the pauses dropped to 1.5 MPa. The loading velocity was 0.66 MPa/minute.

3. Results and discussion

3.1 Behavior of longitudinal and transverse waves in specimens subjected to increasing vertical stress of unconfined compression

It was possible, when analyzing the results from the UPV test on longitudinal and transverse waves in concrete samples subjected to confined compression (Table 3), to observe that the waves behaved differently from each other. The propagating velocity of the longitudinal ultrasonic wave was faster in the concrete mix type “C” and slower in the concrete mix type “F”, at 3,850.71 m/s and 3,363.66 m/s, respectively. Concrete type “C” consists of active silica (microsilica), a chemical element used in concrete to improve its properties, namely, durability and compressive strength. Accordingly, the concrete has better compactness, reducing the void ratio in the sample, favoring propagation of the longitudinal ultrasonic wave. Moreover, concrete type “C” has the smallest water-cement ratio (0.192) of the samples analyzed. Concrete type “F”, which has a slower propagation velocity in the longitudinal wave, is a sample with a smaller water-cement ratio (0.55) and higher consumption of fine mesh aggregate when compared to concrete type “E” (concrete with content similar to that of concrete type “F”). The increase in the water-cement ratio and finer material influenced the propagation of the longitudinal ultrasonic wave, since the fine material absorbs more water due to its larger specific surface, reducing the strength and promoting a higher void ratio in the composite.

Also analyzing the samples subjected to the unconfined compression test with transverse ultrasonic wave propagation, concrete type “B” had a faster wave velocity and concrete type “F” slower velocity of the ultrasonic wave, 2,518.07 m/s and 2,197.33 m/s, respectively. Concrete “B” is the sample with the second smallest water-cement ratio (0.235) of the samples analyzed.

Figure 3
Detail of attaching transducers to tensile diametrical compression test (split test)

Table 3
Summary of results of ultrasonic test and unconfined compressive strength in concrete samples

Mix	Type	Specimen	Average unconfined compressive strength (MPa)	Longitudinal ultrasonic waves	Average longitudinal velocity	Stress level where changes began in longitudinal wave velocity (%)	Transverse ultrasonic waves (m/s)	Average transverse velocity	Stress level where changes began in transverse wave velocity (%)
Concrete	A	A 6	46.25	3,787.0	3,709.0	70	2,407.0	2,363.3	90
		A 5		3,708.0			2,365.7		
		A 10		3,632.6			2,318.0		
	B	B 1	47.91	3,830.0	3,846.3	40	2,504.2	2,518.0	60
		B 2		3,871.0			2,520.0		
		B 3		3,838.0			2,530.0		
	C	C 1	59.69	3,854.1	3,850.7	40	2,521.1	2,500.4	61
		C 2		3,828.0			2,507.0		
		C 3		3,870.0			2,473.0		
	D	E 6	31.92	3,596.0	3,594.3	51	2,322.0	2,334.4	75
		E 1		3,572.0			2,333.4		
		E 4		3,615.0			2,348.0		
	E	F 14	25.51	3,274.0	3,363.6	86	2,177.0	2,197.3	70
		F 12		3,391.0			2,195.0		
		F 7		3,426.0			2,220.0		

When analyzing the behavior of the UPV test of longitudinal (Figure 4) and transverse (Figure 5) ultrasonic wave on all concretes studied, it was found that the concrete mixes with higher compressive strength, such as mix "A", "B" and "C", only showed a drop in the velocity of the longitudinal and transverse wave at the end of loading, that is, close to the specimen's moment of failure.

By comparing the results of propagation velocities of longitudinal and transverse waves for the different concrete mixes investigated, more variation was noticeable in the velocity of the longitudinal waves than in the transverse waves. In fact, the propagation velocity of the transverse waves underwent major alterations from 60% of the last stress, while the longitudinal waves experienced altered velocities from 40% of that stress.

