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Simulation of pathological manifestations in diaphragm wall through ultrasonic wave propagation

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ABSTRACT

This research aimed to simulate pathological manifestations in diaphragm wall using concrete produced with different additions of synthetic polymer, in order to obtain models of strength and stiffness prediction through ultrasound wave propagation. Compression tests were performed to determine strength and stiffness, as well as ultrasound tests by direct and indirect method on concrete produced with different concentrations of synthetic polymer. The results suggested a decrease in the mechanical and acoustic properties of concrete with the increase in the concentration of synthetic polymer. The models generated by the ultrasonic test were statistically significant, at 95% confidence level, and the correlations established in concrete can be applied in the detection of pathological manifestations in loco.
Keywords: diaphragm wall ultrasonic wave propagation; strength and stiffness.

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Contribution of each author
In this study, Silva, R. R.C., contributed to the acquisition of financing activity, methodology, research, preparation of the experimental program of samples, draft and original writing, Pedroso, C.B. contributed to the conceptualization, methodology, supervision, and analysis of data.

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Simulación de manifestaciones patológicas en muro pantalla mediante propagación de pulso ultrasónico

RESUMEN

El objetivo de esta investigación fue simular manifestaciones patológicas en muros pantalla a través de hormigones elaborados con diferentes adiciones de polímero sintético, proponiendo obtener modelos de predicción de resistencia y rigidez a través de la propagación de ondas de ultrasónica. Se realizaron ensayos de compresión para determinar resistencia y rigidez, así como ensayos de ultrasonido por el método directo e indirecto sobre hormigones producidos con diferentes concentraciones de polímero sintético. Los resultados obtenidos indicaron una disminución de las propiedades mecánicas y acústicas del hormigón con el aumento de la concentración de polímero sintético en su confección. Los modelos generados por la prueba ultrasónica fueron estadísticamente significativos, con un nivel de confianza del 95%, y las correlaciones establecidas en concreto pueden ser utilizadas en la detección de manifestaciones patológicas in loco.

Palabras clave: muros pantalla; propagación de pulso ultrasónico; fuerza y rigidez.

Simulação de manifestações patológicas em parede diafragma através de propagação de ondas ultrassônicas

RESUMO

O objetivo dessa pesquisa foi simular manifestações patológicas em parede diafragma através de concretos produzidos com diferentes adições de polímero sintético, propondo obter modelos de predição de resistência e rigidez através de propagação de onda de ultrassom. Foram realizados ensaios de compressão para determinação da resistência e rigidez, assim como ensaios de ultrassom pelo método direto e indireto em concretos produzidos com diferentes concentrações de polímero sintético. Os resultados obtidos indicaram queda nas propriedades mecânicas e acústicas do concreto com o aumento da concentração de polímero sintético em sua confecção. Os modelos gerados pelo ensaio ultrassônico foram estatisticamente significativos, ao nível de confiança em 95%, podendo, as correlações estabelecidas em concreto, serem utilizadas na detecção de manifestações patológicas in loco.

Palavras-chave: parede diafragma; propagação de ondas ultrassônicas; resistência e rigidez

