UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ENGENHARIA AGRÍCOLA

RODRIGO ROGERIO CERQUEIRA DA SILVA

PROPAGAÇÃO DE ONDAS DE ULTRASSOM EM SISTEMAS DE CONTENÇÃO PARA OBRAS DE TERRA

CAMPINAS
2020

RODRIGO ROGERIO CERQUEIRA DA SILVA

PROPAGAÇÃO DE ONDAS DE ULTRASSOM EM SISTEMAS DE CONTENÇÃO PARA OBRAS DE TERRA

Tese apresentada à Faculdade de Engenharia Agrícola da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Doutor em Engenharia Agrícola, na Área de Métodos Não Destrutivos Aplicados a Materiais, Estruturas e Árvores.

Orientador: Profª. Drª. Raquel Gonçalves

Co-Orientador: Profª. Drª. Cinthya Bertoldo Pedroso

ESTE TRABALHO CORRESPONDE À VERSÃO FINAL DA TESE DEFENDIDA PELO ALUNO RODRIGO ROGERIO CERQUEIRA DA SILVA E ORIENTADA PELA PROFA. DRA. RAQUEL GONÇALVES

CAMPINAS

2020

Ficha catalográfica
Universidade Estadual de Campinas
Biblioteca da Área de Engenharia e Arquitetura
Luciana Pietrosanto Milla - CRB 8/8129

Si38p

Silva, Rodrigo Rogerio Cerqueira da, 1983-
Propagação de ondas de ultrassom em sistemas de contenção para obras de terra / Rodrigo Rogerio Cerqueira da Silva. – Campinas, SP : [s.n.], 2020.

Orientador: Raquel Gonçalves.
Coorientador: Cinthya Bertoldo Pedroso.
Tese (doutorado) – Universidade Estadual de Campinas, Faculdade de Engenharia Agrícola.

1. Ultrassom. 2. Concreto. 3. Módulo de elasticidade. 4. Engenharia - Inspeção. 5. Agregados (materiais de construção). I. Gonçalves, Raquel, 1961-. II. Pedroso, Cinthya Bertoldo, 1982-. III. Universidade Estadual de Campinas. Faculdade de Engenharia Agrícola. IV. Título.

Informações para Biblioteca Digital

Título em outro idioma: Ultrasound wave propagation in retaining system for soil works
Palavras-chave em inglês:
Ultrasound
Concrete
Modules of elasticity
Engineering - Inspection
Aggregates (Building materials)
Área de concentração: Métodos Não Destrutivos Aplicados a Materiais, Estruturas e Árvores
Titulação: Doutor em Engenharia Agrícola
Banca examinadora:
Raquel Gonçalves [Orientador]
Vladimir Guilherme Haach
Roberto Caldas de Andrade Pinto
Gisleiva Cristina dos Santos Ferreira
Lia Lorena Pimentel
Data de defesa: 28-02-2020
Programa de Pós-Graduação: Engenharia Agrícola

Identificação e informações acadêmicas do(a) aluno(a)
- ORCID do autor: https://orcid.org/0000-0002-7928-9462
- Currículo Lattes do autor: http://lattes.cnpq.br/3404265115540183

Este exemplar corresponde à redação final da **Tese de Doutorado** defendida por **Rodrigo Rogerio Cerqueira da Silva**, aprovada pela Comissão Julgadora em 28 de fevereiro de 2020, na Faculdade de Engenharia Agrícola da Universidade Estadual de Campinas.

Profa. Dra. Raquel Gonçalves - Presidente e Orientadora
Faculdade de Engenharia Agrícola / UNICAMP

Prof. Dr. Vladimir Guilherme Haach – Membro Titular
Escola de Engenharia de São Carlos / USP

Prof. Dr. Roberto Caldas de Andrade Pinto – Membro Titular
Faculdade de Engenharia Civil / UFSC

Profa. Dra. Gisleiva Cristina dos Santos Ferreira – Membro Titular
Faculdade de Tecnologia / UINICAMP

Profa. Dra. Lia Lorena Pimentel – Membro Titular
Faculdade de Engenharia Civil / PUC-CAMP

A Ata da defesa com as respectivas assinaturas dos membros encontra-se no processo de vida acadêmica do discente.

AGRADECIMENTOS

A Deus, El Shaddai, Adonai, Elohim, para todo sempre, por me abençoar pela oportunidade e sabedoria concedida ao coração e razão à mente, guiando meus passos iluminando minha vida, permitindo concluir mais esta etapa, pois em suas mãos coloquei meus planos e meus sonhos, sendo que seja feita sempre a sua vontade SENHOR.

Aos meus grandes pais (Ramilton Rogerio "Remi" e Ivone "Vonão"), pessoas serenas e humildes que apesar das dificuldades da vida, nunca deixaram de lutar ao meu lado e contribuir com meus sonhos, companheiros de grandes batalhas a quem devo todo meu afeto e minha eterna gratidão, ao qual recompenso com a minha maior riqueza, o meu sincero e puro amor.

À Profa. Dra. Raquel Gonçalves, por acreditar e confiar em minha capacidade, ao qual deixo de lado a formalidade para chamar de amiga a quem sinto maior respeito e afinidade, agradeço a orientação, confiança e ensinamentos tanto acadêmicos como de vida.

Agradeço a Profa. Dra. Cinthya Bertoldo Pedroso pela co-orientação e amizade, exemplo de ser humano e profissional, por sua ajuda desde o início até o fim desta caminhada.

Aos meus irmãos (Robson Rogerio e Rodson Rogerio), pessoas que sempre me espelhei para adquirir caráter como homem e criar responsabilidades.

A minha amada companheira, Wanessa Pessoa Bonetti (minha Honey), pelo carinho, amor, compreensão, paciência, contribuindo muito para suavizar e tornar mais belo o caminho percorrido.

Aos amigos Genebaldo Figueiredo Neto e Paulo Gustavo Krejci Nunes companheiros de todos os momentos de pós-graduação.

Meus sobrinhos (Gabriel, Nicolle, Jullia e Rafaella), aos quais tenho todo carinho e amor, que contribuem para minha vida ser mais alegre e colorida.

A Universidade Estadual de Campinas, por toda infraestrutura fornecida, permitindo qualificar-me com embasamento teórico e prático, para que possa disseminar a aprendizagem, repassando com segurança o conhecimento adquirido durante a pesquisa.

A empresa Geosoluções, pelo apoio técnico, incentivando a criação de novas técnicas, assim como a colaboração dos funcionários de campo, cuja experiência de cada um foi de suma importância para aumentar os meus conhecimentos práticos.

A todos que fazem parte da minha vida, plantando carinho, amizade e conhecimento.

Esta tese é dedicada a minha amada mãe, “Ivone Cerqueira da Silva”, por ser o maior exemplo de humildade que encontrei em toda a minha vida, ser humano encantadora, ao qual abriu mão de sua vida e de todos os seus sonhos, para que eu pudesse ter tido a honra e graça para chegar até esta etapa da minha vida “EU TE AMO”.

Esforço-me para que eles sejam fortalecidos em seu coração, estejam unidos em amor e alcancem toda a riqueza do pleno entendimento, a fim de conhecerem plenamente o mistério de Deus, a saber, Cristo. Nele estão escondidos todos os tesouros da sabedoria e do conhecimento.

(Colossenses 2: 2-3)

RESUMO

Com o crescente aumento de obras civis em áreas de difícil acesso e topografia irregular no Brasil, a utilização de aterros e de contenção de encostas, associados a peças pré-fabricadas de concreto como elemento estrutural, vem ganhando cada vez mais espaço. O *Lock and Load* é um sistema de contenção formado pela união de dois elementos, um painel e um contraforte, podendo ser pré-moldado ou fabricado *in loco*. O conjunto tem sido largamente utilizado em situações de corte e de aterro, porém não há metodologia de inspeção e de acompanhamento da qualidade das peças (placas e contraforte) após sua desmoldagem e instalação. Técnicas não destrutivas, baseadas em propagação de ondas de ultrassom, vêm sendo cada vez mais utilizadas para avaliação da homogeneidade do concreto, para inferência de propriedades mecânicas e para inspeção de descontinuidades ou defeitos não visíveis externamente. Sendo assim, o objetivo dessa pesquisa foi avaliar a viabilidade de serem definidos parâmetros ideais para o uso do ensaio de ultrassom no acompanhamento e na inspeção de peças do sistema *Lock and Load* e, com o uso desses parâmetros, avaliar a viabilidade de inferir a qualidade das peças por meio do ensaio aplicado diretamente nas mesmas. Para atingir os objetivos incialmente foi avaliada a metodologia de inspeção, por ultrassom, considerando o tipo de medição (direta e indireta), o tipo de transdutor (plano e exponencial), o acoplamento e a frequência dos transdutores (25, 45 e 80 kHz). Para a análise de modelos de inferência da qualidade do material por meio do ensaio de ultrassom, foram moldados corpos de prova produzidos com agregados graúdos de quatro diferentes origens mineralógicas (basalto, calcário, gnaisse e granito), os quais foram ensaiados por ultrassom e de forma destrutiva em compressão, para a determinação da resistência e da rigidez, parâmetros adotados para representar a qualidade do material. Por fim foi testada a aplicabilidade do uso do ensaio de ultrassom diretamente nas peças pré-moldadas do sistema na inferência da qualidade do concreto. Os resultados permitiram definir o transdutor de faces planas e de frequência 45 kHz como mais adequado para uso na classificação e nas inspeções visando o controle de qualidade do sistema *Lock and Load* antes da instalação (ensaio direto) ou após instalado (ensaio indireto). Os modelos de predição da resistência e da rigidez foram estatisticamente significativos para os agregados de todas as origens mineralógicas e o ensaio mostrou viabilidade para ser utilizado na classificação e na inspeção das placas e dos contrafortes, considerando a rigidez e a resistência.

Palavras-chave: Ensaio de ultrassom em concreto; Peças pré-moldado de concreto; módulo de elasticidade do concreto; resistência a compressão do concreto.

ABSTRACT

The increasing civil works in areas with difficult access and irregular topography in Brazil are producing the use of embankments and slope containtion, associated with prefabricated concrete parts as a structural element. *Lock and Load* is a containment system formed by the union of two elements, a panel and a buttress, which can be prefabricated or manufactured *on site*. The set has been widely used in cutting and landfill situations, but there is no methodology for inspection and quality monitoring of its components (plates and buttress) after its demoulding and installation. Nondestructive techniques based on ultrasonic wave propagation are increasingly being used to evaluate concrete homogeneity, to infer mechanical properties and to inspect discontinuities or defects not externally visible. Thus, the objective of this research was to evaluate the feasibility of defining ideal parameters for the use of the ultrasound test in monitoring and inspecting the components of the *Lock and Load* system and, using these parameters, to evaluate the feasibility of inferring the quality of its components using the test applied directly to them. To reach the objectives, initially the ultrasound inspection methodology was evaluated, considering the type of measurement (direct and indirect), the type of transducer (flat and exponential), the coupling and the transducers frequency (25, 45 and 80 kHz). For the models analysis, aiming the inference of the material quality using the ultrasound test, specimens were molded with coarse aggregates from four different mineralogical origins (basalt, limestone, gneiss and granite), which were test with ultrasound and with static method (compression) to determine the strength and stiffness, which are parameters adopted to represent the material quality. Finally it was tested the applicability of the ultrasound test applied directly on the prefabricated system to infer concrete quality. The results allowed us to define the 45 kHz frequency flat transducer as the most suitable for use in classification and inspections aiming at quality control of the *Lock and Load* system before installation (direct test) or after installation (indirect test). The prediction models of strength and stiffness were statistically significant for aggregates of all mineralogical origins and the test showed feasibility to be used in the classification and inspection of plates and buttresses, considering stiffness and strength.

Keywords: Ultrasound test in concrete; Prefabricated concrete; concrete modulus of elasticity; concrete compression strenght.

SUMÁRIO

1 INTRODUÇÃO GERAL

Com o crescente aumento de obras civis em áreas de difícil acesso e topografia irregular no Brasil, a utilização de aterros associados a peças pré-fabricadas de concreto como elemento estrutural vem ganhando cada vez mais espaço, já que possibilitam atender a demanda em curto período. Entretanto, como toda linha produtiva, as peças pré-fabricadas também necessitam de controle de qualidade na produção, para identificação de defeitos e/ou erros de moldagem que possam influenciar em sua resistência, durabilidade e estética.

Como consequência da demanda pela utilização de peças de concreto pré-moldados houve também o aumento de estudos sobre o controle tecnológico. No entanto, o controle tecnológico é muitas vezes ignorado, por ser trabalhoso e ser visto como gerador de aumento de custo da obra. As estruturas de aterros e de contenção de encostas são exemplos de aplicação em concreto armado nas quais há dificuldade de acompanhamento e de inspeção.

Nova tecnologia empregada no Brasil, denominada *Lock and Load* (Figura 1a), permite utilização, com versatilidade, em situações de corte e de aterro, como revestimento de obras de contenção, sendo excelente alternativa, do ponto de vista técnico e econômico, em relação aos muros de arrimo clássicos. Esse sistema é constituído por módulos de concreto armado dimensionados para suportar elevadas cargas de compactação junto à face (Figura 1b), evitando erosões, diminuindo a possibilidade de ruptura localizada, aumentando a estabilidade do talude através da redução de suas deformações, além de fornecer excelente acabamento estético.

a b

Figura 1. Sistema de contenção *Lock and Load* (a) e compactação junto a face (b).

O sistema é formado pela união de dois elementos: painel e contraforte (Figura 2), que podem ser pré-fabricados ou produzidos na própria obra. O conjunto tem sido largamente utilizado, porém não há metodologia de acompanhamento do controle de qualidade das peças (painel e contraforte) após a desmoldagem ou após a instalação.

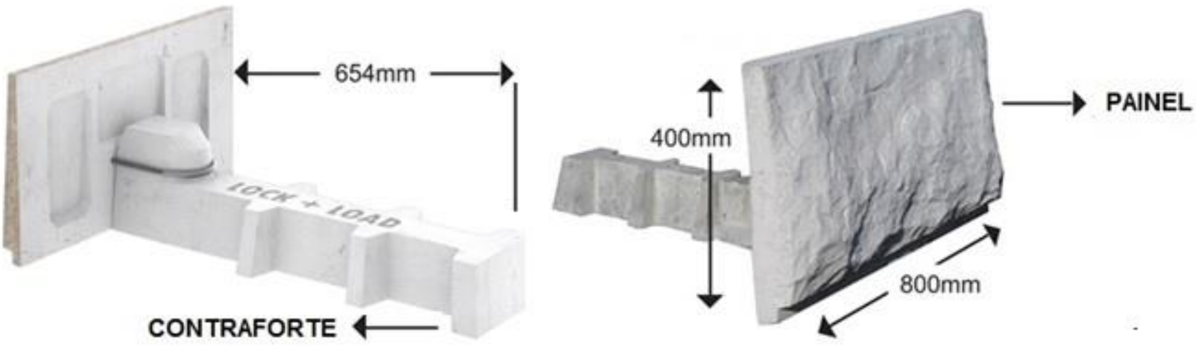
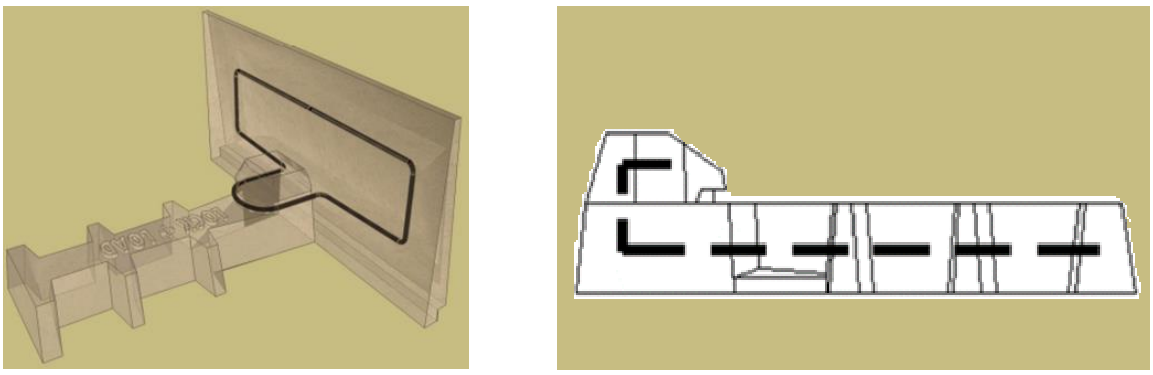


Figura 2. Sistema *Lock and Load*.

Fonte: Gesoluções.

No sistema, ambas as peças (painel e contraforte) são confeccionadas em concreto, com esistência característica a compressão (fck) de 20 a 30 MPa, armadas com aço CA50 ou inoxidável com diâmetro de 6,3 mm, responsável pela conexão durante a montagem do sistema (Figura 3). A armação possui proteção anticorrosiva (galvanizadas, epoxídicos ou poliméricas) especificada de acordo com agressividade ambiental, qualidade das estruturas e outros fatores que afetam sua durabilidade vinculadas a processos de corrosão das armaduras, conforme NBR 6118 (2015).



a b

Figura 3. Posicionamento da armadura no painel (a) e vista armadura no contraforte (b).

Fonte: Gesoluções.

Durante a construção do aterro compactado, na parte central do painel de revestimento, são posicionados reforços com geossintéticos do tipo geotêxteis ou geogrelhas (Figura 4a), responsáveis pela estabilidade das obras de aterro. Estes materiais possuem elevada resistência à tração e desempenham, no solo, função análoga ao aço no concreto, posicionados de modo que não haja contato direto entre o reforço e qualquer elemento rígido que possa causar danos mecânicos ao material. As peças pré-moldadas são independentemente estáveis e não se apoiam diretamente nos módulos inferiores, atrás do painel sobre o contraforte é lançado material granular promovendo o efetivo de travamento e drenagem das peças, formando um conjunto rígido e estável (Figura 4b). Este bloco rígido constitui a fundação das camadas subsequentes dos módulos, fornecendo adequado suporte, sem o risco de esmagamento das peças inferiores.

a b

Figura 4. Reforços com geossintético (a) e material granular para travamento e drenagem (b).

