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Detection of self-compacting concrete bleeding through ultrasonic wave analysis

Detecção da exsudação do concreto autoadensável através da análise de ondas ultrassônicas

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Abstract

Self-compacting concrete represents an advance in concrete technology, combining performance, uniformity, and other requirements that cannot be achieved with vibrated concrete. The main characteristic of this kind of concrete is its flowability, obtained using fine materials, viscosity modifiers, and superplasticizer additives. However, the excessive use of superplasticizer makes the mixture susceptible to segregation and bleeding, changing its mechanical properties in the hardened state. Currently, non-destructive tests (NDT) are used to evaluate concrete's physical and mechanical properties, without causing damage to the analyzed element. Ultrasonography stands out, which makes it possible to evaluate the homogeneity of the concrete through the ultrasonic pulse velocity. Recent studies show that the waveform can bring potentially more effective parameters in the analysis of non-homogeneous concretes. In this context, the present study evaluated the properties of a self-compacting concrete mix with two dosages of superplasticizer additive, using ultrasonic wave parameters to identify concrete bleeding. Results showed that the group velocity and the energy propagated through the material are parameters sensitive to variations in the uniformity of the concrete, demonstrating its capacity to detect concrete bleeding.

Keywords: concrete; self-compacting; superplasticizer additive; ultrasound; bleeding.

Resumo

O concreto autoadensável representa um avanço na tecnologia do concreto, pois é capaz de reunir desempenho, uniformidade e outros requisitos que não se podem alcançar com o concreto convencionalmente vibrado. A principal característica deste concreto é sua elevada fluidez, obtida utilizando materiais finos e aditivos modificador de viscosidade e superplastificante, entretanto, o excesso na dosagem deste último torna a mistura suscetível à segregação e exsudação, alterando suas propriedades no estado endurecido. Atualmente, ensaios não destrutivos (END) são empregados para avaliar as propriedades físicas e mecânicas do concreto, sem causar danos ao elemento analisado, dentre os quais, destaca-se a ultrassonografia, que possibilita realizar uma avaliação da homogeneidade do concreto através da velocidade de pulso ultrassônico, e, estudos recentes demostram que o formato de onda pode trazer parâmetros potencialmente mais eficazes na análise de concretos não-homogêneos. Neste contexto, o presente estudo avaliou as propriedades de um traço de concreto autoadensável com duas dosagens distintas de aditivo superplastificante, utilizando parâmetros advindos do formato de onda ultrassônica para identificar a exsudação do concreto. Os resultados mostraram que a velocidade de grupo e a propagação da energia pelo material apresentam-se como parâmetros sensíveis às variações da uniformidade do concreto, demonstrando capacidade na detecção da exsudação.

Palavras-chave: concreto; autoadensável; aditivo superplastificante; ultrassom; exsudação.

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Introduction

The Brazilian standard NBR 15823 (ABNT, 2010) defines self-compacting concrete (SCC) as one that can flow, self-compacting by its own weight, fill the formworks and pass through the reinforcements while maintaining its homogeneity. In other words, SCC is a high-performance concrete with high fluidity and resistance to segregation, which does not require mechanical vibration.

Currently, the SCC represents a breakthrough in concrete technology because it is a composite capable of bringing together performance, uniformity, and other requirements that cannot be achieved with conventionally vibrated concrete. The self-compacting concrete dosage is complex, requiring a thorough study of the mixture and its behavior in the fresh state (MENDES; BAUER; SILVA, 2017). The flowability of SCC is guaranteed mainly by the use of superplasticizer additives (SP), which, when used in combination with a high content of fine materials (cement and mineral additions), guarantee, in addition to the resistance to segregation, one of the most important principles of self-compacting concrete: its high workability (SILVA; BRITO, 2009).