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1. INTRODUCTION

As civil constructions have been increasing in recent decades, studies have investigated ways to facilitate the execution of major constructions that face difficulties due to unstable soils in which they are located. According to Hachich et al. (2019), the use of a containment system with diaphragm wall which consists of open trench in the ground filled with reinforced concrete stabilized by the synthetic use of polymeric fluids or bentonite clay is one of the alternatives to assist in the excavation of soils.
The use of synthetic polymer in excavations has great advantages over traditional forms of soil stabilization, such the use of bentonite. According to Mota (2010), the economic aspect is an advantage, because polymers although its cubic meter is more expensive than bentonite clay require less amounts of product to obtain better yields than traditional forms (bentonite clay). According to Mota (2010), the environmental factor is also noteworthy, mainly because of some properties of polymers, namely: their high solubility, chemical sensitivity, and ultraviolet ray actions that end up fragmenting their polymer chains and, therefore, preventing bioaccumulations. Thus, the use of polymers as stabilizers in excavations do not affect the environment (Mota 2010).
Studies conducted by Mota (2010) found that the highly concentrated synthetic polymer can be used specifically to chemically interact with all types of soil as the basis of its stabilization. Its molecular structure allows for total water solubility, without changing its primary role of active chemical bonding in the stabilization of soil particles.
The use of this polymer during excavations should follow the recommendations of ABNT-NBR 6122 (2019), with concrete density ranging from 2.1 to 2.8 g/cm³ and minimum cement consumption of 400 kg/m^3, and stabilizing fluid as polymer with water pH between nine and 12, density from 1.005 g/cm^3 to 1.1 g/cm^3 and sand content up to 4.5%. According to Djelal et al. (2020) one of the pathologies found on the diaphragm wall is related to the mixture of polymer fluid during concreting, increasing the infiltration of groundwater from the soil after the execution of the panels, compromising the concrete ability to resist compression.
In loco diaphragm walls are extremely difficult to be assessed, especially regarding the addition of synthetic polymer, and its influence in the quality of the concrete. The ultrasound test is one tests that do not damage the concrete containment system as suggested Silva (2020). Studies conducted by Savaliya et al. (2014), through ultrasound test in concrete structures, demonstrate that the method is able to accurately detect pathologies, identifying defects and its specific location.
Considering the aforementioned aspects, our project used non-destructive ultrasonic wave propagation tests, directly and indirectly, simulating in loco inspection to verify its sensitivity in predicting mechanical (strength and stiffness) and physical (water absorption) properties of concrete made with different concentrations of synthetic polymer.
Thus, this research aimed to simulate pathological manifestations in diaphragm wall with different quantities of synthetic polymer in the concrete, proposing models of prediction of strength and stiffness obtained through ultrasound wave propagation tests to evaluate this containment system in loco.

2. EXPERIMENTAL PROGRAM

For the research, concrete were made with CPII-F cement proportions following the ABNT-NBR 11578 (1997): medium sand and gravel 01 (1:1.8:2.5), and the cement was measured in mass, aggregates by volume and water-cement ratio of 0.6, as specified for concrete structures as diaphragm walls (ABNT- NBR 6122, 2019). Considering the standard mixture, different percentages of synthetic polymer 0%, 20%, 40%, and 60% of granulated anionic polymer and high molecular weight > 21 million and long chains used for flocculation were added in relation to the

cement mass (Figure 1a). The characterization of the aggregates was carried out according to the recommendations of the standards for fine aggregate NBR (NM 248, 2003; NM 52, 2009; NM 45, 2006) and coarse aggregate NBR (NM 248, 2003, NM 53, 2003, NM 45, 2006). After 28 days, the samples were subjected to the immersion absorption test, according to the specifications of ABNT-NBR 9778 (2015).
Table 1 shows the characterization of aggregates within the limits of acceptability, according to ABNT - NBR 7211 (2009).

Table 1. Results of the physical characterization of fine and coarse aggregates.

Aggregate	**Specific Mass (kg/m^3)**	**Unit mass (kg/m^3)**	**Maximum diameter (mm)**	**Fineness modulus**
Granite	2650	1500	25	6.75
Sand	2590	1310	4.8	1.89

The addition of synthetic polymer presented a behavior similar to the addition of water to the concrete, especially when assessing workability (Slump Test values) and density, that is, the increment in polymer quantity increased workability and reduced the density (Table 2).

Table 2. Slump Test and medium density values of concrete produced with different synthetic polymer quantities.

Quantity	**Slump Test (mm)**	**Average density (kg.m^{-3})**
0%	180	2223
20%	210	2097
40%	250	1934
60%	260	1900

After the Slump tests, 12 cylindrical specimens (100 mm in diameter and 200 mm in length) and one prismatic specimen (400 x 400 x 300 mm^3) were molded for each mixture simulating part of a finished diaphragm wall, totaling 48 cylindrical and four prismatic specimens. After 28 days, the cylindrical samples were ultrasound-tested by direct wave propagation method (Figure 1b) and prismatic samples by indirect method (Figure 1c), representing the in loco inspection.

(a) (b) (c)

Figure 1. (a) Synthetic polymer, (b) cylindrical samples subjected to direct ultrasound test (c)

prismatic samples subjected to indirect ultrasound test. Source: authors (2021).