In the compressive strength test, the microcracking that occurred was diffuse, generally on the interfaces of the aggregates with hardened paste. This microcracking increases with the further

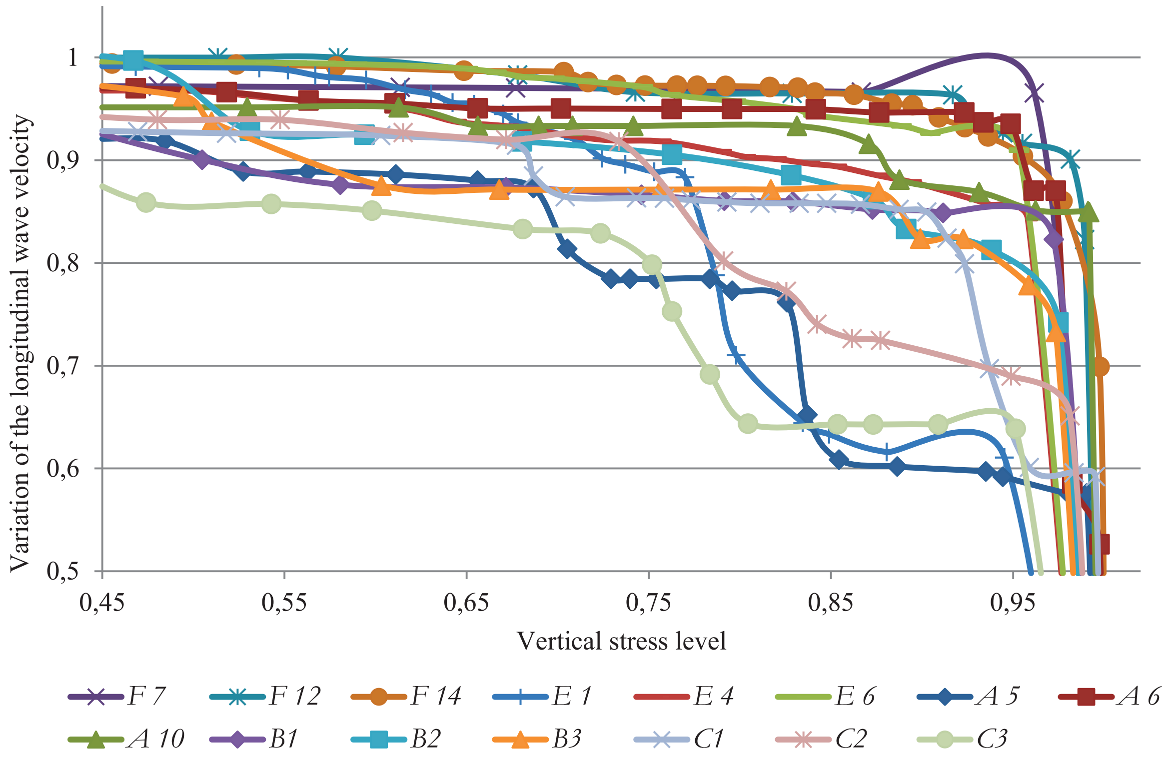

Figure 4
Summary of longitudinal wave behavior in concrete samples subjected to unconfined compression