The SCC needs a large portion of fines in its constitution as a viscosity promoter, and usually, flying ash and fillers of granite, marble, and limestone are used. According to Schankoski *et al.* (2017), diabase and gneiss fillers can be used as alternative materials to limestone fillers in SCC, although they may require a higher amount of superplasticizer additive.

Superplasticizers are additives known as high-efficiency water reducers, permitting a reduction of 30% of the water content, and optimizing the amount of cement and other binders (VERZEGNASSI, 2015). The excessive use of this additive can raise the cost of concrete and cause segregation and bleeding in concrete (HERBUDIMAN; SAPTAJI, 2013), resulting in a reduction in durability and mechanical strength. According to Fenato *et al.* (2007), the viscosity modifier additives are not always necessary but can be used to obtain highly fluid and stable concrete without segregation and bleeding, being these properties important, mainly for pumped concretes.

Segregation can be defined as separating the constituents of a heterogeneous mixture so that their distribution is no longer uniform and may occur in the concrete by sliding the larger particles inside the mortar or by excess water in the mixture (NEVILLE; BROOKS, 2013). Repette (2011) classifies segregation in the SCC as dynamic or static. The first occurs during concrete placement, influencing the flow and passing ability, and is usually associated with the lack of cohesion of the mixture. The second occurs after the concrete placement when coarse aggregates sink in mortar, and the rise of the liquid phase of the material occurs, called bleeding.

The phenomena must be detected during the technological control of the concrete, but sometimes it can go unnoticed during the production and placement, and its effects on the mechanical properties of the material are detected only in the hardened state by cracking of structural elements. The development of increasingly consistent analysis methodologies to evaluate the physical and mechanical conditions of these concretes becomes indispensable. Whereas quality requirements are consolidating, there is great interest in the applicability of non-destructive tests (NDT) in concrete, as these make it possible to evaluate the properties of materials without deterioration, as occurs in chemical and mechanics analysis (CARELLI; SAVARIS; PINTO, 2014).

Among the NDT methods, ultrasonography stands out, which can be considered one of the most promising for the evaluation of concrete structures since the behavior of ultrasonic waves is directly related to the material's mechanical properties. The tests, therefore, are based on the measurement of the ultrasonic pulse velocity (UPV) with which the wave propagates through the element of analysis, and which is mainly dependent on the physical properties of the material (PAYAN; ABRAHAM; GARNIER, 2018; TINOCO; PINTO, 2021).

On the other hand, UPV is characteristic of the fastest energy component, which travels through the shortest path, not considering the arrival of the remaining energy. Because it is the first detectable wave disturbance, UPV is the least sensitive evaluation parameter to the internal variations of the concrete and, therefore, the use of a parameter that considers the whole pulse or a more significant part of it can be of great utility (BRESSAN, 2019; SHIOTANI; AGGELIS, 2009). In this context, some parameters associated with the propagation format of the ultrasonic wave have been studied recently for in-depth evaluations regarding non-homogeneities and internal failures of the concrete from the ultrasonography (BRESSAN, 2019; CÂMARA, 2017; HOFMANN, 2015; SILVA, 2017; TINOCO; PINTO, 2021; VIANA, MORAES; IVO, 2022).

According to Tinoco and Pinto (2021) and Viana, Moraes and Ivo (2022), the signal processing emitted by ultrasound in the tests enables the analysis of attenuation parameters, which can be studied from the analysis of the propagation format of the ultrasonic wave by the concrete. The attenuation of ultrasound results from the loss of wave propagation energy through the concrete as the distance traveled increases. According to Payan, Abraham and Garnier (2018), this phenomenon occurs due to the scattering of the concrete microstructure, which redirects the energy, and due to the dissipation of the water/cement viscoelastic matrix, which is related to energy absorption. The attenuation parameters studied are group velocity, maximum amplitude, and propagated energy.