Os controles tecnológicos em concreto visando manutenção ou diagnostico de obras, geralmente adotam metodologias de ensaios destrutivos, que podem dificultar e/ou comprometer a análise, devido a larga escala de produção. Mesmo quando os elementos deste sistema são produzidos em fábricas, onde existem condições adequadas de controle da dosagem do concreto, da qualidade dos materiais e do tempo de cura, durante o transporte até o local da instalação as peças estão sujeitas a impactos, podendo produzir alterações em relação ao que havia sido recomendado em projeto. Assim, até mesmo nestes casos é importante haver ferramenta adequada de inspeção da qualidade de fabricação.

Na produção *in* loco as peças do sistema *lock and load* estão sujeitas a patologias, geradas em função da dificuldade do controle de qualidade do concreto, das condições de armazenamento improprias, da ausência ou vibração inadequada do concreto, além da presença de trincas e de fissuras atreladas ao procedimento de cura inadequado. Adicionalmente, durante a instalação e a compactação do solo, pode haver trincas e fissuração das placas devido à proximidade de maquinários de grande porte. Todos esses fatores tornam importante o estudo e a proposição de ensaios confiáveis, que possam ser aplicados na verificação da qualidade do sistema.

Uma das razões para a falta de controle tecnológico na construção civil está atrelada à necessidade de recorrer a estrutura laboratorial de ensaios destrutivos, nem sempre próximas aos locais das obras e com custos elevados. Assim, técnicas de avaliação das estruturas por meio da utilização de ensaios não destrutivos vêm crescendo continuamente em todo o mundo, abrangendo vários tipos de ensaios. Dentre os ensaios que se destacam pela praticidade, portabilidade e facilidade no manuseio, está o ultrassom, cuja técnica e princípio de utilização é simples. No entanto, em materiais heterogêneos como concreto, cuja produção envolve diferentes tipos e naturezas de materiais, a acurácia e a confiabilidade dependem de calibração. A norma brasileira ABNT NBR 8802 (2019) indica a viabilidade de expressar a homogeneidade do concreto por meio de parâmetros estatísticos ligados à velocidade de propagação das ondas ultrassom, tais como o desvio padrão ou o coeficiente de variação. Contudo, tais parâmetros só podem ser usados para comparar componentes de concreto similares, por meio da detecção de variações, devendo ser considerados fatores como a distância entre as superfícies de contato dos transdutores, a presença de armadura e as características da microestrutura do concreto. As normas europeias BS 1881:203 (1986), EN 12504 (2004) e americana ACI 228 (2003) propõem que correlações entre velocidade de propagação de ondas de ultrassom e resistência do concreto sejam utilizadas após calibração para um determinado traço e/ou características dos componentes, tais como a proporção dos agregados, relação água-cimento, etc. A EN 12504 (2004) estabelece diretrizes para o uso do ensaio de ultrassom na inferência da resistência em peças pré-fabricadas de concreto, indicando que a velocidade de propagação de ondas deve ser mensurada nas partes mais críticas dos elementos pré-moldados, isto é, nas partes mais suscetíveis à ruptura, considerando as condições de uso.

Assim, o problema que se vislumbra nesta pesquisa é que para que o ensaio de ultrassom tenha viabilidade de aplicação como preditor da resistência e da rigidez, permitindo classificação e acompanhamento da qualidade do sistema de contenção *Lock and Load*, é necessário conhecer o alcance, a precisão e as formas adequadas de aplicação da metodologia.

Considerando esse problema, a hipótese da pesquisa é que, ao conhecer os parâmetros metodológicos adequados e compatíveis com as bases teóricas do ensaio de ultrassom, aplicado ao sistema *Lock and Load,* bem como os modelos de correção de parâmetros do ultrassom com a resistência e a rigidez do material utilizado na moldagem desse sistema, é possível utilizar o ensaio diretamente nas placas e contrafortes para classificar e inspecionar as peças antes e depois da instalação.

Diante dos aspectos mencionados, o objetivo geral da pesquisa foi avaliar a viabilidade de serem definidos parâmetros ideais para o uso do ensaio de ultrassom no acompanhamento e na inspeção de peças do sistema *Lock and Load* e, com o uso desses parâmetros, avaliar a viabilidade de inferir a qualidade das peças por meio do ensaio aplicado diretamente nas mesmas.

Como objetivos específicos foram propostos:

- Avaliar metodologia de inspeção, por ultrassom, de muro de contenção confeccionado com o sistema *Lock and Load*, considerando o tipo de medição (direta e indireta), o tipo de transdutor (plano e exponencial), a frequência do transdutor, o acoplamento do transdutor na peça sob inspeção e a distância entre os transdutores em medições indiretas.
- Avaliar o comportamento de parâmetros obtidos por meio de ensaios de ultrassom, realizados com a metodologia apontada no item anterior, como preditores da resistência e da rigidez de concretos produzidos com agregados graúdos de diferentes origens mineralógicas utilizadas na produção do sistema.
- Avaliar se o ensaio de ultrassom, aplicado nas peças pré-moldadas *Lock and Load* para muros de contenção, antes (classificação) e depois (inspeção) da instalação, permite inferir parâmetros representativo da qualidade (resistência e rigidez) dessas peças utilizando, para isso, modelos de inferência obtidos anteriormente, em corpos de prova moldados com o mesmo traço.

A avaliação detalhada de proposta metodológica para utilização em campo e de modelos de predição da qualidade de estruturas com especificidades da *Lock and Load* diferencia essa pesquisa daquelas que utilizaram somente amostras e modelos produzidos em laboratório, com formatos mais regulares.

A pesquisa foi desenvolvida em três etapas principais, cujos delineamentos experimentais se adequaram aos objetivos específicos:

Na primeira etapa o delineamento experimental consistiu no uso de 5 sistemas pré-moldados de concreto do tipo *Lock and Load*, todos confeccionados com o traço utilizado de forma regular pela empresa, limitando-se assim a variabilidade das peças, porque o foco dessa etapa foi avaliar a metodologia de ensaio de ultrassom mais adequada para ser utilizada na classificação e na inspeção das peças.

Para a segunda etapa foram moldados 128 corpos de prova cilíndricos, com uso de agregado graúdo de diferentes torigens mineralógicas (granito, gnaisse, basalto e calcário) abrangendo todas as regiões do país, e com variabilidade de resistência característica por meio da variação do fator água-cimento, uma vez que o foco dessa etapa foi calibrar os modelos de correlação do ensaio de ultrassom com a resistência e a rigidez dos concretos obtidos em ensaio de compressão.

Finalmente, para a terceira etapa, foram moldadas 48 peças do sistema *Lock and Load*, com os mesmos traços da etapa anterior, uma vez que o foco dessa etapa foi calibrar a velocidade de propagação de ondas nas placas (ensaios *in loco*) com as obtidos em corpos de prova e, assim, utilizar os resultados dos modelos de predição obtidos na etapa anterior para propor o método na avaliação do sistema antes e depois da instalação.

A tese foi redigida em forma de artigos, os quais foram elaborados a partir dos três objetivos específicos. Além dos artigos, que compõem o corpo principal, a Introdução, a Discussão e as Conclusões Gerais apresentam a problematização geral que a pesquisa aborda, as justificativas da importância da pesquisa, a hipótese e os objetivos geral e específicos, assim como ressaltam os principais resultados e conclusões considerando o objetivo geral.

2 ARTIGOS

2.1 Artigo 1 - METHODOLOGICAL ASPECTS FOR QUALITY CONTROL AND ULTRASOUND INSPECTION TESTS ON RETAINING WALLS

ARTIGO SUBMETIDO AO PERIÓDICO JOURNAL OF MATERIALS IN CIVIL ENGINEERING

FORMATAÇÃO E IDIOMA DE ACORDO COM AS NORMAS DO REFERIDO PERIÓDICO

METHODOLOGICAL ASPECTS FOR QUALITY CONTROL AND ULTRASOUND INSPECTION TESTS ON RETAINING WALLS

Rodrigo Rogerio Cerqueira da Silva[1], Raquel Gonçalves[2*], Cinthya Bertoldo Pedroso[3]

[1]Ph.D. Student, Laboratory of Nondestructive Testing - LabEND, School of Agricultural Engineering - FEAGRI, University of Campinas - UNICAMP, Av. Cândido Rondon, 501 - Barão Geraldo 13083-875, Campinas, Brazil. Email: rodrigorogeriodoutorado@gmail.com. Orcid: https://orcid.org/0000-0002-7928-9462

[2]Professor, Laboratory of Nondestructive Testing - LabEND, School of Agricultural Engineering - FEAGRI, University of Campinas - UNICAMP, Av. Cândido Rondon, 501 - Barão Geraldo 13083-875, Campinas, Brazil Email: raquelg@unicamp.br (+55 19 3521-1034). Orcid: https://orcid.org/0000-0003-0406-8988

*corresponding author

[3]Ph.D., Laboratory of Nondestructive Testing - LabEND, School of Agricultural Engineering - FEAGRI, University of Campinas - UNICAMP, Av. Cândido Rondon, 501 - Barão Geraldo 13083-875, Campinas, Brazil. E-mail: cinthyab@unicamp.br. Orcid: https://orcid.org/0000-0001-9039-4805

ABSTRACT

Ultrasonic testing has been used for quality control of various materials, including reinforced concrete. The aim of this study was to evaluate the ultrasound inspection methodology of a retaining wall made with a system (*Lock and Load*) with regard to the type of measurement (direct and indirect), type of transducer (flat and exponential), frequency transducer (25 kHz, 45 kHz, 80 kHz), coupling on the inspected element and distance between the transducers in indirect measurements. The 45 kHz frequency is best suited for quality control inspections of the panels and counterforts of the *Lock and Load* system before and after installation, as this frequency allows for the detection of the differences between panels using direct and indirect testing. The ratio between the indirect and direct velocity is 0.60 both for velocities obtained with flat and exponential surface transducers. The distance between transducers that present best correlation between the velocities obtained directly and indirectly is 300 mm.

Keywords: transducer frequency, ultrasound direct test, ultrasound indirect test, distance between transducers, flat surface transducer, exponential surface transducer.

INTRODUCTION

Retaining walls are very important structures for stabilizing slopes next to buildings in urban or rural areas. As with any structure, the parts used for retaining walls need to undergo quality control and periodic evaluation, so it is important to study the techniques and methodologies that allow for inspections.

Ultrasonic testing has been used for material classification and quality control as well as for inspections of the structural parts of various materials, including reinforced concrete (Shiotani et al. (2009), Masi and Vona (2010), Bautz et al. (2014), Haach and Juliani (2017), Watanabe et al. (2018), Villain et al. (2018), Polimeno et al. (2018) and Tatarinov et al. (2019). It is known, however, that many factors, such as the aggregate type, influence the propagation of waves in concrete due to their size, shape, density, elastic properties, and the amount present in the concrete matrix (Carcaño and Pereyra (2003), Carcaño and Moreno (2008), Ali et al. (2012), Mohammed and Hahman (2016), Yu et al. (2019)). Studies by Chotard et al. (2001), Smith et al. (2002), Ye et al. (2004), Lee et al. (2005) and Camara et al.

(2019) found that changes in the longitudinal and shear wave velocities are related to the process of curing and hydration of the cement over time, affecting the connection of the cementitious particles.

Blitz and Simpson (1996), Naik et al. (2003), Medeiros (2009), Pardo and Perez (2011) and Cruz et al. (2014) showed that the wave velocity for direct and indirect measurements in reinforced concrete is influenced by the presence and position of the reinforcement, reaching values higher than simple concrete on the order of 40 to 70% for reinforcement located parallel to the wave path. However, for researchers such as Puncinoti et al. (2007), Giacon (2009), Ferreira (2011), Cruz et al. (2014) and Adamatti et al. (2016), the wave propagation variations in concrete by reinforcement is depended on factors such as the diameter of the steel bars and the proximity of the transducers to the reinforcement.

The surface of a retaining structure in reinforced ground may be constructed for the purpose of increasing durability, improving aesthetics, facilitating construction of a structure and improving structural performance. The *Lock and Load* retainment system has been used by works in Brazil for cutting and landfill situations, surface covering in soil retaining work, strengthening the reinforcement of the soil structure, and contributing to erosion control. According to Murata et al. (1990), Tatsuoka (1993) and Benjamim (2006), the introduction of elements that have a rigid surface increases the soil confinement, and part of the horizontal stresses generated in the reinforced retaining wall are transferred to the surface, thus reducing the possibility of a localized rupture, increasing the stability of the slope and reducing its deformations. This system (*lock and load*) consists of reinforced concrete modules sized to withstand high compacting loads close to the surface. However, there are problems with the quality control of parts of the system (panels and counterfort), particularly in the case for the parts produced on the site itself. In addition, in the already installed parts, cracks may occur due to the low concrete rigidity caused during the absorption of the displacements produced by the soil mass, which may evolve into future local instability; therefore, there must be a methodology that allows the inspection of the system in-site.

Thus, the aim of this study was to evaluate the ultrasound inspection methodology of a retaining wall with regard to the type of measurement (direct and indirect), type of transducer (flat and exponential), frequency of the transducer, coupling system, and distance between the transducers during the indirect measurements.

MATERIAL AND METHODS

Material

The material used consisted of 5 concrete *Lock and Load* systems, which were composed of a reinforced panel and counterfort (Fig. 1). Ultrasound equipment (USLAB, Agricef, Brazil) and 25 kHz, 45 kHz and 80 kHz frequency flat surface longitudinal transducers and 45 kHz frequency exponential surface longitudinal transducers were used for the tests.

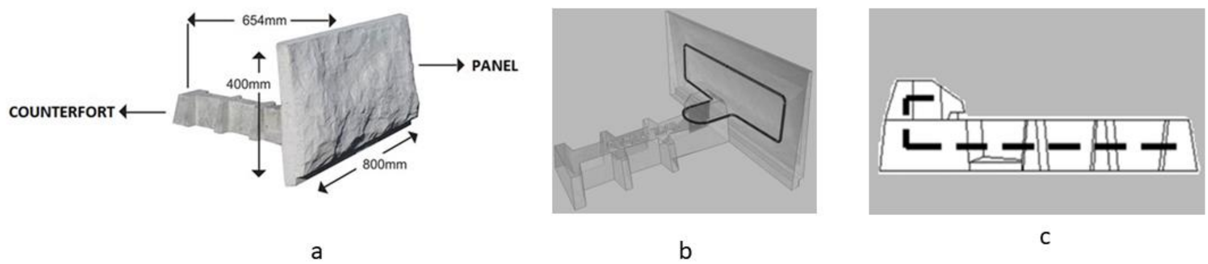


Fig. 1. *Lock and Load* system dimension (a) and positioning of the steel bars in the panel (b) and counterfort (c)

Materials such as potable water, CPII-F-40 cement, medium-sized quartz fine aggregates, coarse aggregate (gravel) of approximately 12 mm in diameter from granite rock, CA-50 steel with a dimeter of 6.3 mm for reinforcement, and polypropylene fibers, included in the mixture to improve ductility, were used. The defined basic trait had material proportions of 1:2:3 (cement, sand, gravel) measured by the mass of the cement and volume of the aggregates, with the addition of 175 grams of polypropylene fiber and a water/cement ratio (w/c) of 0.5 to 0.6 adjusted in-situ.

Production of the system components

The components of the system (panels and counterforts) were molded in plastic forms on a conveyor table, followed by thickening performed with a manual concrete vibrator used to facilitate the molding and ensure good compaction and densification of the aggregates. The vibration completion criterion was performed according to the criteria established by Brazilian standard ABNT NBR 5738 (2015) until the concrete surface had a smooth appearance and practically no air bubbles appeared on its surface. After 24 hours, the elements were demolded and cured under weather conditions and exposed to open air.

Methodology

Ultrasound calibration

At the start of each test or in situations where cable or transducer changes occurred during the inspection of the panels and counterforts, the equipment was calibrated using a calibrator made of an acrylic material, in which the propagation time was constant and known.

Testing Types

The tests were performed directly and indirectly. In the direct test, the transducers were placed on opposite sides of the element (compression wave). With the use of ultrasonic testing, the wave propagation time (t) were obtained, and thus, the velocity (V) was calculated for each distance between the transducers (L) - Eq. 1.

$$V = \frac{L}{t} \quad (1)$$

In the indirect test, the transducers were positioned on the same surface (surface wave), and the velocity calculation was made using the procedure proposed by the European (EN 12504-4 2004) and Brazilian (ABNT NBR 8802 2019) standards. In this procedure, the velocity was calculated using the angular coefficient of the line (ΔY/ΔX) constructed with use of the distance between the transducers (Y axis) versus the propagation time (X axis) obtained for each distance.

*Direct ultrasound tests on panels and counterfort*s

The reading points on the panel were made by considering the two parallel lateral surfaces, every 50 mm (Fig. 2a and 2b). To create the measurement mesh, straight lines joining the points of both ends were drawn on the surface (Fig. 2a and 2b). The wave propagation route coincident with the longer direction of the panel was called longitudinal measurement and the smaller direction called transversal measurement. In the counterfort, demarcations were made in the transverse section every 50 mm starting from the extremities and considering two heights of the transverse section (Fig. 2c). To ensure proper coupling, medical gel was applied to the surfaces of the flat transducers prior to each reading.