For the tests, ultrasound equipment (USLAB, Agricef, Brazil) and 45 KHz-frequency longitudinal transducers of flat faces were used. With the propagation times of ultrasound waves (t), it was possible to calculate, for each distance between transducers (L), the direct propagation velocity of ultrasound waves (V_D), using the equation proposed by ABNT NBR 8802 (2019), as in Equation (1).

$$V = \frac{L}{t} \tag{1}$$

After 28 days, the mass of each specimen was also determined using a precision scale, and with a digital caliper its dimensions were obtained to calculate the volume and the density. From the direct velocity and density of the concrete (ρ), the stiffness coefficient was determined (2).

$$C_{LL} = \rho .\ V_D^2 \tag{2}$$

The prismatic samples, which represent the feasibility of inspection of a finished diaphragm wall using the indirect wave propagation method, were tested according to the methodology proposed by the ABNT-NBR 8802 (2019). The ABNT proposes a way of measuring the ultrasonic propagation velocity by indirect transmission mode (VI), whose procedure consists of calculating the velocity through a propagation time graph versus distance between transducers Figure (2).

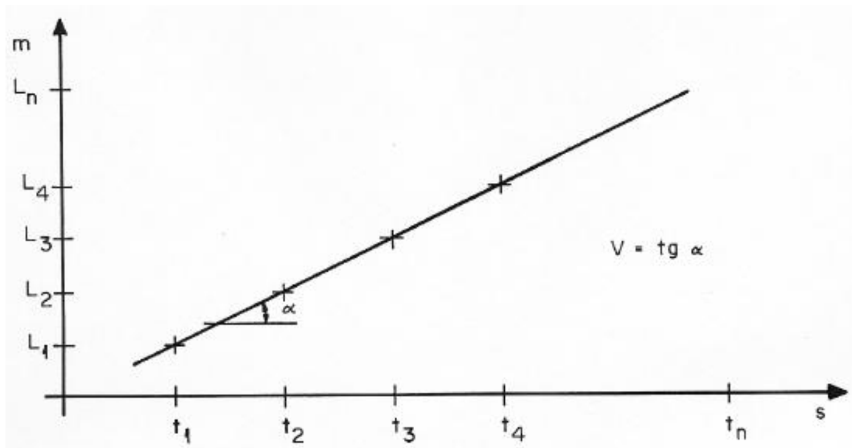

Figure 2. Determination of the propagation velocity of ultrasound waves by indirect method. Source: ABNT-NBR 8802 (2019).

The specimens were then subjected to a compression test in a EMIC machine to determine the strength (f_c - ABNT-NBR 5739, 2018) and the elastic modulus (E_{ci} - ABNT-NBR 8522, 2017). The results of the tests were used in the creation of models to predict the mechanical properties based on the propagation velocity of ultrasound waves.

The results of f_c and E_{ci} and the parameters of propagation of ultrasound velocity waves (V_D), (V_I) and (C_{LL}) were used to analyze regressions in order to verify the existence of statistically significant models between mechanical properties and acoustic properties, obtained through ultrasound wave propagation tests.

3. RESULTS AND DISCUSSIONS

The mechanical (fc and E_{ci}) and acoustic properties (C_{LL}, V_D, and V_I) of the concrete also reduced as polymer quantities increased, a fact related to increased porosity (amount of voids) of the concrete. Table 3 shows the tests performed on the 12 concrete samples for each studied mixture.

Table 3. Minimum, maximum, and mean values of strength (f_c), elasticity (E_{ci}), Stiffness Coefficient (C_{LL}) direct (V_D) and indirect velocity (VI) for the mixtures produced with different polymer quantities.

Quantities	**f_c (MPa)**	**E_{ci} (GPa)**	**C_{LL} (GPa)**	**V_D ($m.s^{-1}$)**	**V_I ($m.s^{-1}$)**
	Min. Max. Mean	Min. Max. Mean	Min. Max. Mean	Min. Max. Mean	Min. Max. Mean
0%	16.9; 20.5; 17.41	19.58; 27.80; 23.28	27.23; 34.38; 30.16	3485; 3885; 3680	2437; 2855; 2639
20%	8.32; 9.6; 8.80	11.44; 16.13; 13.10	19.87; 22.42; 21.26	3095; 3230; 3185	2421; 2628; 2520
40%	5.53; 6.78; 6.17	5.80; 9.85; 7.48	9.81; 17.29; 13.14	2386; 2788; 2615	1886; 2518; 2127
60%	4.13; 4.96; 4.60	2.03; 3.13; 2.95	7.88; 15.69; 12.83	2040; 2858; 2528	804; 1085; 935

To avoid dispersion of the we used the mean of the results of strength, stiffness, and acoustic parameters for statistical analyses. The linear regression models evaluated by analysis of variance (ANOVA) were statistically significant at the 95% confidence level (P-value < 0.05), and the best models for predicting concrete strength (f_c) and stiffness (E_{ci}) properties were obtained based on the stiffness coefficient (C_{LL}) (Table 4).