Group velocity is a measure of the speed at which most energy is propagated; that is, while UPV is the fastest component of energy, which travels through the shortest path, not considering the arrival of the rest of the energy, the group velocity is a measure that considers the latest arrivals. Amplitude is a scalar measure of the oscillation magnitude of a wave and represents the value of the highest peak of the ultrasonic pulse observed during the test. According to Shiotani and Aggelis (2009), the propagated energy can be defined as the area below the rectified signal of the wave envelope, that is, the module of the amplitudes. The accumulated energy represents the sum of all energy portions in the analyzed time interval.

According to Lorenzi *et al.* (2017), with the improvement of methods and the development of portable and reliable equipment, ultrasound can play a relevant role in detecting and evaluating defects and monitoring internal variations of concrete. As already mentioned, self-compacting concrete requires superplasticizer additives (SP) to obtain fluidity, and the high concentration of this additive in the mixture can cause static and/or dynamic segregation of the material. In this sense, this work presents the results of an experimental program using ultrasound tests in self-compacting concrete produced with two different proportions of superplasticizer additive to induce concrete segregation, evaluating how UPV and waveform parameters can contribute to the detection and investigation of these phenomena.

Materials and methods

Experimental procedure

In this study, a concrete mixture with materials mass proportion 1:1.58:0.82:2.80 (cement:sand:filler:gravel) was adopted, with a w/c ratio equal to 0.52, developed by Pufal (2017), which presented average compressive strength close to 40 MPa and met the criteria of classification as CAA of NBR 15823 (ABNT, 2010).

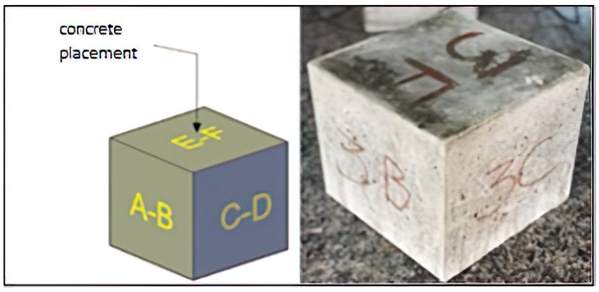
In concrete production, was used Portland cement of high initial strength (CP V-ARI), crushed rock of basaltic origin as coarse aggregate, with a maximum characteristic dimension of 9.5 mm and specific mass of 2.73 g/cm^3. As fine aggregate was used natural quartz sand, with a modulus of fineness equal to 2.67 and specific mass of 2.65 g/cm^3. To promote higher viscosity was used limestone filler from Almirante Tamandaré-PR.

A superplasticizer additive based on sodium polycarboxylate was used to increase fluidity. In the first mixture (K_1), the dosage of this additive was defined based on the results of the slump flow test, performed according to NBR 15823 (ABNT, 2010), reaching the minimum value of 550 mm, using a quantity of additive corresponding to 0.62% of the cement mass. In the second dosage (K_2), an increase of 85.5% to the amount of additive used in K_1 was adopted, where the objective was to induce the concrete to segregation. In the fresh state, concretes were evaluated for slump flow, apparent plastic viscosity (V-Funnel), and passing ability (L-Box), according to tests defined by NBR 15823 (ABNT, 2010).

After the production of the concretes, with each of the dosages, three cylindrical specimens, 10 cm in diameter and 20 cm in height, were molded to perform the axial compressive strength tests, and one cubic specimen, 20 cm edge, was molded to perform the ultrasound tests. The adoption of cubic specimens was necessary to meet the frequency limitations of the apparatus used in the tests since the dimension perpendicular to the path traveled by the ultrasonic pulse could not be less than the wavelength of the vibration pulses.

Three faces of the cubic element were named A-B, C-D, and E-F, the latter corresponding to the direction of concrete placement, as illustrated in Figure 1.

Figure 1 – Cubic specimen faces.



Source: The authors.

All specimens were demolded after 24 hours and cured submerged in water, at a temperature of 21 ± 2 ºC, until 28 days, when the tests were performed.