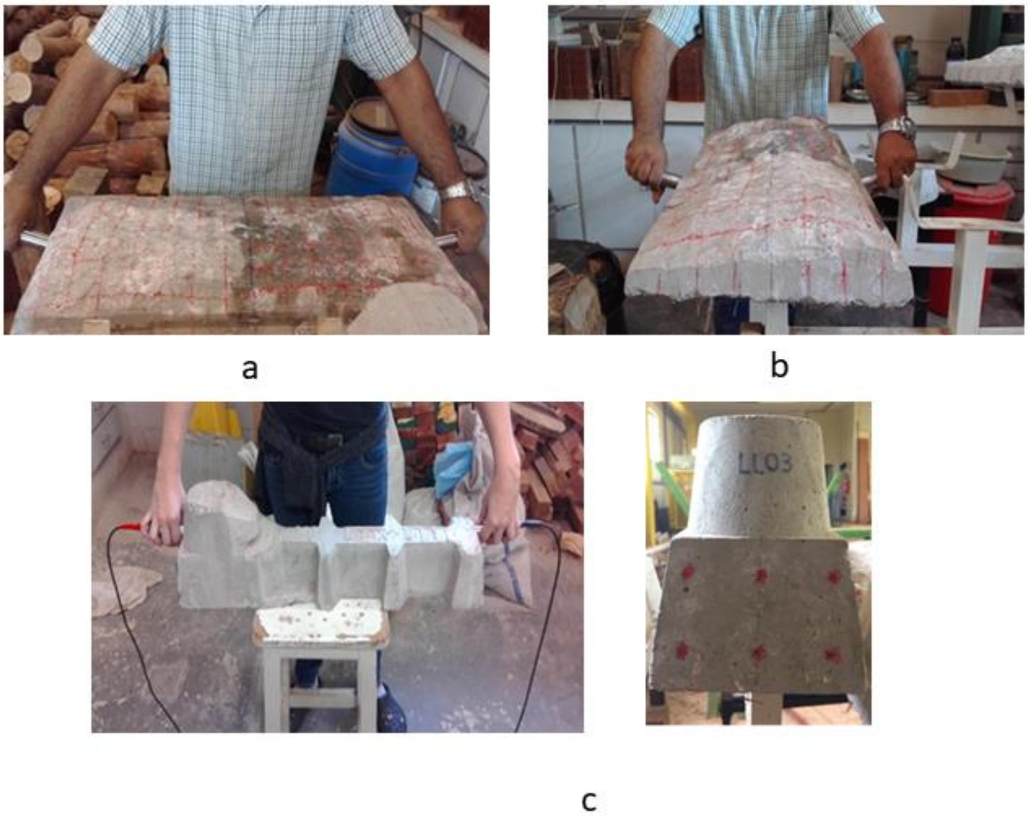


Fig. 2. Direct ultrasonic testing with wave propagation in the longitudinal (a) and transversal (b) direction of the panel and in the counterfort considering two lines in transversal section (c)

Panel indirect tests

For the indirect tests, flat and exponential surface transducers were used, both with 45 kHz frequency. According to Hager et al. (2013), exponential transducers have exponentially curved tips that concentrate ultrasonic energy in a small zone (point) and can be treated as the point source of spherical longitudinal waves. These probes do not require acoustic coupling, and these transducers can be easily applied to irregular surfaces such as the panels used in this study. Nevertheless, the signals provided by the probes are relatively weak compared to plane surfaces transducers (Hager et al., 2013).

The tests, using both exponential and plane transducers, were performed for the longitudinal and transversal direction positioning the transducers 50 mm from each side of the central point of the panel (Fig. 3). Starting from this point, the transducers moved away from the central point following the mesh described above. The surface tests were performed using three methodologies: with flat surface transducers (Fig. 3a), with exponential surface only supported on the panel (Fig. 3b), and with exponential transducers with coupling panel drilling (Fig. 3c). In the experiment with exponential surface transducers, the positioning was approximately 45º inclined to the panel surface, as proposed by Bucur (2006) for the indirect testing of wood and trees. Chaix et al. (2011) showed that the diffusion of the surface waves was influenced by the incidence angle, and for concrete samples with an incidence angle of around 40º, the wave propagation in the medium was constant. Although testing with the drilled part is not suitable for real field inspection conditions, the goal was to assess whether the best coupling of the transducers with a very small contact area and the best guarantee of an angle maintained at 45º would have a significant influence on the results.

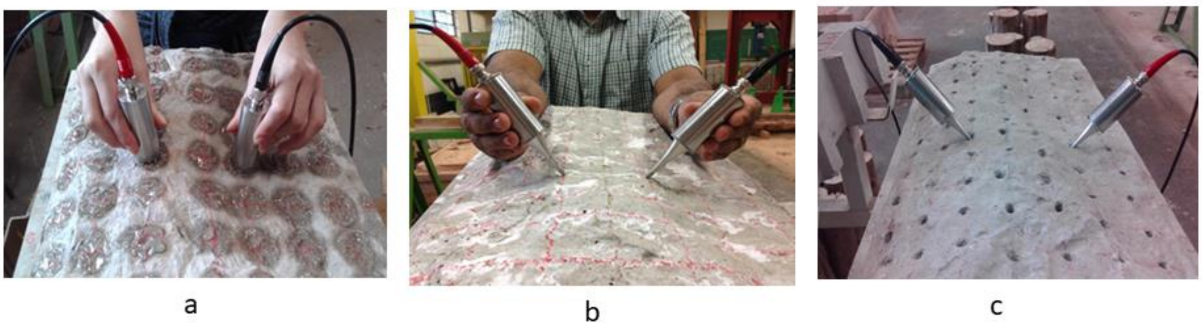


Fig. 3. Indirect ultrasonic testing with flat surface transducers (a), with exponential surface only supported on the panel (b), and with exponential transducers with coupling panel drilling (c)

Analysis of the results

Direct tests

To statistically evaluate the influence of the frequency and direction of measurement (longitudinal and transverse), a statistical analysis was performed using the "Multifactor

ANOVA" test. In this test, the independent variables were considered to be the panels (1 to 5), measurement directions (longitudinal and transverse) and frequencies (25 kHz, 45 kHz and 80 kHz) and the dependent variable was the propagation velocity of the ultrasound waves. The panels were not considering as repetition; in this way, it was possible to evaluate if the manufacturing process allows obtaining homogeneous panels, because they were all made with the same type of concrete and steel and with the same molding process and methodology.

During the statistical analysis, all the results were used in the measurement lines instead of using only the mean values. Thus, for each panel, the analysis was performed with velocities obtained in seven lines in the longitudinal direction for each frequency (7x5x3 = 105 values) and 14 lines in the transverse direction for each frequency (14x5x3 = 210 values). In the case of the counterforts, measurements were only taken in the longitudinal direction, in 6 routes (6x5x3 = 90 values).

Indirect tests

To evaluate the influence of the panel, the direction of propagation (longitudinal and transverse) and the type of transducer/coupling (flat surfaces, exponential surfaces supported only on the plate, and exponential surfaces coupled by drilling), a statistical analysis was performed using the "Multifactor ANOVA" test. Panels (1 to 5), with measuring directions (longitudinal transverse) and transducer/coupling types were considered the treatments (independent variables), and the propagation velocity of the ultrasound waves was considered a dependent variable. All the results were used in the measurement lines for testing instead of using only the mean values. As such, an analysis was performed with 7 velocity routes in the longitudinal direction for each plate and transducer type (7x5x3 = 105 values) and 3 velocity routes in the transverse direction for each plate and transducer type (3x5x3 = 45 values).

RESULTS AND DISCUSSIONS

Direct tests on the panels

Considering the mean velocities obtained for the panels, in both directions (longitudinal and transverse) and for the three frequencies (25 kHz, 45 kHz and 80 kHz), the variability was shown to be small within each panel, with a maximum coefficient of variation of 4% (Table 1).

The ultrasonic testing is performed based on free wave propagation. Free wave propagation occurs when the medium is infinite, which in the case of ultrasound testing is associated with the relationship between the route length dimension (L) and wavelength dimension (λ) (Royer and Dieulesaint, 1996). The wavelength is the relationship between the wave propagation velocity (in infinite media) and the transducer frequency (f), so obtaining the infinite medium condition is also associated with the frequency adopted for the transducer. Thus, wave propagation may be affected when the wavelength (λ) is not suitable for the size of the element through which it propagates (L), rendering the medium finite (Bucur 2006). Some standards have indications concerning the minimum element sizes and the minimum transducer frequencies to prevent testing from impairing the theoretical aspect of wave propagation. ASTM C597 (2016) indicates that the minimum element size is at least equal to the wavelength and that the maximum size needs to be compatible with the power of the equipment, since larger parts usually suffer from attenuation. In the case of EN 12505 (2004), the appropriate frequency for concrete testing lies between 20 kHz and 150 kHz, with the highest frequencies used for small parts (approximately 50 mm) and the lowest frequencies used for larger parts (maximum 15 m). With the values indicated by EN 12505 (2004), it can be seen that for a reference velocity of 4500 m/s propagating in concrete, the wavelength for the highest frequency should be approximately 30 mm. Considering a 50 mm element size, the wavelength to path ratio should be approximately 1.67. According to Naik et al. (2003), for the classification of common concrete the ratio adequate between the path length and wavelength (L/λ) is four. Giacon (2009) conducted prototype studies on reinforced concrete tubular poles with a 45 kHz frequency, concluded that the ratio (L/λ) greater than three times the wavelength, allowed the classification of concrete.

Table 1. Mean wave propagation velocities obtained in the direct tests on different panels with different transducer frequencies

Panel	Velocities ($m.s^{-1}$)					
	Freq. 25 kHz		Freq. 45 kHz		Freq. 80 kHz	
	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal
1	3793 D (1.6)	3809 Ca (1.9)	3876 D (1.5)	3886 Db (1.5)	3910 C (1.6)	3906 Db (0.8)
2	3621 B (2.4)	3655 Ba (0.6)	3710 B (2.0)	3776 Bb (0.7)	3614 B (2.7)	3640 BCa (1.5)
3	3574 B (3.2)	3674 Ba (2.0)	3734 B (2.1)	3759 Bb (1.3)	3531 A (4.0)	3606 Ba (2.3)
4	3721 C (1.6)	3805 Cb (0.9)	3790 C (2.0)	3841 Cb (1.0)	3615 B (2.8)	3699 Ca (2.5)
5	3506 A (2.9)	3578 Aa (1.2)	3534 A (2.0)	3643 Ab (1.3)	3578 AB (2.1)	3525 Aa (1.5)
Mean	**3643 (2.3)**	**3704 (1.3)**	**3729 (1.9)**	**3781 (1.2)**	**3650 (2.6)**	**3675 (1.7)**

Values in parentheses indicate the coefficient of variation in %.

Uppercase letters represent the comparison of the means in each column, and lowercase letters represent the comparison of the longitudinal means in each row. Equal letters indicate statistically equivalent means.

The wave propagation can also be affected when the size of the internal elements that make up the material is very close to the wavelength dimension, causing wave dispersion (Bond et al. 2000, Anugonda et al. 2001; Bucur 2006; Planes and Larose 2013). The issue of dispersion is even more important in heterogeneous materials compared to other materials (Bucur, 2006), which makes dispersion an important issue in concrete. Although the European standard EN 12504 (2004) does not mention the theoretical aspects behind their indicators, it suggests that the minimum length of the parts to be tested with ultrasound testing should be

100 mm for concrete whose maximum aggregate size is 20 mm, and 150 mm for concrete produced with aggregates between 20 mm and 40 mm. This suggestion is based on the fact that longer elements lengths can be evaluated with lower frequencies, which, in turn, have longer wavelengths. Considering the panel and counterfort sizes (Fig. 1) and the mean velocity values found in the system, the wavelengths (λ) are approximately 150 mm, 80 mm and 45 mm at frequencies of 25 kHz, 45 kHz and 80 kHz, respectively. Thus, the ratios of the wave path length (L) and wavelength (λ) (Table 2) were all higher than those indicated as the minimum in EN 12505 (2004) and ASTM C597 (2016). Based on the literature (Naik et al. 2003 and Giacon 2009), only transverse propagation using the 25 kHz transducer did not lie within ideal limits ($L/\lambda \geq 4.0$) (Table 2).

Table 2. Relation between path length (L) and wavelength (λ) in varying propagation directions with differing transducer frequencies

Propagation Frequency/Direction	25 kHz	45 kHz	80 kHz
Longitudinal	5.3	10.0	17.8
Transverse	2.7	5.0	8.9
Counterfort	4.4	8.2	14.5

Considering that the coarse aggregate (gravel) used in the concrete of the panel and the counterfort have an approximate diameter of 12 mm, all the frequencies adopted in the study produced wavelengths that are superior to the size of the gravel (150 mm, 80 mm and 45 mm), with the 80 kHz transducer generating the wavelength that most closely approximates the gravel size, which can influence the wave propagation according to Bond et al. (2000).

A statistical analysis (Table 1) designated heterogeneous groups for the panels (P-value < 0.05) and measurement directions (P-value < 0.05). For the frequencies of 25 kHz and 80 kHz, there was no significant difference in the velocity results (P-value > 0.05) (Table 1). The mean velocity obtained with the 45 kHz transducer was approximately 2% higher and significantly different (P-value < 0.05) than those obtained from the remaining transducers (Table 1). The significant difference in the velocities observed for the different panels shows that the manufacturing process does not lead to obtain fully homogeneous and/or rigid materials and that the method is able to detect such differences. One of the reasons for the differences can be related with the need to adjust the water cement factor (0.5 or 0.6) as described in the methodology. One of the main factors influencing ultrasonic testing, as reported in the literature, is the variation in the w/c factor in concrete, which after hydration is influenced by the amount of air incorporated into the concrete matrix, resulting in the attenuation and dispersion of ultrasound waves, which is reflected in the reduction in the velocity (Ohdaira and Masuzawa (2000), Lin et al. (2003), Del Rio et al. (2004), Yldirin and Sengul (2011), Zhang et al. (2015)). In the literature the ultrasonic testing has been accepted as an alternative method for the evaluation of concrete heterogeneity in structures as columns (Polimeno et al. 2018) and bridge (Sahuinco 2011).

The significant differences in the velocities for both of the wave propagation directions may be related to the presence of the reinforcement bars, since of the seven measurement routes in the longitudinal direction, there are two that are close to or even coincident with the reinforcement direction (Figure 4a). In the transverse direction, of the fourteen measurement routes, only two are close to or coincident with the reinforcement (Figure 4b). The difference was numerically small (2%), but because the velocity variability in the panels is also small, the difference could not be considered negligible, therefore, when using this methodology for panel quality control, it is important to avoid areas close to the reinforcement. According to the RILEM NDT 1 (1972), EN 12504-4 (2004), ACI 228.2R (2013), NBR 8802 (2019), ASTM C597 (2016) standards, the increase in the velocity value depends on the proximity between the steel bars, the wave path, the bars diameter, and the number and direction of the bars with respect to the wave path. These standards recommended, whenever possible, to avoid propagation measurements in regions with steel bars. Researchers such as Malhotra and Carino (2004), Naik et al. (2003) and Medeiros et al. (2009) found that measurements in the region near the reinforcement at the ultrasound velocity are approximately 1.2 to 1.4 times higher than that of simple concrete.

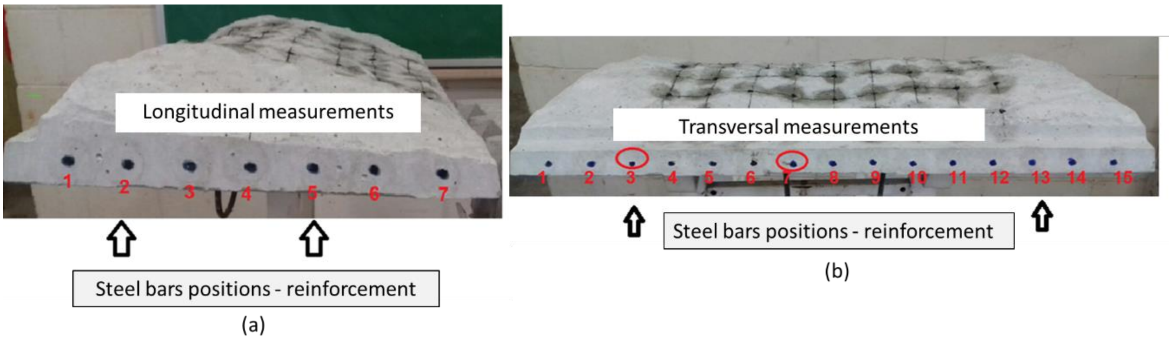


Fig. 4. Position of steel bars considering the longitudinal (a) and transversal (b) measurement direction

Considering the size of the elements, the 25 kHz frequency was the one that presented the smallest relation between the path length and wavelength (Table 2), and considering the dimension of the constituent elements, the 80 kHz frequency showed the wavelength that was closest to the size of the gravel. These two factors may have been responsible for the lower and significantly different values obtained at these two frequencies (25 and 80 kHz) compared to the velocity values obtained with the 45 kHz transducer (Table 1).

To ensure that the 45 kHz frequency, when individually analyzed, would have the same result for the distinction of the panels as that of the multiple analysis considering all the factors, one-way ANOVA was performed, with only the panels being isolated as the independent variable. The results showed that at this frequency (45 kHz), the velocities in the panel also showed significant differences (P-value = 0.0000), and the distinction was the same as what was previously obtained.

Direct tests on the counterforts

The coefficient of variation corresponding to the velocities for the counterfort (Table 3) was higher than those obtained in the panels (Table 1) but can still be considered suitable for a heterogeneous material such as concrete. The same wave propagation velocity band found in this research (Table 1) was found for the classification of the concrete structures and samples through direct measurements in the studies by Bungey and Millard (2006), Giacon (2009), Sahuinco (2011), Haach and Ramirez (2016), Rocha (2017), indicating that the coefficients of variation corresponding to the velocity in concrete between 1.75 and 3.90% were within the range of the values presented in this study.

For the counterforts, the ratios of the path length to the wavelength ranged from 4.4 (25 kHz) to 14.5 (80 kHz) and, therefore, they were within an adequate range for the wave to propagate freely, according to the literature.

Table 3. Mean results of the wave propagation velocity for direct tests performed on the counterforts, considering the different frequencies of the transducers

Counterfort	Velocity (m.s-1)		
	Freq. 25 kHz	**Freq. 45 kHz**	**Freq. 80 kHz**
1	3958 Cb (2.8)	3861 Bb (3.2)	3704 Ba (2.9)
2	3781 Bb (2.1)	3840 Bb (2.1)	3689 Ba (1.7)
3	3848 BCb (2.1)	3832 Bb (2.2)	3412 Aa (5.7)
4	3803 Bb (4.6)	3794 Bb (3.0)	3405 Aa (5.3)
5	3607 Ab (2.7)	3633 Ab (2.1)	3548 ABa (2.2)
Mean	**3799 (2.8)**	**3792 (2.5)**	**3551 (3.5)**

* Values in parentheses indicate the coefficient of variation in %.
Uppercase letters represent the comparison of the means in each column, and lowercase letters represent the comparison of the means in each row. Equal letters indicate statistically equivalent means.

The statistical analysis (Table 3) indicated that the counterforts (P-value < 0.05) and frequencies (P-value < 0.05) are heterogenous groups. Once again, it is evident that the manufacturing process does not allow elements with the same characteristics to be obtained and that the test has enough sensitivity to detect the differences.

In the case of the frequencies, the velocities obtained with the 25 kHz and 45 kHz transducers were statistically equivalent (P-value < 0.05) and higher than those obtained with the 80 kHz transducer (Table 3). This result could be related to the fact that the relations between the path length (L) and the wavelength (λ) were always higher than 4.0 for the counterfort, indicating that all the frequencies is adequate. As the size of the aggregates was the same for the plate and the counterfort, the 80 kHz frequency was the closest wavelength to the constituent element of the material and suffer the strongest interference during propagation.