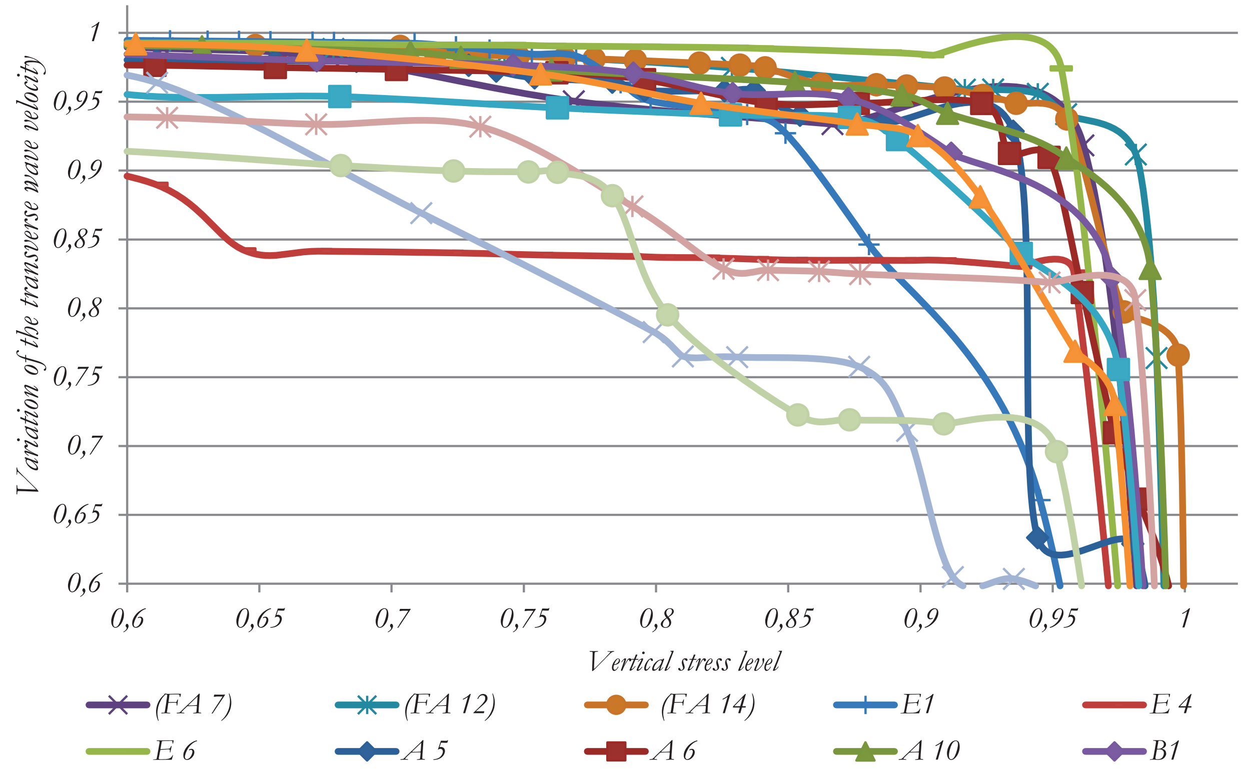

Figure 5
Summary of transverse wave behavior in concrete samples subjected to unconfined compression

loading that caused the concrete to fail [2]. In the concretes with higher compressive strength, however, microcracking normally develops through the aggregates, splitting them [13]. The different behavior in the failure between the stronger and the weaker concretes could justify the differences found in the UPV tests. This is because the mixes of stronger concretes showed much slower velocities and this finding may indicate the occurrence of microcracking through the aggregates and not only around them. Hence the results help conclude that, for the diffuse damage in the concrete (microcracking caused by compression), the longitudinal and transverse ultrasonic waves could be used to evaluate the integrity of the material. Running more tests, however, in a group of samples with wider interval of strengths is recommended to better assess and quantify the differences in the UPV

Table 4
Summary of ultrasonic test and tensile diametrical compressive test in concrete samples

Mix	Type	Specimen	Tensile strength by compression (MPa)	Longitudinal ultrasonic waves	Average longitudinal velocity	Stress level where changes began in longitudinal wave velocity (%)	Transverse ultrasonic waves (m/s)	Average transverse velocity	Stress level where changes began in transverse wave velocity (%)
Concrete	A	A 7	4.88	3,513.00	3,554.67	68	2,457.00	2,381.70	83
		A 8		3,555.00			2,388.00		
		A 9		3,596.00			2,310.10		
	B	B 4	3.67	3,540.00	3,682.61	42	2,316.61	2,434.87	66
		B 5		3,871.47			2,539.00		
		B 6		3,636.36			2,449.00		
	C	C 4	4.51	3,900.37	3,782.88	29	2,507.02	2,450.00	94
		C 5		3,561.28			2,405.00		
		C 6		3,887.00			2,438.00		
	D	E 7	3.61	3,525.94	3,530.60	30	2,311.69	2,287.50	55
		E 9		3,521.00			2,282.00		
		E 11		3,544.84			2,268.79		
	E	F 1	2.96	3,395.37	3,400.78	76	2,176.21	2,188.78	88
		F 9		3,403.69			2,203.44		
		F 10		3,403.28			2,186.70		

test behavior, when applied to the evaluation of diffuse damage in normal and high strength concretes.

3.2 Behavior of longitudinal and transverse waves in specimens undergoing tensile by diametrical compression

Table 4 offers a summary of the results of the longitudinal and transverse UPV test on the concrete specimens, before undergoing the tensile by diametrical compression test. The concrete mix that had the fastest propagation velocity of longitudinal and transverse wave was mix "C" (velocities: 3,782.88 m/s and 2,450.00 m/s, respectively) and the mix with slowest observed propagation velocity of a longitudinal and transverse wave was mix "F" (velocities: 3,400.78 m/s and 2,188.78 m/s, respectively). This behavior is similar to that found in the samples subjected to the aforementioned unconfined compression test.

Figures 6 and 7 show the behavior of the longitudinal and transverse wave for all concrete samples submitted to the split test.