Ultrasound tests

The ultrasound tests were performed using the ultrasonic equipment Pundit Lab, with transducers of 54 kHz, which in addition to the pulse propagation time, also provides data on the shape of the wave propagated by the concrete over time, and allows you to adjust some usage parameters, such as pulse amplitude, gain in the received signal (amplification) and time to display the curve. After some previous and comparative tests that aimed to evaluate the behavior of the wave propagated by the concrete, the pulse output amplitude was fixed at 125 V, without the need to amplify the received signal, and the curve display time was set at 0.2 ms (0.0002 s).

To ensure uniform contact between the transducers and the surface of the specimen, the ultrasonic gel was used as a coupling agent. The ultrasonic wave transmission was made directly, with the transducers positioned on opposite faces of the specimen, as shown in Figure 2. Thus, eight readings were performed on each of the element's three opposite faces, resulting in twenty-four ultrasound readings per specimen.

Figure 2 – An ultrasound test using direct transmission mode.

Source: The authors.

After the ultrasound tests, the data were analyzed and compared the ultrasonic pulse and group velocity, as well as the propagation energy of the ultrasonic pulse in the two concretes.

Results and discussion

Concrete properties in the fresh and hardened state

The properties of the two concrete mixtures in the fresh and hardened state are presented in Table 1, where, in concrete K_1, the additive superplasticizer/cement ratio (SP/c) of 0.62% was sufficient for the concrete to overcome the minimum standard scattering, reaching 560 mm, with flow time in V Funnel equal to 9 seconds and height ratio in L Box of 0.82. In concrete K_2, with an SP/c ratio of 1.15%, there was an increase in concrete flow to 795 mm, viscosity reduction, with V Funnel time of 5.1 seconds, and an increase of the ratio between the heights in L Box to 0.88.

Table 1 – Properties of concretes in the fresh and hardened state.

Concrete	SP/c (%)	Slump flow (mm)	V Funnel (s)	L Box
K_1	0.62	560	9.0	0.82
K_2	1.15	795	5.1	0.88

Source: The authors.

In concrete K_2, bleeding was observed, with the formation of a halo in the slump flow test, as shown in Figure 3(a), and especially after the molding of the cylindrical and cubic specimens, as can be seen in Figure 3(b), where, it was observed at the top of the specimen a film of water and cementitious particles.

Figure 3 – Bleeding of concrete K_2 detected during: (a) slump flow test; (b) and in the specimen molding.

(a) (b)

Source: The authors.

Both concrete presented average axial compressive strength close to 40 MPa, as shown in Table 2, and despite the segregation, the concrete K_2 presented mean compressive strength slightly higher than the concrete K_1.

Ultrasonic pulse velocity

Table 3 shows the mean values of the pulse velocity readings and the group of the two concretes in the three perpendicular directions of the cubic specimen.

Comparing only the results of UPV, in Table 3, there are higher velocities in concrete K_2, indicating a concrete with better compaction and lower presence of voids. Also, evaluating the standard deviation between the UPV readings, it is found that the concrete K_2 has less uniformity in the material in relation to the three perpendicular directions analyzed. In addition, there is a reduction of UPV in the direction of concrete release (E-F), which is more significant in bled concrete, K_2.

Table 2 – Axial compressive strength.

Concrete	Specimen	Strength (MPa)	Average Strength (MPa)	Standard deviation (MPa)
	1	31.72		
K_1	2	44.12	37.96	6.20
	3	38.04		
	1	39.18		
K_2	2	44.32	39.08	5.29
	3	33.73		

Source: The authors.

Table 3 – Pulse (UPV) and Group (V_G) velocity.

Direction	Mean UPV (m/s)		Mean V_G (m/s)	
	K_1	K_2	K_1	K_2
A-B	4,276.80	4,609.70	1,562.50	1,652.89
C-D	4,193.88	4,467.44	1,550.39	1,646.09
E-F	4,142.60	4,309.79	1,538.46	1,048.39
Standard deviation	55.29	122.49	9.81	283.38

Source: The authors.