Indirect test on the panels

The velocities obtained indirectly in the panels has higher variability (Table 4) than those obtained directly (Table 1). The mean coefficient of variation (CV) values are compatible with those found in the literature by Petro Jr. et al. (2012), with 6.0 to 10% (CV) in measurements using a flat surface transducer, and Rocha (2017), with 8 to 20% (CV) in measurements using an exponential transducer, performed with indirect measurements on the reinforced concrete elements.

Table 4. Mean wave propagation velocities obtained during the indirect tests on different panels and with different types of transducers and coupling

Panel	**Velocities (m.s^{-1})**					
	Flat Transducer		**Exponential Transducer no drilling**		**Exponential Transducer with drilling**	
	Transverse P-value = 0.0339	**Longitudinal** P-value = 0.0000	**Transverse** P-value = 0.1147	**Longitudinal** P-value = 0.0001	**Transverse** P-value = 0.2198	**Longitudinal** P-value = 0.0216
1	2650 A (7.5)	2265 BC (7.7)	2575 B (7.7)	2494 C (7.0)	3548 A (5.6)	2678 A (6.5)
2	2983 AB (5.7)	2548 D (5.3)	2179 AB (7.9)	2161 B (6.3)	3817 A (4.5)	2663 A (5.1)
3	2869 A (4.5)	2134 AB (8.5)	2154 AB (6.0)	2207 B (8.3)	3324 B (3.9)	2988 B (6.1)
4	2874 A (10.8)	2102 A (4.1)	2354 AB (13.1)	2376 BC (3.6)	3048 B (10.1)	2899 B (3.0)
5	3251 B (3.3)	2379 C (5.5)	2033 C (5.3)	1895 A (6.9)	3213 AB (3.4)	2788 AB (4.7)
Mean	**2926 (6.3)**	**2285 (6.2)**	**2259 (8.0)**	**2227 (6.4)**	**3390 (5.5)**	**2803 (5.1)**

Values in parentheses indicate the coefficient of variation in %.

Capital letters represent the comparison between means in each column (panels). Equal letters indicate statistically equivalent means.

The surface wave velocity (Table 4) is lower than that obtained directly (Tables 1), a result already consolidated in the literature (Qixian and Bulbey 1996, Camara 2006, Rheinheimer 2007, Petro Jr. et al. 2012 and Azreen et al. 2016) through samples and concrete structures using transducer frequencies between 20 and 150 kHz. The researchers found a 20–40% reduction in the surface velocity relative to the longitudinal velocity. Part of this difference can be explained by the concrete exudation, because a more porous and less resistant layer is formed at the surface. But there is another part explained by the difference in the wave propagation, because this same phenomenon occur in another materials, as in wood (Bucur 2006), for example.

The differences between direct and indirect tests were dependent on the transducer/coupling type and also by the direction of the wave propagation in the panel. The smallest difference (10%) was obtained for the exponential surface transducer with drilling and in the transverse direction, whereas the largest difference (70%) was found for the exponential surface transducer without drilling and in both directions. The exponential surface transducer, applied at 45° and with the coupling being favored by the orifice, makes the surface wave convert faster and more efficiently into a longitudinal wave (In et al., 2009), which may explain the great similarity between the results when using compression waves. However, in practice, such a test (drilling the concrete) in-site is not feasible. In the longitudinal direction, the flat and exponential surface transducers without drilling showed high and similar differences (60% and 70%, respectively), but in the transverse direction, the differences were smaller for the flat surface transducer (20%). This result may be related to the interference of steel bars in this propagation direction, which is associated with the wave depth reached in each of the tests (perpendicular transducer and transducer at 45°) and the shorter distances between the transducers in this test direction (up to 0.3 m instead up to 0.7 m in the longitudinal direction), which results in higher velocities, as previously discussed. In addition, the flat transducer is less error prone since it has a larger contact surface and does not depend on the maintenance of a specific angle. On the other hand, it must be used with coupling gel, making practical field applications difficult.

A statistical analysis of the indirectly obtained velocities in the different panels shows that the distinction between them is much less clear (Table 4) than that obtained directly (Table 1), demonstrating that the test is less sensitive to the differentiation in the panels in terms of the stiffness and/or homogeneity. This result is negative from a practical point of view, that is, when aiming for the use of this tool in quality monitoring in-situ. The velocity obtained indirectly in the longitudinal direction with the exponential surface transducer without drilling was the only result that rated the panel better (1) and worse (5) in the same way (Table 4) that obtained directly (Table 1). Given that the indirect test is, in practice, the only one that can be applied to monitor the quality of the panels that are already installed, it is important to assess whether it is possible to correlate the velocities obtained indirectly with those obtained directly. Although numerical differences between the velocities obtained directly and indirectly were lower in the transverse direction, the previous analyses have shown that this is the direction that suffers the most interference, possibly due to the presence of the reinforcement. Thus, the following correlation analyses will be performed only for the velocities obtained in the longitudinal direction.

By analyzing the behavior of the linear models, as well as the correlation between the mean velocities obtained in the direct and indirect longitudinal tests in each panel (considering the velocities obtained directly as independent variable (X) and indirectly as the dependent variable (Y), it can be seen that the angular coefficient of the line is 0.61 on average (Table 5), with only a 5% coefficient of variation for the flat surface transducer and 0.60 with a 4% coefficient of variation for the exponential surface transducer (Table 5). However, the indirect velocity is better explained by the direct velocity for all the scenarios (R^2) for a distance of 300 mm between the transducers. For both the flat and exponential transducer, the worse result for the determination coefficient is for the shortest distances (100 and 200 mm). Indirect velocities were best explained by the velocities obtained directly using the flat surface transducer (Table 5).

Table 5. Angular coefficient and coefficient of determination (R^2) of the model that correlates the velocity obtained indirectly (Y) with the velocity obtained directly (X)

Distance between transducers (mm)	**100**	**200**	**300**	**400**	**500**	**600**	**700**
Flat surface transducers positioned perpendicular to the panel surface							
Angular coefficient of the line	0.62	0.65	0.63	0.61	0.57	0.58	0.61
R^2(%)	16	5	93	54	40	35	54
Exponential surface transducers positioned at 45° relative to panel surface							
Angular coefficient of the line	0.60	0.63	0.61	0.59	0.56	0.58	0.62
R^2(%)	11	29	56	49	52	41	28

By analyzing the behavior of the velocities individually for each panel as a function of the distances between the transducers, no significant difference was found between the velocities, neither in the longitudinal nor transverse measurements (P-value > 0.05). However, in the case of the longitudinal measurements, there is a large velocity dispersion at the shortest (0.1 and 0.2 m) and largest (0.6 and 0.7 m) distances for all the panels. This dispersion might be responsible for the small correlations with the velocities obtained directly (Table 5). Cross-sectional (tangential) measurements were made only at three distances, but we verified a reduction in the variability at a distance of 0.3 m for all the panels compared to the shortest distances (0.1 and 0.2 m). For concrete samples with both reinforced and nonreinforced sections, Ferreira (2011), Petro Jr. et al. (2012) and Paiva (2017) also showed more consistent and less varied results for 0.30 m distance between the transducers. By using the mean velocities on the panels for each distance, it is possible to verify this same behavior (more variability for shorter distances), as well as that the velocities obtained in the longitudinal measurements presenting less variability than the transverse measurements (Fig. 5). We also note that the velocity values obtained in the longitudinal and transverse measurements approach at a distance of 0.3 m between the transducers (Fig. 5), which also explain the results shown in Table 5. By adopting 0.3 m as the distance between the transducers, the wavelength of this test was approximately 60 mm (assuming a mean velocity value of 2700 $m.s^{-1}$), indicating that the path length would be approximately 5 times the wavelength.

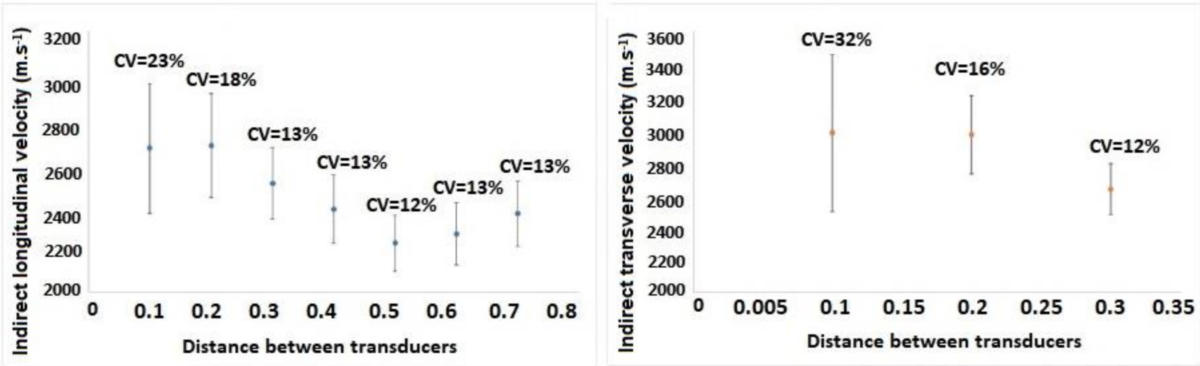


Fig. 5. Behavior of the velocity variation with the distance between the transducers for indirect measurements taken in the longitudinal and transverse directions
Error bars = standard deviation and CV = coefficient of variation of the results obtained for the 5 panels

From a theoretical point of view, the classification of the materials is more appropriate with velocities obtained directly. Our results indicating that the correlation of the direct and indirect velocities obtained with the flat surface transducer is better than with exponential one (Table 5), showing superior adequacy. On the other hand, the panel classification using exponential surface transducers (without drilling) presented a classification of the panels similar to the obtained using flat transducer and it is more applicable to field inspection conditions.

Conclusion

- The 45 kHz frequency is best suited for quality control inspections of the panels and counterforts of the *Lock and Load* system (minimum route length 400 mm and maximum gravel diameter 12 mm) before and after installation, as this frequency allows for the detection of the differences between panels using direct and indirect testing.

- The ratio between the indirect and direct velocity is 0.60 both for velocities obtained with flat and exponential surface transducers.

- The distance between transducers that present best correlation between the velocities obtained directly and indirectly is 300 mm.

Acknowledgements

The authors would like to thank the Sao Paulo Research Foundation (FAPESP), São Paulo for the financing of several projects of the research group, which allowed the facilities used in this research and Geosoluções for the logistic support, materials and permission to use the Lock and Load forms.

References

Associação brasileira de normas tecnicas. NBR 8802. (2019). Concreto endurecido – determinação da velocidade de propagação da onda ultrassônica. Rio de janeiro.

______. NBR 5738. Concreto: procedimento para moldagem e cura de corpos de prova. (2015) Rio de janeiro.

Adamatti, D. S., Lorenzi, A., Chies, J. A., da Silva Filho, L. C. P. (2016). Análise de estruturas de concreto armado através da velocidade de propagação do pulso ultrassônico: estudo de parâmetros tecnológicos intervenientes. Riem-ibracon structures and materials journal, v. 10, n. 2.

Ali, M., Liu, A., Sou, H., Chouw, N. (2012). Mechanical and dynamic properties of coconut fibre reinforced concrete, construction and building materials, v. 30, p. 814-825.

American concrete institute. Aci 228. 2r. (2013). Report on nondestructive test methods for evaluation of concrete in structures, Detroit.

American society for testing and materials. C597-16. (2016). Standard test method for pulse velocity through concrete. West Conshohocken.

Anugonda, P., Wiehn, J. S., Turner, J. (2001). A. Diffusion of ultrasound in concrete. Ultrasonics, v. 39, n. 6, p. 429-435.

Azreen, M. N., Pauzi, I. M., Nasharuddin, I., Haniza, M. M., Akasyah, J., Karsono, A. D., Lei, V. Y. (2016). Prediction of concrete compression strength using ultrasonic pulse velocity. In: aip conference proceedings. Aip publishing. Vol. 1704, no. 1, p. 040006.

Bautz, R. S., Macioski, G., Weber, S. L., Moreira, A. R. (2014). Análise da qualidade do concreto em pilares de viadutos por meio de ensaios não destrutivos para fins de reabilitação. 1º congresso brasileiro de patologia das fundações. Foz do Iguaçu - Paraná.

Benjamim, C. V. S. (2006). Avaliação experimental de protótipos de estruturas de contenção em solo reforçado com geotêxtil. Tese de doutorado. Universidade de São Paulo.

Blitz, J., Simpson, G. (1996). Ultrasonic methods of non-destructive testing. London: chapman & hall.

Bond, L. J., Kepler, W. F., Frangopol, D. M. (2000). Improved assessment of mass concrete dams using acoustic travel time tomography. Part i - Theory. Construction and Building Materials, v. 14, n. 3, p. 133-146.

Bucur, Voichita. (2006). Acoustics of wood. Editora Springer Verlage – N.Y. 393p.

Bungey, J. H., Millard, M. G. (2006). Testing of concrete in structures. 4.ed. New work, USA: Champan e Hall. 310p. 2006.

Carcaño, R. S, Pereyra, J. B. (2003). The influence of the physical properties of aggregates on the ultrasound pulse technique in predicting the compressive strength of concrete. Revista Técnica de la Facultad de Ingeniería Universidad del Zulia, v. 26, n. 1.

Carcaño, R. S, Moreno, E. I. (2008). Evaluation of concrete made with crushed limestone aggregate based on ultrasonic pulse velocity. Construction and Building Materials, v. 22, n. 6, p. 1225-1231.

Câmara, E. (2006). Avaliação da resistência à compressão de concretos utilizados na grande Florianópolis através de ensaios não destrutivos. Dissertação de Mestrado. Universidade Federal de Santa Catarina. p.212.

Camara, L.A., Wons, M., Esteves, I.C., Medeiros-Junior, R. A. (2019). Monitoring the self-healing of concrete from the ultrasonic pulse velocity. Journal of Composites Science, v. 3, n. 1, p. 16.

Chaix, J. F., Ack-Baraly, C., Garnierg, V., Salim, J. (2011). Etude de la propagation des ondes de volume et de surface dans du béton. Les Journées COFREND, 2011.

Chotard, T., Gimet-Breart, N., Smith, A., Fargeot, D., Bonett, J. P., Gault, C. (2001). Application of ultrasonic testing to describe the hydration of calcium aluminate cement at the early age. Cement and Concrete Research, v. 31, n. 3, p. 405-412.

Cruz, R., Quintero, L. A., Herrera, J. (2014). Evaluación del efecto de barras de refuerzo en concreto sobre las medidas de velocidad de pulso ultrasónico (VPU). Revista Colombiana de Materiales, n. 5, p. 107-113.

Del Rio, L. M., Jimenez, A., Lopez, F., Rosa, F. J., Rufo, M. M., Paniagua, J. M. (2004). Characterization and hardening of concrete with ultrasonic testing. Ultrasonics, v. 42, n. 1-9, p. 527-530.

European Commitee for Standardization, BS EN 12504:4, Testing Concrete. (2004). Determination of ultrasonic pulse velocity, Brussels.

Ferreira, G. Estudo sobre fatores influentes nos resultados de ensaios não destrutivos em concreto endurecido. (2011). Dissertação (Mestrado em Engenharias) - Universidade Federal de Uberlândia, Uberlândia-MG, p.199.

Giacon Jr, M. Propagação de ondas de ultra-som em prototipos de postes tubulares de concreto armado. Dissertação de Mestrado. Universidade Estadual de Campinas. 2009.

Haach, V. G., Juliani, L. M. (2017). Possibilities of using ultrasound for the technological control of concrete of hollow-core slabs. Construction and Building Materials, v. 133, p. 409-415.

Haach, V. G., Ramirez, F. C. (2016). Qualitative assessment of concrete by ultrasound tomography. Construction and Building Materials, v. 119, p. 61-70.

Hager, I., Carré, H., krzemie, k. (2013). Damage assessment of concrete subjected to high temperature by means of the ultrasonic pulse velocity-UPV method. Studies and Researches, v. 32, n. 1, p. 197-211.

In, C. W., Kim, J. Y., Kurtis, k. E., Jaconbs, L. J. (2009). Characterization of ultrasonic rayleigh surface waves in asphaltic concrete. NDT & International, v. 42, n. 7, p. 610-617.

Lee, H. K., Lee, k. M., Kim, Y. H., Yim, H., Bae, D. B. (2004). Ultrasonic in-situ monitoring of setting process of high-performance concrete. Cement and Concrete Research, v. 34, n. 4, p. 631-640.

Lin, Y., Lai, C. P., Yen, T. (2003). Prediction of ultrasonic pulse velocity (UPV) in concrete. Materials Journal, v. 100, n. 1, p. 21-28.

Malhotra, V. M, Carino N. J. (2004). Nondestructive testing of concrete. 2. Ed. London: American Society for Testing and Materials.

Masi, A., Vona, M. (2010). Experimental and numerical evaluation of the fundamental period of undamaged and damaged RC framed buildings. Bulletin of Earthquake Engineering, v. 8, n. 3, p. 643-656.

Medeiros, A., Padaratz, I. J., Pinto, R. C. A. (2009). Influência da presença de armaduras na estimativa da profundidade de fissuras superficiais em concreto armado através do ultra-som. Congressso Brasileiro do Concreto (COBRACON), v. 51.

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.

Murata, O., Tateyama, M., Tatsuoka, F. (1990). Steep reinforced with a planar geotextile having a rigid facing. Fourth International Conference on Geotextiles, Geomembranes and Related Products, The Hauge, Netherlandas, v.1, p.122.

Naik, T. R., Malhotra, V. M., Popovics, J. S. (2003). The ultrasonic pulse velocity method. In: Handbook on Nondestructive Testing of Concrete. CRC Press. P. 182-200.

Ohdaira, E., Masuzawa, N. (2000). Water content and its effect on ultrasound propagation in concrete-the possibility of nde. Ultrasonics, v. 38, n. 1-8, p. 546-552.

Paiva, M. A. C. (2017). Análise das propriedades mecânicas nas primeiras idades do concreto de lajes alveolares utilizando o ensaio de ultrassom. Tese de doutorado. Universidade de São Paulo.

Pardo, F., Perez, E. (2010). Evaluación del efecto de las barras de refuerzo del concreto sobre las medidas de velocidad de pulso ultrasónico. Bucaramanga, Colombia, Universidad Industrial de Santander, p.123.

Petro Jr, J. T., Kim, J. (2012). Detection of delamination in concrete using ultrasonic pulse velocity test. Construction and Building Materials, v. 26, n. 1, p. 574-582.

Planès, T., Larose, E. (2013). A review of ultrasonic coda wave interferometry in concrete. Cement and Concrete Research, v. 53, p. 248-255.