The models found are within the ranges of coefficients of determination (R^2) found in the literature regarding mechanical tests and wave propagation. For the prediction of f_c, the R^2 in the studies conducted by Mohamad et al. (2016) and Silva et al. (2020), ranged from 60 to 98% and, for E_{ci}, from 50 to 96%, (Giacon et al., 2010; Mohamed et al., 2016, and Silva et al., 2020). Correlations between the stiffness parameters (C_{LL}) and the mechanical properties of strength (f_c) and elastic modulus (E_{ci}) obtained in ultrasound and compression tests were found by Giacon et al., (2010) and Silva (2020), with linear models and R^2 values ranging from 85% to 97% for Ec_i and from 79% to 95% for f_c.

Absolute error values of the strength and elastic modulus of the concrete range from 25% to 50% when based on models with wave propagation parameters (Bungey and Millard, 2006). In our research, the absolute errors found (9.70% to 20% – Table 4) are below those found in the literature, suggesting that the models for predicting strength and stiffness are valid in the evaluation of the quality of concrete used in diaphragm walls, using acoustic parameters of wave propagation.

Table 4. Correlation models between direct velocity (V_D), indirect velocity (V_I) and stiffness coefficient (C_{LL}) parameters with compressive strength (fc) and initial Elastic Modulus (E_{ci}).

Parameter	Model	P-Value	R^2 (%)	Estimation error	Absolute error* (%)
fc x V_D	$fc = -20.34 + 0.0098*V_D$	0.03	92.81	1.70	18.40
fc x V_I	$fc = -5.25 + 0.0068*V_I$	0.04	81.65	1.87	20.3
fc x C_{LL}	$fc = -3.96 + 0.68* C_{LL}$	0.025	97.46	1.57	9.70
E_{ci} x V_D	$E_{ci} = -35.13 + 0.015*V_D$	0.01	96.91	1.83	18.90
E_{ci} x V_I	$E_{ci} = -11.68 + 0.012*V_I$	0.04	89.00	1.90	20.60
E_{ci} x C_{LL}	$E_{ci} = -8.56 + 1.05*C_{LL}$	0.020	97.97	2.14	12.37

*Relationship between estimated error and mean value.

Table 5 shows the results obtained from immersion absorption and the longitudinal velocity of the tested samples after saturation. Notably, the addition of synthetic polymer increased water absorption (Table 5), leaving more voids (pores) after the drying process. This aspect occurs because of the release of internal curing, which leads to the swell of polymer particles, changing the porous structure of cement (Araújo and May, 2019).

Table 5. Absorption values by immersion and average direct velocity (V_D), for the shapes produced with different additions of synthetic polymer.

Sample	Absorption	V_D ($m.s^{-1}$)
0%	12.0	3087
20%	12.4	2777
40%	17.3	2291
60%	18.4	1846

Note that, due to the change in the absorbed volume of water, changes in acoustic properties are observed (Tables 3 and 5), Also, it can be noted that the velocitys of sound propagation decrease as the amount of polymer used increases; the voids found in dry concrete are a significant factor in the transmission of sound waves, since the ultrasonic pulse velocity is lower in the air than in solids (Godinho, et al., 2020), thus explaining the increase in the amount of pores, reducing the propagation velocity of ultrasonic waves in the specimens.

The regression between ultrasound velocity and absorption showed a model with R^2 of 92% (Figure 3) and P-Value of $0.04 < 0.05$, demonstrating that there is a statistically significant relationship between the parameters, with a 95% confidence level, obtained through ANOVA. The outcomes suggest that the wave propagation method is sensitive to the increase of water content inside the samples, caused by increased porosity after drying the synthetic polymer within the cement, decreasing its ultrasound velocity. Thus, the concrete will present more voids (pores) and, therefore, absorbing more water and presenting lower density and mechanical properties. Water is the main erosive agent in concrete, therefore concrete performance as a barrier to reduce the transport of potentially corrosion-causing agents is related to its porosity (Dudhal, 2016; Liu et al., 2020; Matiko, 2000).