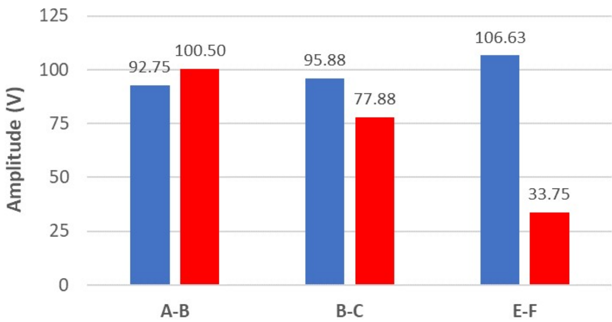
According to Bauer (1987), pulse velocities in the direction parallel to the concrete placement direction are lower than in the transverse direction because the superficial layers of concrete have inferior quality due to the wall effect and bleeding phenomena. This fact was evidenced in the two concretes; however, for the concrete K_2, a higher variation of UPV was observed, and there was also variation between the faces perpendicular to the placement direction, indicating that UPV can detect the bleeding of the SCC in this study.

The group velocity presented a considerable reduction in the direction of the E-F face of the K_2 concrete, indicating the possibility of some failure in the concrete production. The group velocity reduction in this direction was higher than 36% when compared to the mean values observed in the transverse faces. The concrete K_1, on the other hand, presented more uniform velocities between the perpendicular directions. Thus, it is plausible to state that the group velocity is presented as a parameter sensitive to internal variations caused by the excessive use of the superplasticizer additive in the direction of concrete release, being able to detect the bleeding visually observed in K_2.

Maximum amplitude

Shiotani and Aggelis (2009) and Hofmann (2015) demonstrated that the amplitude of the transmitted signal is reduced in non-homogeneous concretes. As shown in Figure 4, in the direction of E-F, there is a significant reduction of the wave amplitude in concrete K_2 to K_1. However, there are also slight variations in the other directions.

Figure 4 – Maximum amplitude measured on each face: K_1 (blue color) and K_2 (red color).



Source: The authors.

The lowest maximum amplitude observed in K_2 concrete, Figure 4, can be attributed to the segregation of the concrete with greater aggregate deposition at the bottom of the cube and a layer of cement paste at the top, as was observed in the molding of the cylindrical specimens in Figure 3(b).

Energy propagation

The energy propagated by concrete is defined as the area below the signal rectified by ultrasound. To determine this parameter, was used numerical integration about the time interval analyzed. Table 4 presents the results of initial energy and total energy, the first being the portion of energy propagated by the ultrasonic pulse until the time corresponding to the maximum amplitude of the wave, while the total energy considers the whole signal of the wave emitted in the test.

Table 4 – Energy propagated by concrete.

Direction	Initial Energy (V.μs)		Total Energy (V.μs)	
	K_1	K_2	K_1	K_2
A-B	3,219.97	4,609.70	1,562.50	1,652.89
A-B	3,219.97	4,067.44	4,762.03	5,292.69
C-D	3,221.00	3,454.22	4,580.94	4,405.59
E-F	3,265.56	1,013.91	5,069.72	1,783.13
Standard Deviation	21.25	1,318.89	201.76	1,490.02

Source: The authors.