Polimeno, M. R., Roslelli, I., Luprano, V. A., Mongelli, M., Tati, A., de Canio, G. A. (2018). Non-destructive testing methodology for damage assessment of reinforced concrete buildings after seismic events. Engineering Structures, v. 163, p. 122-136.

Puncinoti, R., Hinterholz, L., D'elia, A., De Loenzo, R. A. (2007). Influence of steel reinforcement on ultrasonic pulses velocity. In: 4 th International Conference on NDT (11-14 octubre, Chania, Crete-Grecia), Italy. 2007.

Qixian, L., Bungey, J. H. (1996). Using compression wave ultrasonic transducers to measure the velocity of surface waves and hence determine dynamic modulus of elasticity for concrete. Construction and Building Materials, v. 10, n. 4, p. 237-242.

Reunion internationale de laboratoires d'essais et materiaux. Rilem NDT 1. (1972). Testing of Concrete by the Ultrasonic Pulse Method. Paris.

Rheinheimer, V. (2007). Utilização de ensaios não destrutivos no controle tecnológico de execução de pavimentos de concreto tipo Fast Track. Dissertação de Mestrado. Universidade Federal de SCatarina. P. 266.

Rocha, A. I. C. B. (2017). Identificação de patologias em vigas de concreto armado utilizando inspeção por ultrassom. Dissertação de Mestrado. Unicamp-Universidade Estadual de Campinas.

Royer, D., Dieulesaint, E. (1996). Elastic waves in solids II: Generation, acousto-optic interaction, applications. Springer Science & Business Media.

Sahuinco, C., H., M. (2011). Utilização de métodos não destrutivos e semi-destrutivos na avaliação de pontes de concreto. Tese de Doutorado. Universidade de São Paulo. P.170.

Shiotani, T., Aggelis, D. G., Makishima, O. (2009). Global monitoring of large concrete structures using acoustic emission and ultrasonic techniques: case study. Journal of Bridge Engineering, v. 14, n. 3, p. 188-192.

Smith, A., Chotard, T., Gimet-Breat, N., Fargeot, D. (2002). Correlation between hydration mechanism and ultrasonic measurements in an aluminous cement: effect of setting time and temperature on the early hydration. Journal of the European Ceramic Society, v. 22, n. 12, p. 1947-1958.

Tatarinov, A., Rumjancevs, A., Mironovs, V. (2019). Assessment of cracks in pre-stressed concrete railway sleepers by ultrasonic testing. Procedia Computer Science, v. 149, p. 324-330.

Tatsuoka, F. (1993). Keynote lecture: roles of facing rigidity in soil reinforcing. In: Ochiai, Hayashi & Otani (EDS), Earth Reinforcement Practice, A. A. Balkema, Rotterdam, pp. 831-870.

Villain, G., Garnier, V., Sbartai, Z. M., Derobert, X., Balayssac, J. P. (2018). Development of a calibration methodology to improve the on-site non-destructive evaluation of concrete durability indicators. Materials and Structures, v. 51, n. 2, p. 40

Watanabe, S., Hishikawa, K., Kamae, K., Namiki, S. (2018). Study on estimation of compressive strength of concrete in structure using ultrasonic method. Japan Architectural Review, v. 1, n. 1, p. 87-95.

Ye, G., Lura, P., Breugel, K., Fraaij, A. L. (2004) Ultrasonic in-situ monitoring of setting process of high-performance concrete. Cement and Concrete Research, v. 34, p. 631-640.

Yildirim, H., Sengul, O. (2011). Modulus of elasticity of substandard and normal concretes. Construction and Building Materials, v. 25, n. 4, p. 1645-1652.

Yu, T., Chaix, J. F., Audibert, L., Komatitsch, D., Garnier, V., Henault, J. M. (2019). Simulations of propagation of ultrasonic waves in concrete based on a two-dimensional numerical model validated analytically and experimentally. Ultrasonics, 92, 21-34.

Zhang, J., Fan, T., Ma, H., Li, Z. (2015). Monitoring setting and hardening of concrete by active acoustic method: effects of water-to-cement ratio and pozzolanic materials. Construction and Building Materials, v. 88, p. 118-125.

2.2 Artigo 2 - INFERENCE OF MECHANICAL PROPERTIES OF CONCRETE PRODUCED WITH COARSE AGGREGATES FROM DIFFERENT MINERALOGICAL ORIGINS USING ULTRASONIC TESTS

ARTIGO SUBMETIDO AO PERIÓDICO CONSTRUCTION AND BUILDING MATERIALS

FORMATAÇÃO E IDIOMA DE ACORDO COM AS NORMAS DO REFERIDO PERIÓDICO

INFERENCE OF MECHANICAL PROPERTIES OF CONCRETE PRODUCED WITH COARSE AGGREGATES FROM DIFFERENT MINERALOGICAL ORIGINS USING ULTRASONIC TESTS

Rodrigo Rogerio Cerqueira da Silva[1], Raquel Gonçalves[2*], Cinthya Bertoldo Pedroso[3]

[1]Ph.D. Student, Laboratory of Nondestructive Testing - LabEND, School of Agricultural Engineering - FEAGRI, University of Campinas - UNICAMP, Av. Cândido Rondon, 501 - Barão Geraldo 13083-875, Campinas, Brazil. Email: rodrigorogeriodoutorado@gmail.com. Orcid: https://orcid.org/0000-0002-7928-9462

[2]Professor, Laboratory of Nondestructive Testing - LabEND, School of Agricultural Engineering - FEAGRI, University of Campinas - UNICAMP, Av. Cândido Rondon, 501 - Barão Geraldo 13083-875, Campinas, Brazil Email: raquelg@unicamp.br (+55 19 3521-1034). https://orcid.org/0000-0003-0406-8988
*corresponding author

[3]Ph.D., Laboratory of Nondestructive Testing - LabEND, School of Agricultural Engineering - FEAGRI, University of Campinas - UNICAMP, Av. Cândido Rondon, 501 - Barão Geraldo 13083-875, Campinas, Brazil. E-mail: cinthyab@unicamp.br. Orcid: https://orcid.org/0000-0001-9039-4805

Abstract
Nondestructive techniques, as ultrasound, is desirable for on-site inspections, because allows to monitor the condition of the material without affecting its properties. However, many factors may interfere with the wave propagation, including the mineralogical origins of the gravel. This research aims to evaluate the behavior of the parameters obtained by ultrasonic testing as predictor of the concrete strength and stiffness produced with coarse aggregates from four different mineralogical origins (basalt, limestone, gneiss, and granite). The inference models are statistically significant (P-value < 0,05) for concrete produced with all the studied rocks, with coefficients of determination higher than 85%.

Keywords: basalt, limestone, gneiss, granite, modulus of elasticity of concrete, compressive strength of concrete, quality control of concrete

1 INTRODUCTION

The technological control of concrete is very important in several types of applications of this material. Studies carried out by [1 - 4] have shown that the technological control of concrete allows us to deepen our knowledge about its mechanical properties and about parameters related to its response leading to the limit state, allowing the structural design to be closer to the real behavior of the structure. However, technological control requires tools, methods, and models capable of inferring concrete properties with enough accuracy.

By allowing material evaluations without interfering with their properties and thus making it possible to perform on-site inspections and material tracking over time, nondestructive techniques are important tools used for technological control. Nevertheless, the increased accuracy of nondestructive testing on the inference of the mechanical properties of concrete is obtained using correlation models with destructive testing for the same type of concrete under analysis [5-7]. Similar results have been reported by authors [8-11] who attribute the achievement of reliable results to nondestructive techniques when used along with correlation models developed for the same type of concrete under study.

For concrete, the challenge of obtaining generalist models of the correlation between field-applicable (nondestructive) testing and the mechanical properties is amplified because different compositions will affect the rheology [12-14], making models that are adjusted for one composition not directly applicable to others. In particular, different rock types react differently with water absorption, thus altering the compactness of the concrete transition zone [15] and altering the strength and stiffness.

One of the nondestructive techniques that is considered feasible for the evaluation of the concrete quality is the ultrasound. For this type of testing, the literature proposes several models to examine the correlation between the wave propagation velocity and the compressive strength (fc) of concrete [4, 10, 11, 16-32]. Nevertheless a few studies have examined correlation models between the initial modulus of elasticity of concrete (Eci) obtained during static testing and the stiffness coefficient obtained by ultrasonic testing [25, 28, 31, 33-36]. These correlation models involve concretes with variations of different parameters, such as the water-cement ratio, aggregate amount and type, curing time and conditions, porosity, cement type, and concrete age.

Although there are several studies that focus on evaluating the influence of different parameters (including aggregate properties) on the physical, mechanical, and acoustic properties of concrete, few studies present an approach involving the analysis of concrete produced with more than two types of aggregates wherein the aggregate type is the only factor of variation in the concrete. In addition, few studies have focused on prediction models of the strength (fc) and stiffness (Eci) properties from more than one ultrasonic testing parameter obtained with different transducer frequencies. Thus, these aims constitute the differential scientific contributions of this paper.

In Brazil, the types of rock used in the production of aggregates are granite and gneiss (85%), limestone (10%), and basalt (5%) [37], which are distributed in different regions of the country. As a result, concrete produced with aggregates from these rocks can be found throughout the country, internally expanding the importance of studies aiming at technological control.

Considering the abovementioned factors, this research mainly aims to evaluate the behavior of the parameters obtained by ultrasonic testing, with two different transducer frequencies, as predictors of the strength and stiffness of concrete produced with coarse aggregates from four different mineralogical origins (granite, gneiss, basalt, and limestone).

2 MATERIAL AND METHODS

2.1 Sampling

The samples consisted of 128 specimens with a diameter of 150 mm and a height of 300 mm [38], with 8 replications of each of the four aggregate mineralogical origins (granite, gneiss, basalt, and limestone) produced with four mix ratios, varying only the water-cement ratio (0.5; 0.7; 0.9, and 1.0). The water/cement ratio variation was used to obtain the range of the characteristic compressive strengths (fck), allowing fundamental variability for the regression model evaluation. The concrete specimens were cured in the open, weather-protected, and demolded after 24 hours.

2.2 Preparation and characteristics of the specimen concrete

The following ingredients were used to prepare the mix ratio: drinking water, CP II-F-40 Portland cement [39] (commonly used in structural elements), quartz natural fine aggregates (sand), polypropylene macrofiber, and crushed coarse aggregates (gravel) of different types of mineralogy, chosen from the most abundant of the five regions of Brazil (granite, gneiss, basalt, and limestone). No additives were used during the experimental design.

Aggregate characterization was performed according to the recommendations of the NBR standards for fine aggregates [40-43] and coarse aggregates [40, 41, 44]. The results of both (Table 1) were within the acceptable limits [45].

Aggregates	**Specific mass ($kg.m^{-3}$)**	**Unit mass ($kg.m^{-3}$)**	**Maximum aggregate size (mm)**	**Absorption (%)**	**Fineness modulus**
Granite	2520	1510	9.5	0.62	5.24
Gneiss	2550	1310	9.5	0.57	5.65
Basalt	2810	1680	10	1.12	5.58
Limestone	2710	1600	9.5	0.32	5.96
Sand	2590	1390	4.8	0.7	2.71

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

The defined basic mix had a 1:2:3 ratio between the materials (cement, sand, gravel). The sand moisture content was corrected to define the water-cement ratio. The cement and the aggregates were measured by mass, with the addition of 175 grams of polypropylene macrofiber. The polypropylene macrofiber content used in the concrete mixes was considered low (less than 1% by 50 kg of cement). Mechanical behavior of concrete produced with a low polypropylene macrofiber content has no significant effect on the compressive strength and modulus of elasticity [46-48]. The addition of this fraction of fibers was solely for the purpose of reducing the cracking of the pieces.

2.3 Density

At 28 days, the mass of each specimen was determined by weighing them on a precision scale (0.1 g resolution), and their dimensions were measured with a digital caliper to calculate the volume; then, the density (ρ) of the specimens was calculated.

The average densities of the concrete produced with different aggregates decreased as the water-cement ratio increased, as expected (Table 2). Additionally, there was an increase in the slump [49] as the water-cement ratio increased, also as expected (Table 2). Despite the variations in the densities, the values of all the densities were within the limits that are considered normal for concrete, from 2000 $kg.m^{-3}$ to 2800 $kg.m^{-3}$, according to the Brazilian standard [50] and the literature [30, 51].

Aggregates used in concrete production	W/C ratio	Slump (mm)	Average density ($kg.m^{-3}$)
Granite	0.5	20	2295
	0.7	220	2145
	0.9	250	2065
	1.0	280	2044
Gneiss	0.5	70	2264
	0.7	100	2231
	0.9	200	2155
	1.0	280	2150
Limestone	0.5	30	2330
	0.7	170	2291
	0.9	270	2127
	1.0	290	2123
Basalt	0.5	80	2134
	0.7	200	2240
	0.9	230	2164
	1.0	280	2135

Table 2. Slump and average density values of concretes produced with aggregates from different mineralogical origins and water/cement (W/C) ratios.

2.4 Ultrasonic testing

Prior to testing, the equipment was calibrated using an acrylic material in which the propagation time was constant and known. To minimize signal attenuation, a medical gel was used as a coupler on the transducer faces.

The specimens were subjected to ultrasonic testing at 28 days using ultrasound equipment (USLAB, Agricef, Brazil) and 45 and 80 kHz frequency longitudinal transducers with plane faces. The direct test (volume or compression wave) was performed by placing the transducers on opposite sides of the specimen, as proposed by Brazilian [52], American [53], English [5], and European [7] standards. To produce an overall evaluation of the specimen, propagation time measurements were performed by placing the transducers at three different points on the cross-sectional face of the specimen, one in the center and the other two near the ends, adopting the average as the final time value (t). From the specimen length (L) and the results of the wave propagation time (t), the propagation velocity of the ultrasound waves (V) was calculated. With the velocity and density of the specimen, the stiffness coefficient (C) was calculated – Equation 1.

$$C = \rho . V^2 \quad \text{Equation 1}$$

where C = the stiffness coefficient (MPa), V = the wave propagation velocity ($m.s^{-1}$), and ρ = the concrete density ($kg.m^{-3}$).

2.5 Static compression tests

After ultrasonic testing, the specimens were capped with sulfur paste to ensure the parallelism of the faces during the compression tests, as specified in the Brazilian standard [54].

Compression tests were performed at 28 days on a 300-kN load capacity testing machine (EMIC, Brazil), following the specifications of the Brazilian standard [54]. These tests allowed the calculation of the compression strength (fc) – Equation 2. The specimens were also instrumented with 0.01-mm-resolution strain gauges to determine the initial modulus of elasticity (Eci), calculated according to the Brazilian standard [55] – Equation 3.

$$fc = \frac{4.F}{\pi.D^2} \qquad \text{Equation 2}$$

$$E_{ci} = \frac{\sigma_b - 0.5}{\varepsilon_b - \varepsilon_a} \qquad \text{Equation 3}$$

where fc = the compression strength (MPa); F = the maximum force (N); D = the diameter (mm); σ_b = the stress (MPa) obtained at 30% of the maximum compression force; 0.5 = the initial reference stress (MPa); and ε_b and ε_a = the concrete-specific deformations under a stress corresponding to 30% of the maximum force and under the initial reference stress, respectively.

2.6 Characteristic compressive strength

The characteristic compressive strength was estimated using the Brazilian standard [56] – Equation 4.

$$f_{ck,est} = 2\frac{f_1 + f_2 + \cdots + f_{m-1}}{m-1} - f_m \qquad \text{Equation 4}$$

where $f_{ck,est}$ = the estimated characteristic strength; m = the number of specimens/2, in the case of this research m = 8/2 = 4; f_1, f_2,..., f_m = the values of the individual strengths of the specimens, in ascending order. For $f_{ck,est}$, one does not assume a value lower than Ψ_6 x f_1, adopting Ψ_6 according to the table as a function of the variability (standard deviation) and the number of specimens in the sample, which in the case of this research was 0.95 (corresponding to 8 specimens and a standard deviation below 4.0 MPa - Table 3).

Since the objective of the research is to obtain regression models, the characteristic compressive strength (fck) was important for indicating the degree of variability of the sample. The results showed that it was possible to obtain the variability of fck (from 6,3 to 27.1 MPa, considering all types of gravel) by varying the W/C ratio (Table 3). Considering the sampling (8 specimens) within the same water-cement ratio, as expected the variability was low, with coefficients of variation (CV) generally ranging between 5% and 15% for the strength (fc) and between 3% and 8% for the modulus of elasticity (Eci), which could be considered as minimally dispersed [57]. In addition, the range of the coefficient of variation obtained in this study was of the same order of magnitude as that obtained by [58 - 63] between 5% and 10% for fc, and 3% and 12% for Eci.

For limestone and gneiss, fck decreased with increasing W/C (Table 3), as generally expected. However, for basalt and granite, this behavior was verified up to W/C = 0.9, increasing again for W/C = 1.0 (Table 3), indicating that the influence of this relationship depended on the aggregate characteristics and how these characteristics affected the concrete rheology [13, 64]. Table 3 presents the differential impact that the W/C ratio has on the characteristic strength of each rock type and confirms that the acoustic parameters and the modulus of elasticity depend not only on the strength and density of the aggregates but also on the porosity and consequent water absorption, which in turn will affect the rheological properties.

W/C RATIO	AGGREGATE MINERALOGICAL ORIGINS			
	BASALT	LIMESTONE	GNEISS	GRANITE
0.5	18.3 (21.3; 2.0)	21.7 (26.3; 2.4)	22.0 (24.8; 2.1)	27.1 (30.3; 1.7)
0.7	12.5 (15.1; 1.3)	18.0 (21.0; 1.7)	20.0 (23.0; 1.9)	12.5 (16.4; 2.2)
0.9	8.0 (11.6; 1.8)	9.3 (10.6; 0.7)	12.2 (14.0; 0.9)	6.3 (10.2; 1.8)
1.0	8.8 (9.8; 0.6)	8.4 (9.8; 0.8)	9.6 (11.3; 0.8)	7.7 (9.2; 1.1)

Table 3. Characteristic compressive strengths (first line, in MPa), average strengths and standard deviation (second line, in MPa) for concrete produced with aggregates from different mineralogical origins and water/cement (W/C) ratios.