A first and significant observation for the results obtained from the tensile tests is that the two waves, longitudinal and transverse, dropped in the velocities close to the tensile strength of the concrete. This drop in velocities shows the capacity of the ultrasonic pulses to detect the formation of the crack from stress inside the samples during load application. It should be emphasized that, in the tensile by diametrical compression tests, unlike the finding in the uniaxial compression test, there is no diffuse damage (resulting from microcracking); the damage associated with the diametrical compression is local: formation of plane strain and later of a tensile crack, perpendicular to the wave propagation. Thus, the tests showed that, in addition to being fully applicable to check for diffuse damage in concrete, the UPV test can also be used to evaluate concentrated damage – formation of a crack resulting from applied stress. Furthermore, the most sudden and sharpest drop in pulse velocities when close to tensile strength, indicates the sudden nature (not progressive) of the formation of tensile cracking. Again, the ultrasonic pulses appear to fully apply to evaluating the formation of tensile cracking – even though such formation occurs suddenly.

4. Conclusions

The level of mechanically imposed damage to the specimen from applying stresses (unconfined compression or tensile by diametrical compression) directly affects the propagation velocity of the longitudinal and transverse ultrasonic waves in the concrete. Both types of ultrasonic wave used in the study revealed slower

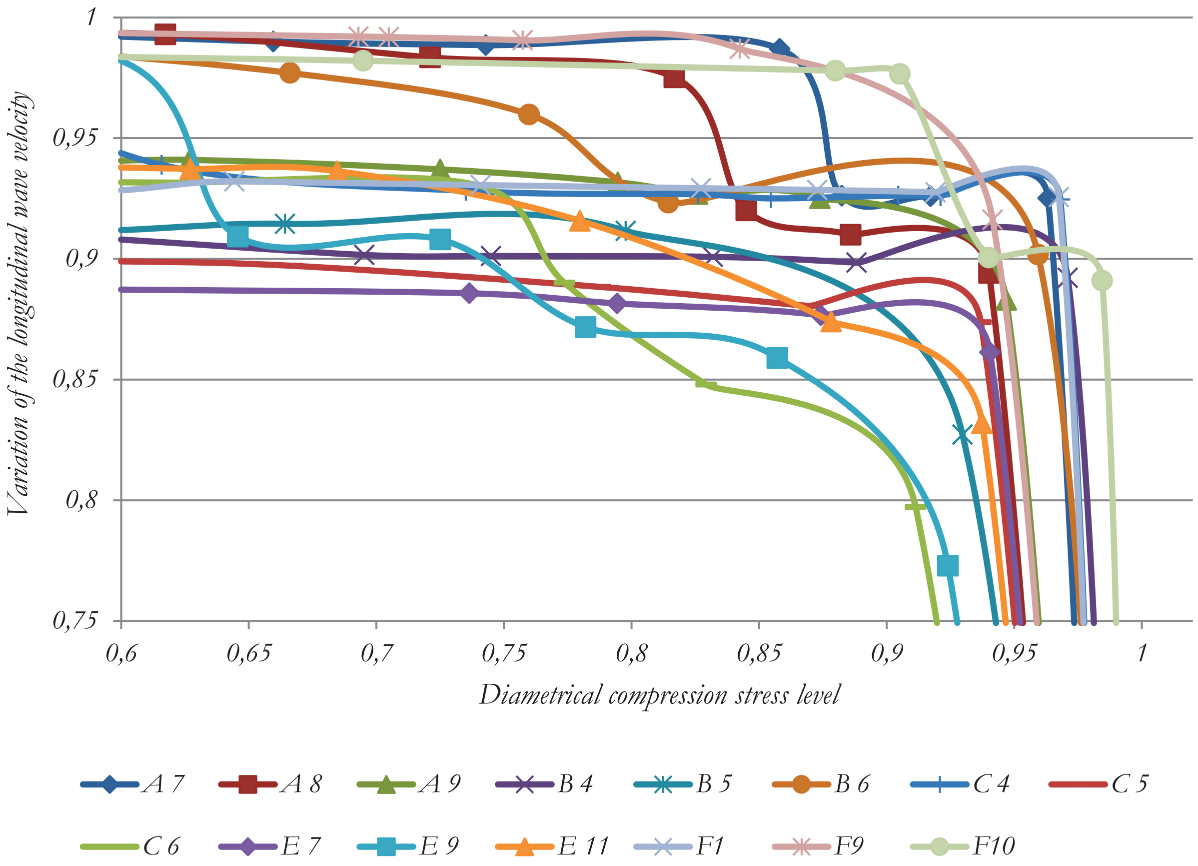

Figure 6
Summary of longitudinal wave behavior in concrete samples subjected to split test