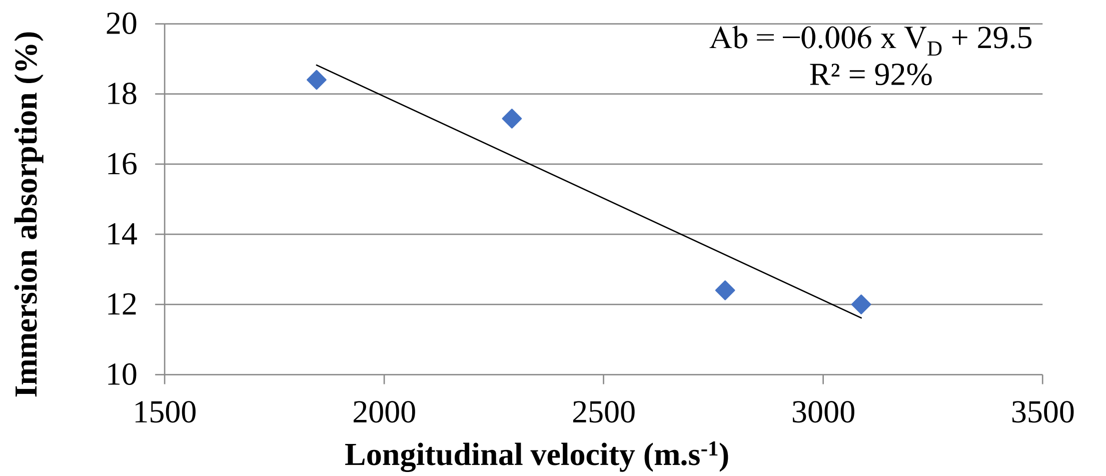

Figure 3. Regression model between immersion absorption and longitudinal velocity.
Source: Authors (2021).

The polymer aggregates and forms a film on the surface of cement particles during the hydration, avoiding additional contact between cement and water, increasing the cement porosity, thus affecting the compressive strength and elastic modulus of polymer-added concrete (Liu et al., 2020).

Our research corroborates with the literature. Table 3 shows a 26% reduction for the mean values of f_c and 13% for the mean values of E_{ci}, after an 18% increase in absorption for concrete samples with the addition of 60% of synthetic polymer in relation to the samples without it (Table 5).

The models obtained can be used as a non-destructive alternative test to estimate mechanical and physical properties, such as water absorption in samples and diaphragm wall structures, verifying the infiltration of groundwater from the soil mass after the execution of the panels, a fact that may compromise concrete ability to resist compression.

4. CONCLUSIONS

The increment in the concentration of synthetic polymer used in the different concrete mixtures increased its workability, reducing its density and its mechanical (f_c and E_{ci}) and acoustic (V_D, V_I, and C_{LL}) properties.

The models of prediction of mechanical properties by ultrasound velocity were statistically significant, showing coefficients of determination higher than 80% and errors inferior to those found in the literature.

Thus, the sensitivity of the direct or indirect ultrasound wave propagation test is demonstrated, for concrete with physical and mechanical properties similar to those used in our research, and the correlations established here in concrete samples can be used to support the detection of in loco pathological manifestations.

Moreover, the increase in synthetic polymer content in the production of concrete directly interferes with the amount of water absorption and, consequently, in the acoustic properties of the material.

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6. REFERÊNCIAS BIBLIOGRAFICAS