2.7 Data Analysis

The first aspects that were analyzed were the frequency distribution of all the parameters obtained during ultrasonic testing (propagation velocity and stiffness coefficient) and static compression test (strength and modulus of elasticity). This analysis aimed to verify whether normality could be accepted for these parameters, thus validating the use of parametric statistics. The normality was assessed by the asymmetry and kurtosis limits, between −2 and +2. After evaluating the normality of the data, regression models were determined between the parameters obtained in the ultrasonic (wave propagation velocity and stiffness coefficient) and static compression (strength and modulus of elasticity) tests. The regression models that best fit the data and that presented higher correlation coefficients and lower prediction errors were highlighted by statistical analysis program.

3. RESULTS AND DISCUSSION

The parameters obtained during ultrasonic testing, i.e., the velocity (V) and stiffness coefficient (C) for both frequencies (45 and 80 kHz), and the parameters obtained during static compression testing, i.e., the strength (fc) and modulus of elasticity (Eci), for concrete produced with coarse aggregates from different mineralogical origins and with different water-cement ratios were normally distributed (Tables 4 and 5). The velocities presented values that were consistent with the results from the literature for concrete produced with the same rock types [10, 17, 23], indicating that the methodology was properly applied.

Since coarse aggregates occupied approximately 70% to 80% of the total volume of concrete, the aggregate quality and strength are expected to be determinants of the concrete strength and stiffness [31, 46, 47, 65]. Considering the average compressive strength ranges for the coarse aggregates (Table 4), the strength rating in descending order would be granite (22.5 MPa), basalt (22.0 MPa), gneiss (20.0 MPa), and limestone (15.0 MPa). However, different authors [4, 9, 17, 18, 23, 24] have already reported that aspects other than the rock strength affect the properties of concretes produced with aggregates originating from these rock types, such as the density (basalt ≅ 2710 $kg.m^{-3}$, granite and gneiss ≅ 2600. $kg.m^{-3}$, and limestone ≅ 2009 $kg.m^{-3}$) and porosity (gneiss, the porosity is usually very low; basalt and granite <1.5%; and limestone ≅ 5%). These parameters are in turn, related to water absorption and therefore to the reactions that affect the concrete rheology. These findings may explain the results of this research, in which the concrete compression strengths (Figure 1) did not follow the same expected strength order for the rocks from which the aggregates were obtained. Figure 1 also shows that the behavior of the ultrasonic parameters, mainly the stiffness coefficient, is more consistent for the stiffness than for the strength obtained from the static compression test.

The acoustic parameters and the modulus of elasticity depend not only on the strength and density of the aggregates (Table 3) but also on the porosity and consequent water absorption, which in turn will affect the rheological properties. The propagation of the ultrasonic waves is much more closely related to the rigidity and the internal configuration of the elements that make up the internal structure of the material than to the density [66]; therefore, compatible with the behavior of the results. The production of concrete with different workability (W/C ratio) but with the same types of aggregates generates changes in the volumes of the mortar and coarse aggregates. These volumetric changes affect the wave propagation velocity of the ultrasonic pulses but not necessarily the compressive strength.

Gravel Type	**Parameter**	**45 kHz**				**80 kHz**			
		Min.	**Max.**	**Average**	**CV (%)**	**Min.**	**Max.**	**Average**	**CV (%)**
Basalt	V ($\mathrm{m.s^{-1}}$)	3287	3927	3547	6.9	3306	3944	3575	6.7
	A and K		1.5 and −1.1				1.3 and −1.0		
	C (GPa)	23.1	35.7	28.1	17.3	23.4	36.0	28.5	16.9
	A and K		1.5 and −1.1				1.4 and −1.1		
Limestone	V ($\mathrm{m.s^{-1}}$)	3501	4497	3956	10.8	3563	4515	3996	10.5
	A and K		0.3 and −2.0				0.2 and −2.0		
	C (GPa)	26.0	47.1	35.4	25.7	27.0	47.5	36.1	25.1
	A and K		0.4 and −2.0				0.3 and −2.0		
Gneiss	V ($\mathrm{m.s^{-1}}$)	3347	4106	3704	8.1	3361	4176	3736	8.5
	A and K		0.3 and −1.6				0.5 and −1.6		
	C (GPa)	24.1	38.2	30.5	18.5	24.3	39.5	31.0	19.3
	A and K		0.5 and −1.7				0.7 and −1.6		
Granite	V ($\mathrm{m.s^{-1}}$)	3350	4283	3688	9.5	3358	4322	3721	10
	A and K		1.6 and −0.9				1.5 and −1.2		
	C (GPa)	23.0	42.1	29.4	24.4	23.0	42.9	30.0	25.6
	A and K			2.0 and −0.7			1.9 and −1.0		
General	**V ($\mathrm{m.s^{-1}}$)**	**3371**	**4203**	**3724**	**8.8**	**3397**	**4239**	**3757**	**8.9**
	C (GPa)	**24.1**	**40.8**	**30.9**	**21.5**	**24.4**	**41.5**	**31.4**	**21.7**

Table 4. Minimum (Min), maximum (Max), average values, coefficients of variation (CV), asymmetry (A), and kurtosis (K) for the ultrasonic wave propagation velocity (V) and stiffness coefficient (C) obtained from ultrasound testing at frequencies of 45 kHz and 80 kHz for the mix ratios produced with different types of coarse aggregates.

Gravel Type	Parameter	Min.	Max.	Average	CV (%)
Basalt	fc (MPa)	15.1	21.3	14.5	**32.5**
	A and K		1.5 and −0.8		
	Eci (GPa)	13.6	22.0	16.7	**20.5**
	A and K		2.0 and −0.6		
Limestone	fc (MPa)	9.8	26.3	16.9	**42.9**
	A and K		0.7 and 1.9		
	Eci (GPa)	17.5	28.7	21.4	**33.1**
	A and K		0.7 and −1.8		
Gneiss	fc (MPa)	11.4	24.8	18.3	**32.9**
	A and K		0.2 and −1.9		
	Eci (GPa)	13.4	22.6	17.2	**22.0**
	A and K		0.7 and −1.5		
Granite	fc (MPa)	9.2	30.3	16.5	**52.7**
	A and K		1.9 and −1.0		
	Eci (GPa)	17.0	30.2	19.7	**31.2**
	A and K		2.0 and −0.5		
General	**fc (MPa)**	**11.4**	**25.7**	**16.6**	**40.3**
	Eci (GPa)	**15.4**	**25.9**	**18.8**	**26.7**

Table 5. Minimum (Min), maximum (Max), average values, coefficients of variation (CV), asymmetry (A), and kurtosis (K) for the strength (fc) and initial modulus of elasticity (Eci) obtained from the concrete compression test for the mix ratios produced with different types of coarse aggregates.

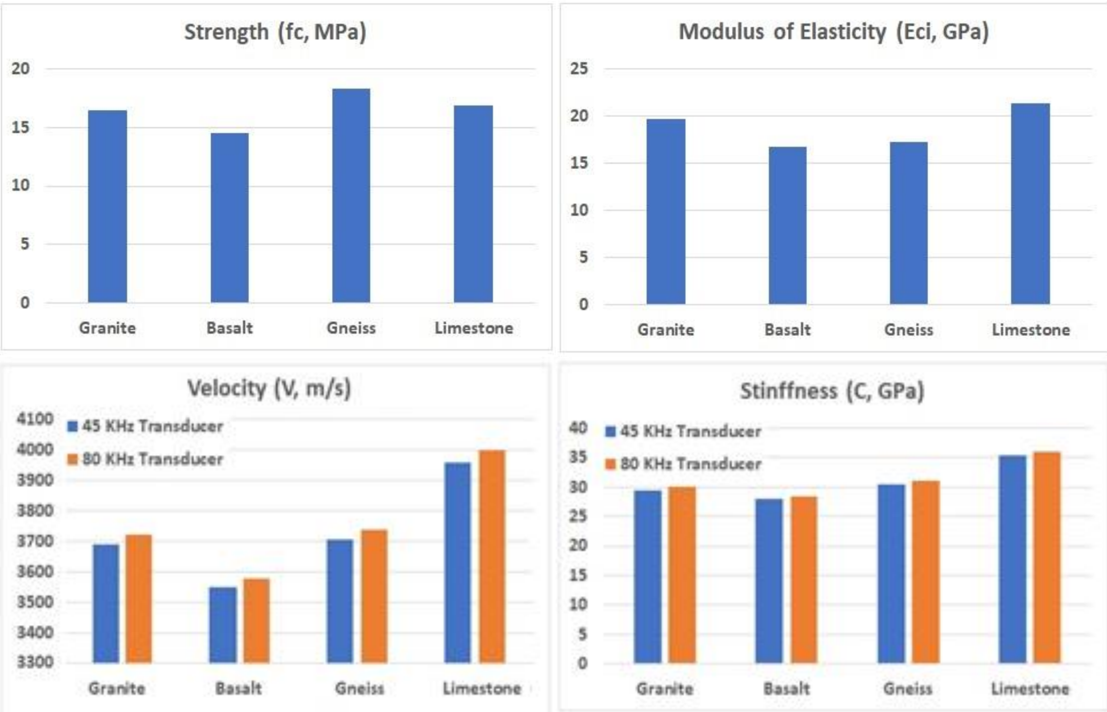


Figure 1. Behavior of the average strength (fc) and modulus of elasticity (Eci) values of the concrete obtained in the static compression tests and velocity and stiffness coefficient obtained in the ultrasonic tests.

All regression models associating compression and ultrasonic tests were statistically significant at a 95% significance level (P-value < 0.05) for both of the evaluated transducer frequencies (Tables 6 and 7). The types of regression models that best explained the variations in the properties obtained from static compression testing due to the properties obtained from ultrasound testing were the same for the different gravel types (Tables 6 and 7). The numerical variations of the model parameters were generally higher for granite (Tables 6 and 7). Given the magnitude of the differences in the coefficients of determination and error, we found that if the type of gravel is known, the use of the specific model is more appropriate; however, the general models are also statistically significant (P < 0.05), with the coefficients of determination showing that the parameters obtained by from ultrasound testing account for 78.5% to 93.6% of the variability in the parameters obtained from static compression testing for the 45 kHz transducer (Table 6) and 78.8% to 92.8% for the 80 kHz transducer (Table 7). The best correlations occur between the initial modulus of elasticity (Eci) and the stiffness coefficient (C), and the worst correlations occur between the compressive strength (fc) and the velocity (V) – Tables 6 and 7.

The best correlations between the parameters obtained from ultrasound and compression testing were found in limestone (Tables 6 and 7). This result can be explained by the microstructure characteristics arising from the relationship of limestone with water absorption (W/C ratio). Comparing concrete produced with limestone and granite, better correlations between the ultrasonic wave propagation velocity and water absorption were obtained for limestone [24]. Additionally, the literature indicates that the propagation velocity in the limestone samples is higher than the velocities in other rocks because the compactness of the concrete transition zone is higher [15]. However, the concrete porosity is related to the microstructural characteristics of the transition zone due to the chemical reactivity of the coarse aggregates. Limestone minerals have better reactivity with Portland cement by bonding with the cement paste, contributing to the transition zone properties around the limestone particles [64], which explains the more stable behavior of wave propagation in this type of rock, thus favoring good correlations with the mechanical properties.

Although the overall correlations were slightly higher and the errors were slightly lower for the 45 kHz transducer frequency than for the 80 kHz transducer frequency, both frequencies made it possible to obtain statistically significant models for the concrete strength and stiffness prediction for all gravel types (Tables 6 and 7). This result is expected since, considering the average velocity values, the wavelength (λ) is approximately 87 mm for the 45 kHz transducer and 49 mm for the 80 kHz transducer. These values indicate that the path length (specimen height) was between 3.5 and 6.0 times the wavelength. The relationship between the path length and wavelength is important for ensuring the theoretical free wave propagation condition, which minimizes the influence of the frequency on the propagation velocity. It is recommended that the frequency range of the transducers used in concrete ultrasonic testing should be between 20 kHz and 100 kHz and that the path length should be at least equal to the wavelength [67]. Another suggestion is that frequencies from 20 kHz to 150 kHz and path lengths at least equal to the wavelength should be used, so that the velocity is not affected [7]. This same standard [7] indicates that a frequency of 150 kHz should be adopted for small dimension parts (approximately 50 mm), resulting in a path length/wavelength ratio on the order of two, which was lower than the one obtained in this research. Although the correlation models between the initial modulus of elasticity (Eci) and the stiffness coefficient (C) presented good correlation coefficients, the relationship between the estimated error and the average value (relative error) was low for the direct correlation models with the wave propagation velocity (Tables 6 and 7). The same was not true for the correlation models between the strength (fc) and velocity, whose relative errors were the highest compared to that of other correlations (Tables 6 and 7).

The correlation models between the static compressive strength (fc) and ultrasonic wave propagation velocity (V) were obtained by different authors for concrete produced with aggregates from different rocks [17] (gneiss, exponential model); [10] (gneiss, power model); [26] (limestone, exponential model); [25] (basalt, power model); [29] (limestone, exponential model); [31] (basalt, power model)), with the coefficients of determination ranging from 60 to 98%. Similarly, models were obtained to correlate the modulus of elasticity (Eci) obtained during static compression with the ultrasonic wave propagation velocity (V) [18] (granite and mica schist, exponential model); [21] (mica schist, exponential model [25] (basalt, linear model); [10] (gneiss, polynomial model); [27] (limestone, exponential model)), with the coefficients of determination ranging from 50 to 96%. The correlations between the stiffness and strength parameters obtained during the compression test and the stiffness coefficients obtained by ultrasound testing were only found in few studies [25, 28], with linear correlation models for basalt aggregate concrete and coefficients of determination of 87% (stiffness) and 79% (strength). Thus, this research is different due to the fact that all the types of aggregates were evaluated in the concrete that is produced by fixing all other parameters, including the methodology and equipment, which allows the effective measurement of the influence of the type of aggregate.

Parameters	Gravel type	Model	P-value	R^2 (%)	Estimate error	Relative error* (%)
Eci x C	Basalt	Eci = 7.5 + 0.011*C^2	0.0000	91.5	1.02	6.1
Eci x C	Limestone	Eci = 7.2 + 0.011*C^2	0.0000	97.6	1.11	5.2
Eci x C	Gneiss	Eci = 7.1 + 0.011*C^2	0.0000	94.1	0.94	5.5
Eci x C	Granite	Eci = 8.9 + 0.011*C^2	0.0000	97.0	0.93	4.7
Eci x C	**General**	**Eci = 8.1 + 0.010*C^2**	**0.0000**	**93.6**	**1.37**	**7.2**
Eci x V	Basalt	Eci = (1.30 + 2.2E-7*V^2)^2	0.0000	90.7	0.13	0.8
Eci x V	Limestone	Eci = (1.05 + 2.2E-7*V^2)^2	0.0000	97.6	0.12	0.6
Eci x V	Gneiss	Eci = (1.43 + 1.9E-7*V^2)^2	0.0000	92.5	0.13	0.8
Eci x V	Granite	Eci = (1.51 + 2.1E-7*V^2)^2	0.0000	94.5	0.13	0.7
Eci x V	**General**	**Eci = (1.44 + 2.0E-7*V^2)^2**	**0.0000**	**92.5**	**0.16**	**0.9**
fc x C	Basalt	fc = (7.24 - 95.4/C)^2	0.0000	86.0	0.23	1.6
fc x C	Limestone	fc = (7.47 – 114.5/C)^2	0.0000	95.9	0.18	1.1
fc x C	Gneiss	fc = (7.92 – 109.3/C)^2	0.0000	89.4	0.24	1.3
fc x C	Granite	fc = (8.21 – 122.9/C)^2	0.0000	87.7	0.35	2.0
fc x C	**General**	**fc = (7.48 – 103.4/C)^2**	**0.0000**	**82.7**	**0.34**	**2.0**
fc x V	Basalt	fc = -17.1 + 0.0000025*V^2	0.0000	88.1	1.65	11.4
fc x V	Limestone	fc = -16.1 + 0.0000021*V^2	0.0000	95.5	1.57	9.3
fc x V	Gneiss	fc = -16.1 + 0.0000025*V^2	0.0000	86.2	2.27	12.4
fc x V	Granite	fc = -25.7 + 0.0000030*V^2	0.0000	91.5	2.49	15.1
fc x V	**General**	**fc = -13.5 + 0.0000021*V^2**	**0.0000**	**78.5**	**3.15**	**19.0**

Table 6. Correlation models between the velocity (V) and stiffness coefficient (C), obtained by ultrasound testing, and the initial modulus of elasticity (Eci) and strength (fc), obtained by static compression testing for each type of rock from which the gravel was obtained – 45 kHz frequency transducer.

*ratio between the estimated error and the average value.

Parameters	Gravel type	Model	P-value	R^2 (%)	Estimate error	Relative error* (%)
Eci x C	Basalt	Eci = 7.2 + 0.011*C^2	0.0000	91.2	1.04	6.2
Eci x C	Limestone	Eci = 6.9 + 0.011*C^2	0.0000	97.4	1.16	5.4
Eci x C	Gneiss	Eci = 7.6 + 0.010*C^2	0.0000	95.5	0.82	4.7
Eci x C	Granite	Eci = 9.1 + 0.011*C^2	0.0000	97.1	0.99	5.0
Eci x C	**General**	**Eci = 8.1 + 0.010*C^2**	**0.0000**	**92.8**	**1.47**	**8.9**
Eci x V	Basalt	Eci = (1.24 + 2.2E-7*V^2)^2	0.0000	90.0	0.13	0.8
Eci x V	Limestone	Eci = (0.96 + 2.2E-7*V^2)^2	0.0000	97.4	0.13	0.6
Eci x V	Gneiss	Eci = (1.55 + 1.85E-7*V^2)^2	0.0000	94.3	0.11	0.6
Eci x V	Granite	Eci = (1.45 + 2.0E-7*V^2)^2	0.0000	95.0	0.14	0.7
Eci x V	**General**	**Eci = (1.45 + 2E-7*V^2)^2**	**0.0000**	**91.6**	**0.17**	**1.0**
fc x C	Basalt	fc = (7.24 - 95.4/C)^2	0.0000	86.0	0.23	1.6
fc x C	Limestone	fc = (7.51 – 118.4/C)^2	0.0000	95.4	0.19	1.1
fc x C	Gneiss	fc = (7.77 – 106.5/C)^2	0.0000	88.6	0.24	1.3
fc x C	Granite	fc = (8.18 – 122.5/C)^2	0.0000	89.1	0.34	2.0
fc x C	**General**	**fc = (7.44 – 103.8/C)^2**	**0.0000**	**82.0**	**0.35**	**2.1**
fc x V	Basalt	fc = -17.8 + 0.0000025*V^2	0.0000	87.0	1.72	11.9
fc x V	Limestone	fc = -17.1 + 0.0000021*V^2	0.0000	95.6	1.54	9.1
fc x V	Gneiss	fc = -14.1 + 0.0000023*V^2	0.0000	84.7	2.39	13.1
fc x V	Granite	fc = -24.4 + 0.0000029*V^2	0.0000	92.8	2.36	14.3
fc x V	**General**	**fc = -13.5 + 0.0000021*V^2**	**0.0000**	**78.8**	**3.16**	**19.2**

Table 7. Correlation models between the velocity (V) and stiffness coefficient (C), obtained by ultrasound testing, and the initial modulus of elasticity (Eci) and strength (fc), obtained by static compression testing for each type of rock from which the gravel was obtained – 80 kHz frequency.
*ratio between the estimated error and the average value

CONCLUSIONS

– The regression models between the ultrasonic and compression tests, obtained using transducers at two frequencies (45 kHz and 80 kHz), are statistically significant (P-value = 0.0000) for concrete produced with all the studied rocks (basalt, limestone, gneiss, and granite), and the coefficients of determination are higher than around 85%, indicating that both frequencies can be used to infer the strength and stiffness of the concrete.
– As expected by the theoretical framework of the wave propagation test, the concrete stiffness (modulus of elasticity – Eci) predicted models by ultrasonic testing has better correlations than the strength (fc) prediction models. The stiffness coefficient obtained by ultrasound testing (C) present a better correlation with the stiffness (R^2 > 92,8%) and strength (R^2 > 82%) of the concrete than with the wave propagation velocity (V). This result is also expected since the stiffness coefficient includes a physical parameter of the concrete (density).
– By separating the regression models by aggregate type, the same prediction model type can be considered for all aggregates for the inference of Eci and fc by the velocity (V) or by the stiffness coefficient (C).
– General regression models, regardless of the gravel type, were also statistically significant (P-value < 0.05) at the 95% confidence level, with coefficients of determination higher than 79% and prediction errors higher than those obtained for the specific models for different rock types.