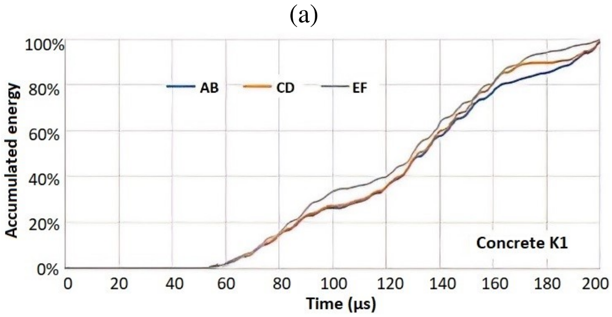
It is observed through the results obtained for the initial energy of the concrete K_1, the slight variation in the energies between the three directions, while in the concrete K_2, there is a great attenuation in the direction of the face E-F. For the total energy, despite more significant variation in concrete K_1 about the initial energy, there is a similar behavior, with a considerable reduction in the E-F direction in concrete K_2, indicating that there is less uniformity of the material in this direction.

In addition to analyzing the absolute values calculated for the energy parameters, the curves representing the distribution of energy propagated over time were also evaluated.

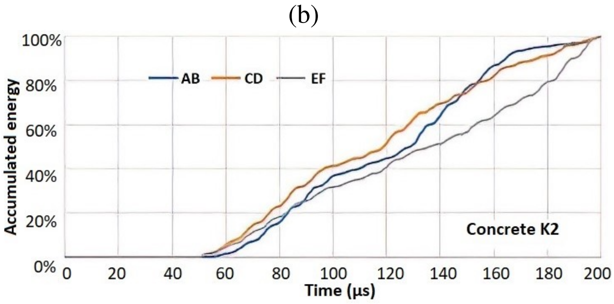
Figure 5 shows the energies accumulated over the reading time for the two concretes, considering the three analysis directions.

Figure 5 – Curves of accumulated energy: (a) Concrete K_1; (b) Concrete K_2.

(a)



(b)



Source: The authors.

In concrete K_2, it is noted that the curve representing the accumulated energy in the direction of concrete placement (E-F) presents a significant reduction in its inclination compared to the other two transverse directions. This means that in the direction where dynamic segregation occurs, a longer time interval is required to achieve the same percentage of the accumulated energy propagated in the direction transverse to concrete placement.

In addition, it is noted that this attenuation in the energy distribution in the E-F direction is more pronounced, mainly from the time of 140 μs, indicating a more significant delay in the arrival of the first amplitudes in the direction of casting the bled concrete. Such attenuation occurs so that approximately 50% of the emitted energy is propagated after that time, while this value is about 33% in the transverse direction.

In contrast, in concrete K_1, this phenomenon was not evidenced since there was no segregation or bleeding of the mixture. Therefore, the energy distribution was more uniform and less predictable.

Conclusion

In this research, the ultrasound test was used to detect self-compacting concrete bleeding due to excessive superplasticizer additive use, and the following results were obtained:

Even with a high dosage of superplasticizer additive, which resulted in static and dynamic segregation, the concrete reached an axial compressive strength at 28 days of age, close to 40 MPa, similar to concrete with an adequate dosage of this additive.

The ultrasonic pulse velocity (UPV) presented results that can be correlated to concrete compressive strength, demonstrating to be a very useful parameter. However, a higher number of tests must be realized to evaluate the sensitivity of this parameter to identify the segregation phenomenon.

The group velocity presented a considerable attenuation in transversal directions for static and dynamic segregation, demonstrating sensitivity to the internal variations of the concrete physical properties that were not identified through the UPV, and can be used in the evaluation of concrete with internal failures.

The maximum amplitude of the wave also presented significant attenuation in the placement direction, where the bleeding was observed. However, the directions transverse to the concrete placement showed greater dispersion in their absolute values.

As well as group velocity, initial energy, total energy, and accumulated energy presented significative attenuations in the placement direction, demonstrating the ability to detect failures in concrete not observed through UPV, which is the only parameter commonly evaluated in the analysis of concrete structures using ultrasound.

Finally, we emphasize the importance of more studies about these parameters obtained through the propagation format of the ultrasound wave in the time domain. They were able to detect internal failures that did not manifest immediately in concrete, but during the structure life can serve as a trigger for the entry of aggressive agents, causing deleterious effects that can compromise the functionality and durability of concrete structures.

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