Associação Brasileira de Normas Técnicas (1997). *NBR 11578: Cimento Portland Composto*. Rio de Janeiro.
Associação Brasileira de Normas Técnicas (2003). *NBR NM 248: Agregados: Determinação da composição granulométrica*. Rio de Janeiro.
Associação Brasileira de Normas Técnicas (2006). *NBR NM 45: Agregados: Determinação da massa unitária e do volume de vazios.* Rio de Janeiro. 2006.
Associação Brasileira de Normas Técnicas (2009). *NBR NM 53: Agregado graúdo – Determinação da massa específica, massa específica aparente e absorção de água.* Rio de Janeiro.
Associação Brasileira de Normas Técnicas (2009). *NBR NM 52: Determinação da massa específica de agregados miúdos por meio de frasco Chapman.* Rio de Janeiro.
Associação Brasileira de Normas Técnicas (1998). *NBR NM 67: Concreto: determinação da consistência pelo abatimento do tronco de cone.* Rio de Janeiro.
Associação Brasileira de Normas Técnicas (2005*). NBR 9778: Argamassa e concreto endurecidos – Determinação da absorção de água por imersão – Índice de vazios e massa específica.* Rio de Janeiro.
Associação Brasileira de Normas Técnicas (2009). *NBR 7211: Agregados para concreto - Especificação.* Rio de Janeiro.
Associação Brasileira de Normas Técnicas (2016). *NBR 5738: Concreto: Procedimento para moldagem e cura de corpos de prova.* Rio de Janeiro.
Associação Brasileira de Normas Técnicas (2018) *NBR 5739: Ensaio de compressão de corpos-de-prova cilíndricos de concreto.* Rio de Janeiro.
Associação Brasileira de Normas Técnicas (2017). *NBR 8522: Concreto – Determinação dos módulos estáticos de elasticidade e de deformação à compressão.* Rio de Janeiro.
Associação Brasileira de Normas Técnicas (2019). *NBR 8802: Concreto Endurecido – Determinação da velocidade de propagação da onda ultra-sônica.* Rio de Janeiro.
Araújo, C. M. M, May, C. A. (2019). *Durabilidade de concretos de alta resistência com adição de polímero superabsorvente e nano partículas de sílica.* Monografia de projeto final em engenharia civil; Brasília; p. 124.
Bungey J., Millard, S. (2006). *Testing of concrete in structures.* 3 ed. London: Blackie Academic e Professional.
Djelal, C., Vanhove, Y., Azzi, A., Madec, O. (2020). *Recommendation for concrete mix design to prevent bleed channels on diaphragm walls.* European Journal of Environmental and Civil Engineering, p.1-13.
Giacon Jr, M., Goncalves, R., Soriano, J., Amalfi, G. (2010). *Caracterização do concreto utilizando ultrassom.* In: XXVIII CONAENDI - Congresso de Ensaios Não Destrutivos e Inspeção, Santos - SP. Anais CONAENDI 2010. v. 1. p. 1-9.
Godinho, J. P., Junior, T. F. S; Medeiros, M. H. F; Silva, M. S. A. (2020). *Factors influencing ultrasonic pulse velocity in concrete:* 13. ed. Curitiba: Revista Ibracon de Estruturas e Materiais.
Hachich, W. et al. (2019). Fundações: Teoria e Prática. 2ª ed. São Paulo, Pini.
Liu, B., Shi, J., Sun, M., He, Z., Xu, H., Tan, J. (2020). Mechanical and permeability properties of polymer-modified concrete using hydrophobic agent. Journal of Building Engineering, v. 31, p. 101337. https://doi.org/10.1016/j.jobe.2020.101337.
Matiko, N. N. S. (2000). *Análise da porosidade e de propriedades de transporte de massa em concretos.* FAPESP.
Mohammed, T. U., Rahman, M. N. (2016). *Effect of types of aggregate and sand-to-aggregate*

volume ratio on UPV in concrete. Construction and Building Materials, v. 125, p. 832-841. https://doi.org/10.1016/j.conbuildmat.2016.08.102.
Savaliya, K. D., Thaker, K. K., Dave, U. V. (2014). *Comparison between Different Methods of Ultrasonic Pulse Velocity Tests on Concrete.* International Journal of Engineering Research and Applications (IJERA), (March), p. 41–44.
Silva, R. R. C. (2020). *Propagação de ondas de ultrassom em sistemas de contenção par obras de terra*. Tese de Doutorado. UNICAMP - Universidade Estadual de Campinas. p.113.
Silva, R. R. C., Gonçalves, R., Bertoldo, C. P. (2020). *Classification and inspection of reinforced concrete elements for use in retaining walls using ultrasound tests*. Construction and Building Materials, v. 262, p. 120010. https://doi.org/10.1016/j.conbuildmat.2020.120010.
Hirde, S. K., Dudhal, Omprakash S. (2016). *Review on polymer modified concrete and its application to concrete structures.* International Journal of Engineering Research, ISSN, v. 3. P.766-769. https://doi.org/10.17950/ijer/v5i3/053.