ACKNOWLEDGEMENTS

The authors would like to thank the Sao Paulo Research Foundation (FAPESP), São Paulo for the financing of several projects of the research group, which allowed the facilities used in this research and Geosoluções for the logistic support, materials and permission to use the Lock and Load forms.

REFERENCES

[1] Neto, A. A. M.; Helene, P. R L. Módulo de elasticidade: dosagem e avaliação de modelos de previsão do módulo de elasticidade de concretos. In: Congresso Brasileiro do Concreto, 44º, Belo Horizonte - MG. 2002.

[2] Fortes, R. M.; Merighi, J. V. Controle Tecnológico e Controle de Qualidade-Um alerta sobre sua importância. In: Congresso Brasileiro de Ensino de Engenharia. 2004.

[3] Bezerra, A. C. S.; Silva, F. M.; Soares, M. N. S.; Aguilar, M. T. P. Relações do módulo de elasticidade dinâmico, estático e resistência à compressão do concreto. In: Congresso Brasileiro do Concreto, 51º, Curitiba-PR. 2009.

[4] Mehta, P. K.; Monteiro, P. J. M. Concreto. Microestrutura, propriedades e materiais. 2 ed .São Paulo: IBRACON, 2014. 751 p.

[5] British Standards Institution. BS 1881 - PART 203: Recommendations for measurement of velocity pulses in concrete. London: 1988. 20 p.

[6] American concrete institute. ACI 228. 1R-03, In-place methods to estimate concrete strength, Detroit, 2003.

[7] European Commitee For Standardization, BS EN 12504:4, Testing Concrete. Determination of ultrasonic pulse velocity, Brussels, 2004.

[8] Popovics, S.; Popovics, J. S. A critique of the ultrasonic pulse velocity method for testing concrete. NDT and E International, v. 4, n. 30, p. 260, 1997.

[9] Evangelista, A. C. J.; Shehata, I. A. E. M. ; Shehata, L. C. D. . Parameter that Influence the Results of Nondestructive Methods for Concrete Strength. In: International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE), Berlim. 2003.

[10] Machado, M. D.; Shehata, L. D.; Shehata, I. A. E. M. Curvas de correlação para caracterizar concretos usados no Rio de Janeiro por meio de ensaios não destrutivos. RIEM-IBRACON Structures and Materials Journal, v. 2, n. 2, 2009.

[11] Mahure, N. V.; Vijh, G. K.; Sharma, P.; Sivakumar, N.; Ratnam, M. Correlation between pulse velocity and compressive strength of concrete. International Journal of Earth Sciences and Engineering, v. 4, n. 6, p. 871-874, 2011.

[12] Gjorv, O. E. Quality Control and Quality Assurance for Concrete Durability. In: Key Engineering Materials. Trans Tech Publications, 2016. p. 76-83.

[13] Schmidt, W.; Kühne, H. C.; Leinitz, S. Concrete casting robustness improvement due to active rheology. In: MATEC Web of Conferences. EDP Sciences, 2018.

[14] Berodier, E.; Gibson, L. R.; Burns, E.; Roberts, L.; Cheung, J. Robust production of sustainable concrete through the use of admixtures and in-transit concrete management systems. Cement and Concrete Composites, 2018.

[15] Mohammed, T. U.; Mahmood, A. H. Effects of maximum aggregate size on UPV of brick aggregate concrete. Ultrasonics, v. 69, p. 129-136, 2016.

[16] Popovics. S. Analysis of the concrete strength versus ultrasonic pulse velocity relationship Mater. Eval. 59 123-30. 2001.

[17] Evangelista, A. Avaliação da resistência do concreto usando diferentes ensaios não destrutivos. 239f. Tese (Doutorado em Engenharia) – Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2002.

[18] Rodrigues, G. S. S.; Figueiredo, E. I. P. Módulo de deformação estático do concreto pelo método ultrassônico: Estudo da correlação. In: 46º Congresso Brasileiro do Concreto, Florianópolis, 2004. Anais. IBRACON, Florianópolis, p.1309-1324, 2004.

[19] Abo-qudai, S. A. Effect of concrete mixing parameters on propagation of ultrasonic waves Constr. Build. Mater. 19 257-63. 2005.

[20] Câmara, E. Avaliação da resistência à compressão do concreto utilizado usualmente na grande Florianópolis através de métodos de ensaios não destrutivos. 152f. Dissertação (Mestrado Engenharia Civil) – Universidade Federal de Santa Catarina, Florianópolis, 2006.

[21] Prado, L.A., Módulo de deformação estático do concreto de Baixa e alta relação a/c pelo método ultrassônico, 2006, 226p. Dissertação (Mestrado em Engenharia Civil) – Escola de Engenharia Civil Universidade Federal de Goiás, Goiânia, 2006.

[22] Lin, Y., Shih-Fang, K., Hsiao, C., Chao-Peng, L. Investigation of pulse velocity-strength relationship of hardened concrete. ACI Materials Journal, v. 104, n. 4, p. 344, 2007.

[23] Lorenzi, A., Tisbierek, F. T., Silva, L. C. P. Ultrasonic pulse velocity analysis in concrete specimens. In: IV Conferencia Panamericana de END, Buenos Aires. 2007.

[24] Torgal, F. P.; Gomes, J. P. C. Influence of physical and geometrical properties of granite and limestone aggregates on the durability of a C20/25 strength class concrete. Construction and Building Materials, v. 20, n. 10, p. 1079-1088, 2006.

[25] Giacon Jr, M. Propagação de ondas de ultrassom em protótipos de postes tubulares de concreto armado. Dissertação de Mestrado. UNICAMP-Universidade Estadual De Campinas. 2009.

[26] Trtnik, G.; Kavčič, F.; Turk, G. Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks. Ultrasonics, v. 49, n. 1, p. 53-60, 2009.

[27] Yildirim, H.; Sengul, O. Modulus of elasticity of substandard and normal concretes. Construction and Building Materials, v. 25, n. 4, p. 1645-1652, 2011.

[28] Giacon Jr, M., GONCALVES, R., SORIANO, J., AMALFI, G. Caracterização do concreto utilizando ultrassom. In: XXVIII CONAENDI - Congresso de Ensaios Não Destrutivos e Inspeção, 2010, Santos - SP. Anais CONAENDI 2010. v. 1. p. 1-9.

[29] Lawson I.; Danso, K.A.; Odoi, H.C.; Adjei, C.A.; Quashie, F.K.; Mumuni, I.I.; Ibrahim, I.S. Non-Destructive Evaluation of Concrete using Ultrasonic Pulse Velocity. Research Journal of Applied Sciences, Engineering and Technology Published. PP 409-504. 2011.

[30] Gonçalves, R.; Júnior, M. G.; Lopes, I. M. Determining the concrete stiffness matrix through ultrasonic testing. Engenharia Agrícola, v. 31:3, p. 427–437, 2011.

[31] Mohamad, G., Obregon, P., Oliveira, M. J. D, TEMP, A.L. Métodos combinados para a avaliação da resistência de concretos. Revista Matéria, v. 20, n. 1, pp. 86-102, 2015.

[32] Al-Zharani, T. M., Demirboga, R., Khushafati, W. H. Relationship Between Core Compressive Strength and UPV Values for Different Core Slenderness of High Strength Concrete Beam. 2016.

[33] Carbonari, B. M. T; Cavalaro, S. H., Castanha, J. C. M., Guacelli, P. a G., Silva, C. C. Utilização do método ultra-sônico para avaliação da performance do concreto de alto desempenho. Revista Ibracon de Estrututas e Materiais, V. 3, n.4, p. 494–502, dez., 2010.

[34] Santos, A. M.; Cabral, L. M. C.; Monteiro, E. B.; Helene, P. R. L. Análise do módulo de elasticidade estático e dinâmico para diferentes dosagens de concreto. In: Ibracon 55º Congresso Brasileiro do Concreto. 2013.

[35] Bogas, J. A.; Gomes. A. Static and dynamic modulus of elasticity of structural lightweight and modified density concrete with and without nanosilica–characterization and normalization. International Journal of Civil Engineering, Vol. 12, N. 2, p. 269-278, June 2014.

[36] Martínez, M. W.; Torres, A. A. A.; Jáuregui, J. C., Chávez, G. H. L., Alonso, G., E. M.; Graff, M., Arteaga, A. J. C. Predicting concrete compressive strength and modulus of rupture using different NDT techniques. Advances in Materials Science and Engineering, 2014.

[37] Anepac - Associação Nacional das Entidades de Produtores de Agregados para a construção civil. Disponível em: www.anepac.org.br . Acesso em: 21 outubro. 2019.

[38] ______. NBR 5738. Concreto: Procedimento para moldagem e cura de corpos de prova. Rio de Janeiro, 2015.

[39] Associação brasileira de normas tecnicas. NBR 11578: Cimento Portland Composto. Rio de Janeiro, 1997.

[40] ______. NBR NM 248. Agregados: Determinação da composição granulométrica. Rio de Janeiro, 2003.

[41] ______. NBR NM 45: Agregados: Determinação da massa unitária e do volume de vazios. Rio de Janeiro. 2006.

[42] ______. NBR NM 52: Determinação da massa específica de agregados miúdos por meio de frasco Chapman. Rio de Janeiro, 2009.

[43] _______. NBR NM 30: Agregado miúdo - Determinação da absorção de água. Rio de Janeiro, 2001.

[44] ______. NBR NM 53. Agregado graúdo – Determinação da massa específica, massa específica aparente e absorção de água. Rio de Janeiro. 2009.

[45] ______. NBR 7211. Agregados para concreto - Especificação. Rio de Janeiro. 2009.

[46] Kim, Y.; Hu, J.; Lee, S.; You, B. Mechanical properties of fiber reinforced lightweight concrete containing surfactant. Advances in Civil Engineering, v. 2010, 8 p, 2010.

[47] Hassanpour, M.; Shafigh, P.; Mahmud, H.B. Lightweight aggregate concrete fiber reinforcement – a review. Construction and Building Materials, v. 37, p. 452 – 461, 2012.

[48] Bentur, A.; Mindess, S. Fibre Reinforced Cementitious Composites. Fibre reinforced cementitious composites. CRC Press, 2014.

[49]_______. NBR NM 67. Concreto: determinação da consistência pelo abatimento do tronco de cone. Rio de Janeiro, 1998.

[50] _______. NBR 6118: Projeto de estruturas de concreto – Procedimento. Rio de Janeiro, 2015.

[51] Turgut, P. “Research into the correlation between concrete strength and UPV values”, J. Nondestruct. Test. V. 12. 2004.

[52] ______. NBR 8802. Concreto Endurecido – Determinação da velocidade de propagação da onda ultra-sônica. Rio de Janeiro, 2019.

[53] ______. ACI 228. 2R. Report On Nondestructive Test Methods For Evaluation Of Concrete In Structures, Detroit, 2013.

[54] ______. NBR 5739. Ensaio de compressão de corpos-de-prova cilíndricos de concreto. Rio de Janeiro, 2018.

[55] ______. NBR 8522 - Concreto – Determinação dos módulos estáticos de elasticidade e de deformação a compressão. Rio de Janeiro, 2017.

[56] ______. NBR 12655. Concreto de cimento Portland - Preparo, controle, recebimento e aceitação - Procedimento. Rio de Janeiro, 2015.

[57] Crespo, A. A. Estatística fácil. 18ª edição. São Paulo: Editora Saraiva. 224p. 2002.

[58] Martins, D. G. Influência do tamanho do corpo de prova nos resultados de ensaios e módulo de deformação e resistência à Compressão e suas correlações para concretos produzidos em Goiânia-Go. Dissertação de Mestrado, Departamento de Engenharia Civil, Universidade Federal de Goiás. 2008.

[59] Santiago, W. C.; Beck, A. T. Estudo da (não-) conformidade de concretos produzidos no Brasil e sua influência na confiabilidade de pilares curtos. RIEM-IBRACON Structures and Materials Journal, v. 4, n. 4, 2011.

[60] Leal, A.C.F.S. Investigação experimental do módulo de elasticidade nos concretos produzidos em Brasília. Dissertação de Mestrado em Estruturas e Construção Civil. Departamento de Engenharia Civil e Ambiental, Universidade de Brasília, Brasília-DF, 151p. 2012.

[61] Araújo, S. S.; Guimarães, G. N.; Geyer, A. L. B. Influência do Tipo de Medição na Determinação do Módulo Estático de Elasticidade do Concreto. RIEM-IBRACON Structures and Materials Journal, v. 5, n. 5, 2012.

[62] Araújo, S. S.; Guimarães, G. N.; Geyer, A. L. B. Influência do tipo de concreto, da dimensão do corpo de prova e do tipo de laboratório na determinação da resistência à compressão do concreto. Revista Engenharia Civil, Uminho, v. 52. Uminho, Portugal, 2016.

[63] Comité Euro-International du béton. 1993, “CEB-FIP Model Code 1990”. London, Thomas Telford.

[64] Ollivier, J. P.; Maso, J. C.; Bourdette, B. Interfacial transition zone in concrete. Advanced Cement Based Materials, v. 2, n. 1, p. 30-38, 1995.

[65] Bayan, S. A.; Bestoon, R. A.; Sabr, A. A.; Sirwan E. K. Effect of Aggregate Content on the Concrete Compressive Strength - Ultrasonic Pulse Velocity Relationship. American Journal of Civil Engineering and Architecture, 2016, Vol. 4, No. 1, 1-5.

[66] Bucur, V. Acoustics of Wood. Editora Springer Verlage – N.Y. 2006 -393p.

[67] American society for testing and materials. ASTM C597-02. Standard test method for pulse velocity through concrete. West Conshohocken, 2016.

2.3 Artigo 3 - CLASSIFICATION AND INSPECTION OF REINFORCED CONCRETE ELEMENTS FOR USE IN RETAINING WALLS EMPLOYING ULTRASOUND TESTING

ARTIGO SUBMETIDO AO PERIÓDICO CONSTRUCTION AND BUILDING MATERIALS

FORMATAÇÃO E IDIOMA DE ACORDO COM AS NORMAS DO REFERIDO PERIÓDICO

CLASSIFICATION AND INSPECTION OF REINFORCED CONCRETE ELEMENTS FOR USE IN RETAINING WALLS EMPLOYING ULTRASOUND TESTING

Rodrigo Rogerio Cerqueira da Silva[1], Raquel Gonçalves[2*], Cinthya Bertoldo Pedroso[3]

[1]Ph.D. Student, Laboratory of Nondestructive Testing - LabEND, School of Agricultural Engineering - FEAGRI, University of Campinas - UNICAMP, Av. Cândido Rondon, 501 - Barão Geraldo 13083-875, Campinas, Brazil. Email: rodrigorogeriodoutorado@gmail.com. Orcid: https://orcid.org/0000-0002-7928-9462

[2]Professor, Laboratory of Nondestructive Testing - LabEND, School of Agricultural Engineering - FEAGRI, University of Campinas - UNICAMP, Av. Cândido Rondon, 501 - Barão Geraldo 13083-875, Campinas, Brazil Email: raquelg@unicamp.br (+55 19 3521-1034). https://orcid.org/0000-0003-0406-8988
*corresponding author

[3]Ph.D., Laboratory of Nondestructive Testing - LabEND, School of Agricultural Engineering - FEAGRI, University of Campinas - UNICAMP, Av. Cândido Rondon, 501 - Barão Geraldo 13083-875, Campinas, Brazil. E-mail: cinthyab@unicamp.br. Orcid: https://orcid.org/0000-0001-9039-4805

Abstract
Like all types of structural element, precast retaining walls should be produced with quality and be inspected during service life. The objective of our research was to evaluate whether the ultrasound testing, applied in precast parts for containment walls, before (classification) and after (inspection) the installation, allows to infer parameters representative of its quality (strength and stiffness). Assuming 5% as the maximum safety-related error limit (property prediction higher than the actual value of the property) the technique showed feasibility to be used in monitoring and assessing the integrity of the precast systems during their manufacture and throughout their useful life.

Keywords: Retaining walls, propagation of ultrasound waves, monitoring of precast concrete parts.

1 INTRODUCTION

Economic and social development, associated with population growth and the valorization and occupation of urban and rural areas, has determined the exponential increase in civil works in areas of difficult access and irregular topography in Brazil. Hence, containment structures are being used on a large scale, in cut-off and landfill situations, and the construction of retaining walls, associated with techniques for slope covering, with prefabricated concrete parts as a structural element, has been gaining more and more prominence in civil construction, since they allow to meet aesthetic, cost-related, and productivity advantages.