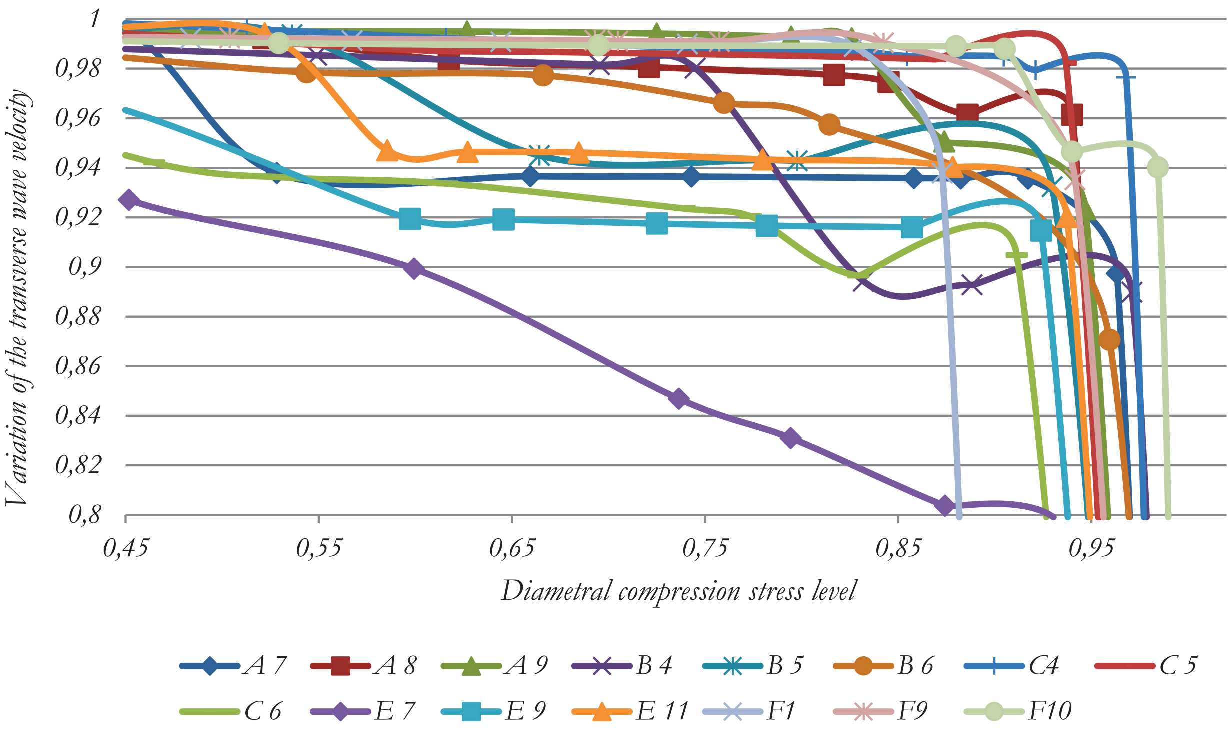

Figure 7
Summary of transverse wave behavior in concrete samples subjected to split test

velocities close to the failure load of the tested specimens. This drop in velocities shows the capacity of ultrasonic pulses to detect the formation of tensile microcracking inside the samples when applying loads and detecting microcracking caused by uniaxial compression; hence, the test is efficient for samples undergoing tensile and compressive loads, thereby evaluating the integrity of the material.

For local damage, as a result of diametrical compression (with the formation of a tensile plane and, later, tensile crack, perpendicular to the wave propagation), the tests showed that the UPV test is efficient in its evaluation. In the unconfined compression tests, however, for the concrete samples tested, the propagation velocity of the longitudinal wave proved more sensitive to the level of stress applied, when compared to the transverse wave. In other words, the longitudinal ultrasonic wave more often used by researchers in this type of test best represents the reality and integrity of the tested sample, and also detects any kind of void that might exist in the sample, probably due to the form of the wave's propagation therein.

The composition of the concrete influences the behavior of the ultrasonic wave, whether longitudinal or transverse, and in addition, it is very much worth considering the information of the water-cement ratio and concrete strength when analyzing the results of the UPV test.

The results overall for the two types of ultrasonic pulses used attest to the feasibility of applying non-destructive ultrasonic tests when examining the diffuse damage and concentrated damage in the concrete.

Several studies are required in order to be able to learn about the behavior of the concrete in use through non-destructive tests. But based on the results in this study, it is noticeable that the ultrasonic velocity is an extremely valuable test for the technological control of concrete, principally when correlated with the water-cement ratio, this datum being obtained at the start of mixing the concrete, since its strength will be obtained after 28 days and with the concrete element in use.

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