However, as any production line, precast elements also require control in the production, in order to identify defects and/or molding errors that can influence their strength, durability, and aesthetics. The demand for the use of precast concrete elements has stimulated studies on technological control, which in some cases is still considered a major challenge due to the need for requiring the laboratory structure of destructive testing, which is rarely accessible in the vicinity of the construction works, in addition to the high costs. Therefore, it is vitally important to develop alternatives that effectively enable the evaluation of the quality of these concrete structures.

The technique for evaluating structures by using non-destructive testing (NDT) has been continuously growing worldwide, comprising several tests. Among the tests that outstand due to their practicality, portability, and easiness in handling is the ultrasound, whose technique and principle of use is simple and uncostly when compared with destructive tests. However, in the case of a heterogeneous material, such as concrete, the use of such techniques has limited accuracy when the intention is to widely apply them, without considering specificities inherent in their specific composition, thus requiring careful studies on the behavior of the techniques associated with the intrinsic conditions of each mixture.

In Brazil, the technology called Lock and Load, consisting of reinforced concrete modules (panel and counterfort), designed to withstand high compression loads, is strongly accessing in the market. The system can be prefabricated or produced at the construction location; for instance, we can mention its application to reinforced concrete, in which there is difficulty in monitoring quality and inspection after being installed, requiring monitoring and continuous evaluation of its state by a procedure that does not affect its integrity. In this sense, the application of the inspection methodology using wave propagation techniques allows favoring decision-making at the time the Lock and Load system is installed at the construction work, besides monitoring and evaluating its integrity throughout its useful life, preventing problems from being checked after the construction of landfills and stabilization of slopes.

During ultrasound testing, the wave propagation type is affected by the positioning of the transducers in the part to be inspected. This issue is addressed in the standards [1- 6]. The direct testing is considered the most suitable to correlate mechanical properties with the velocity of waves propagation [7-11], since there are lower signal attenuation, and the material excitation occurs in the same direction as the forces that operate in conventional mechanical tests [12]. Nevertheless, for service structures, we rarely have access to the ends of the part under inspection, in such a way we must perform the indirect testing such as is the case of panels of the Lock and Load system after being installed.

Comparison analyses of ultrasonic measurement methods in concrete samples showed that the direct testing has more sensitivity to detect defects, but it does not enable detecting their location, whereas the indirect testing allows locating the defect in a more suitable way after it has been detected [13 -17].

The technique based on ultrasonic pulse, overall, does not present good accuracy when used in the inference of concrete strength produced with unknown aggregates and proportions. Therefore, it is necessary to determine characteristic calibration curves for the concrete under analysis, considering specimens of the same composition, batch, and curing conditions of the structure [4]. According to recommendations of the standard [2], the most suitable correlation is obtained from tests performed on materials whose proportions are the same as those used in the structure under inspection itself.

Since the precast Lock and Load system is produced throughout the Brazilian territory, concrete mixtures are produced with coarse aggregates of four different mineralogical origins, consisting in the most abundant types (granite, gneiss, basalt, and limestone) within the five Brazilian regions. Thus, it is expected that density, physical, mechanical and elastic properties of these aggregates will influence the velocity of ultrasonic pulses in the concrete matrix [9, 18-20].

The deterioration process of reinforced concrete structures can lead to degradation of the structure over time, affecting its strength and stiffness properties, thus inducing collapse. Therefore, periodic inspections must be carried-out to assess the current state of the deterioration process. Several researches [18, 21-26] evaluating reinforced concrete structures on-site proposed the adoption of a specific classification for assessing different elements of structures, indicating an approximate index of concrete quality depending on the measured propagation velocity range. Thus, for the containment system addressed in our research, it is necessary to feed a database with information about composition, density, strength, stiffness, and velocity of ultrasonic waves propagation, in such a way classification ranges can be obtained. The specific structural system of Lock and Load will certainly differ from previous research, especially concerning those whose authors only used samples and models produced in the laboratory, with more regular shapes, being one of the differentials of our research.

Thus, the objective of our research was to evaluate whether the ultrasound testing, applied to Lock and Load precast elements for containment walls, before (classification) and after (inspection) the installation, allows to infer parameters representative of quality (strength and stiffness) of these parts.

To do so, the experimental design consisted of the molding of three sets of the Lock and Load system for four different mineralogical origins of aggregates (granite, gneiss, basalt, and limestone) produced with four mixtures ranging according to the water/cement ratio (0.5; 0.7; 0.9; and 1.0), totaling 48 panels and counterforts.

2 MATERIAL AND METHODS

In order to meet the proposed objective, the basic mixture defined for preparing the panels and counterforts was of 1:2:3 (cement, sand, gravel), considering cement in mass and aggregates in volume, with the addition of 175 grams of polypropylene macrofiber (less than 1% per 50 kg of cement). We only inserted the fibers aiming at reducing the cracking. Studies conducted on similar fibers (steel, polypropylene, rubber, and glass) incorporated into concrete showed no interference in the propagation of ultrasonic waves [15, 27-32].

For all panels and counterforts, we used a natural quartz fine aggregate (sand) with the same granulometry and moisture condition. For the coarse aggregate (gravel), we used materials of different types of mineralogy, chosen among the most abundant ones in Brazilian regions (granite, gneiss, basalt, and limestone), allowing to comprise the manufacture conditions of this system throughout the country. Considering for achieving our objective we needed to apply the methodology to panels and counterforts with variability in terms of quality, precast parts were produced maintaining the basic mixture, but with variations in the water/cement ratio (0.5; 0.7; 0.9; and 1.0). The water/cement ratio is a factor that is more susceptible to molding errors during the production on-site. For the molding of panels and counterforts, we used drinking water and Portland cement of the CP II-F-40 [33] (commonly used in structural elements). No additive was used during the preparation of experimental mixtures.

For each water-cement ratio and type of mineralogy of the coarse aggregate, we produced three panels and counterforts (replications). Thus, 48 elements of the Lock and Load system were molded. The panels and counterforts were molded into plastic shapes on a vibrating table, subjected to curing in climatic conditions after molding and dismounting, aiming at representing the same characteristics on-site, and remaining as such until the performance of the ultrasound testing at the 28th day.

The same material used in the manufacture of precast parts was used previously [34], in which 128 cylindrical specimens with 150 mm diameter x 300 mm high were molded, subjected to the same vibrating and curing conditions of the panels and counterforts, to obtain characteristics similar to those obtained from the manufacture of the parts of the Lock and Load system. The characterization of the aggregates is presented in detail in [34] where the authors proposed models of strength (fc) and stiffness (Eci) inference of the concrete produced with materials and mixtures used for the manufacture of parts of the Lock and Load system, using parameters of the ultrasound testing (velocity and stiffness coefficient). So, considering our objective, in this research we used the models for predicting strength and stiffness using the ultrasonic waves propagation obtained by [34] for specimens.

There are differences between ultrasonic velocity of waves propagation in specimens and in molded elements, even if influences regarding the theoretical bases of the testing have been discarded, such as the ratio between the path length and the wavelength and considering the same type of measurement (direct). These differences occur depending on the molding of the elements, such as compaction in a given direction, sample size, conditions of curing, production, or type of vibration, concreting by casting or parallel layers in relation to the positioning of transducers, the distance of transducers, as well as the presence of reinforcement bars [25, 35-42].

Thus, although considering that precast parts and specimens have been produced with the same material and mixture, differences in velocities are expected. Therefore, the results of velocity of ultrasound wave propagation obtained from specimens [34] were used in this article to obtain prediction models of these velocities (specimens) based on velocities obtained from the molded panels and counterforts (on-site).

2.1 Ultrasound testing

Panels were submitted to non-destructive testing directly and indirectly performed and the counterforts were submitted to non-destructive testing only directly, both using the ultrasound equipment (USLAB, Agricef, Brazil) and longitudinal transducers, with 45 kHz frequency. The European standard [4] recommends transducers with frequency between 40 kHz and 60 kHz for most applications to reinforced concrete structures.

Direct measurements on the panels were performed with transducers positioned on two parallel faces, every 50 mm from the ends of each face, and in two directions, namely longitudinal (Figure 1a) and transverse (Figure 1b). For indirect testing, a measurement grid was prepared on the surface side, in which straight lines were traced for uniting the points of both ends with maximum distances of 400 mm in the longitudinal (Figure 1c) and 300 mm in the transverse (Figure 1d) directions. The determination of the grid under study follow specifications of the standard [4], which recommends that the minimum path should account for 100 mm for concrete produced with aggregates whose maximum nominal dimension is 20 mm. In the counterfort, demarcations were performed in the transverse section every 50 mm from the axis, considering three points in the transverse section (Figure 1e) and direct testing only (Figure 1f).

Figure 1. Direct ultrasound testing in the longitudinal (a) and transverse (b) directions of the panel; indirect ultrasound testing with measurement in the longitudinal (c) and transverse (d) directions of the panel; reading points on the counterfort face (e); and direct ultrasound testing with measurement in the larger dimension of the counterfort (f).

Based on the direct ultrasound testing, we obtained the propagation times of the waves (t), and thus we calculated, for each distance between transducers (L), the velocity of ultrasound wave propagation (V) – Equation 1.

$$V = \frac{L}{t} \qquad \text{Equation 1}$$

The Indirect measurements on the panel were made in the longitudinal and transversal direction, placing the transducers at 50 mm on each side of the central point of the panel (Figura 1c and 1d). The indirect testing for concrete is proposed by several standards [1, 2, 4-6, 43]. Among these, only the standards [4] and [5] propose a way for calculating average propagation velocity. In this procedure, velocity is calculated using the angular coefficient of a line (ΔY/ΔX) given by the distance between the transducers (Y-axis), which is consecutively increased, versus the propagation time (X-axis) obtained for each distance.

2.2 Analysis of velocities (direct and indirect) in the different lines of the measurement grid

Considering the direct measurements mesh proposed, ultrasound measurements were performed using three different positions in the counterfort and seven lines, in the longitudinal direction, and fifteen lines, in the transverse direction, on the panels (Figure 1). This thorough detailing was done in the laboratory, in such a way we could evaluate if there were significant differences between velocities. Clearly, in field measurements it is not feasible to use such a fine mesh; thus, statistical analysis of the velocities obtained from the different positions was performed to verify if there are a better position to be used in field inspections. For this analysis, velocities in the different positions of the measurement meshes were statistically evaluated using the Multiple Sample Comparison test.

2.3 Adequacy of velocities in the components of the system and in the specimens

Firstly, it was necessary to acquire correlation models between velocities obtained from precast elements and the respective velocities obtained from specimens molded with the same concrete (mixture, cement type, and aggregates). For this analysis, the results achieved in specimens molded with the same concrete mixture and the same types of aggregates [34], were used.

2.4 Inference of stiffness and strength of counterforts and panels

After obtaining correlation models of the inferred velocities (direct and indirect) for the specimen, using the velocities directly and indirectly obtained from the counterforts and panels (previous item), we inferred the strength and stiffness predicted using the models proposed in [34].

2.5 Evaluation of hits and errors of stiffness and strength inference based on ultrasound tests in panels and counterforts

Considering that the sorting and inspection of structural elements using nondestructive techniques are based on statistical correlation models, which imply prediction errors, properties are inferred using ranges of expected values instead of single values. Thus, initially, we should define these ranges and, to do so, we used statistical analyses of frequency distribution of stiffness and strength values obtained from static compression test of specimens [34], and three ranges were adopted for each parameter (stiffness and strength) – Table 1.

Intervals	**Eci (GPa)**	**fc (MPa)**
Range 1	Up to 15.3	Up to 13.3
Range 2	Between 15.4 and 22	Between 13.4 and 20
Range 3	Over 22	Over 20

Table 1. Stiffness (Eci) and strength (fc) ranges to be used in sorting and inspection of parts (panels and counterforts) of the system by ultrasound.

After obtaining stiffness and strength values inferred by the directly and indirectly ultrasound testing on the panels and direct testing counterforts, we analyzed the percentages of hits and errors of the inference, considering the stiffness ranges obtained in static compression test (Table 1). Results were distributed into three categories, similar to the proposal of literature [44]:

- Category A – Inferred values within the range expected by the classification;
- Category B – Inferred values lower than the expected by the classification;
- Category C – Inferred values higher than the expected by the classification.

The results presented in Categories A and B are deemed hits, because in Category B the inferred value is lower than the actual value, constituting an error associated with economy instead of safety [44]. Also according to [44], the results in Category C are deemed errors, because the test infers a value that exceeds the actual one and, therefore, consists in an error associated with safety, being tolerated for only 5% of the results.

3. RESULTS AND DISCUSSION

3.1 Velocities (direct and indirect) in the different lines that compose the measurement grid

The statistical analysis of Multiple Sample Comparison showed that the measurement lines do not consistently differ from each other for any type of rock used in the preparation of panels and counterforts, and neither for any measurement type (direct and indirect) and direction (longitudinal and transverse). There are cases (30%) in which analysis demonstrates statistical differences between some of the measurement lines, with 95% confidence level (p-values < 0.05); however, there are no lines that repeatedly outstand as different. Lines were expected to coincide with the position of the reinforcement bars on the panel (lines 2 and 5 longitudinally, and lines 1 and 9 transversely), and the counterfort (central position) was expected to present statistical differences in velocities, which did not occur. This result seem to indicate lack of coherence considering the recommendations of standards [1, 3-6] and, considering some literature results which indicate higher velocities in the region next to the reinforcement bars than other parts of the concrete [45-52]. However, authors of research carried out in concrete samples and structures with different reinforcement bars diameters have concluded that, for bars with diameters of less than 10 mm and wave propagation perpendicular to the bars, the influence on the propagation velocity of waves is not significant, accounting for a difference of only ± 3% in relation to the velocity obtained on concrete [51, 53-61]. Conditions of the *Lock and Load* system can be applied to the findings of the aforementioned researchers, since the system contains only a 6-mm steel bar. This non-significant influence of the reinforcement is also reported in the standard [2], according to which for bars parallel to the propagation of waves smaller than 6-mm diameter, and bars perpendicular to the propagation of waves smaller than 20-mm diameter, variations in velocities are negligible. Although they were not consistent in all cases in which there was statistical variation of velocities, lines at the very ends of the panels were the ones that most presented differences. Considering this finding, field measurements can be performed at any position, avoiding the edges.

3.2 Adequacy of velocities obtained in parts of the system and in the specimens

The direct velocities obtained from the specimens were always higher than the direct or indirect velocities obtained from the elements of the system molded with the same concrete. As expected, velocities differences between the precast parts and the specimens were greater for indirect measurements than for direct measurements (Table 2). The standard [2] indicates differences between 5 and 20% for velocities directly and indirectly obtained. [14, 62-64] achieved variations from 4 to 30% between these two waves propagation modes. The aforementioned researchers have reported that, in superficial measurements, decrease in velocity occurs due to the increased porosity caused by segregation and accumulation of damages on the surface layer of the concrete, reducing strength and stiffness. Variation in velocity can also be explained by the mode of propagation, which in the case of surface waves do not occur in the same way as in pure longitudinal waves [12].

	VCP/VDL	VCP/VDT	VCP/VIL	VCP/VIT
		Counterfort		
RATIO	1.05	–	–	–
CV (%)	3.8	–	–	–
MIN	1.00	–	–	–
MAX	1.18	–	–	–
		PANEL		
RATIO	1.09	1.13	2.00	1.85
CV (%)	3.7	4.4	6.1	5.4
MIN	1.04	1.03	1.84	1.67
MAX	1.16	1.23	2.21	2.02

Table 2. Average ratios between the direct velocity obtained from the specimen (VCP) and the longitudinal direct velocity (VDL), the transverse direct velocity (VDT), the longitudinal indirect velocity (VIL) and transverse indirect velocity (VIT) obtained from the parts of the system molded with the same concrete; coefficients of variation (CV) of these ratios; and minimum (min) and maximum (max) ratios for each case.

To infer the velocity in the specimen based on velocities measurements in molded elements of the system (counterforts and panels), there were two ways: One of them is the application of a modification coefficient to velocities obtained from the elements of the system, and the other is the use of a correlation model. In our research, we adopted the correlation model, since, although the coefficients of variation of the ratios were not very high (Table 2), we think that the use of a correlation model, despite containing an intrinsic error, considers intrinsic variations in a more appropriate manner than the use of a fixed modification coefficient, so minimizing the consequences for sorting and inspection of the parts of the system. Considering the good adjustments of the general models for counterfort (Table 3) and panels (Table 4), regardless of the type of rock used, these were adopted for the following calculations.

TYPE OF GRAVEL	**MODEL**	**P-VALUE**	**R^2 (%)**	**ESTIMATION ERROR**	**RELATIVE ERROR* (%)**
GNEISS	VCP=402+0.93*VDL	0.0050	99.90	12.72	0.34
GRANITE	VCP=598+0.85*VDL	0.0040	99.20	45.13	1.21
LIMESTONE	VCP=483+0.91*VDL	0.0117	97.67	90.35	2.28
BASALT	VCP=1594+0.59*VDL	0.0311	93.87	83.56	2.36
GENERAL	**VCP=789+0.82* VDL**	**0.0019**	**96.20**	**28.01**	**0.74**

Table 3. Linear correlations between ultrasound velocities obtained from specimens (VCP) and longitudinal velocities obtained from the counterfort by the direct method (VDL).

*Ratio between the estimation error and the average value.

Type of gravel	Model	p-value	R^2 (%)	Estimation error	Relative error* (%)
Gneiss	VCP=1166+0.74*VDL	0.0040	99.20	37.03	0.01
	VCP=1103+0.79*VDT	0.0110	99.78	19.46	0.01
	VCP=499+1.64*VIL	0.0029	99.42	31.40	0.01
	VCP=751+1.39*VIT	0.0379	92.56	112.92	0.03
Granite	VCP=700+ 0.86*VDL	0.0229	95.46	64.51	1.73
	VCP=389+ 1.00*VDT	0.0281	94.47	68.62	1.84
	VCP=1251+1.29*VIL	0.0071	98.57	60.51	1.62
	VCP=508+1.69*VIT	0.0020	99.59	32.12	0.86
Limestone	VCP=31 + 1.09*VDL	0.0161	96.80	105.79	0.03
	VCP=223+1.05*VDT	0.0081	98.38	75.2	0.02
	VCP=-97+2.4*VIL	0.0367	92.80	158.88	0.04
	VCP=508+ 1.69*VIT	0.0042	99.15	54.50	0.01
Basalt	VCP=1516+0.63*VDL	0.0272	94.64	78.13	0.02
	VCP=1620+0.63*VDT	0.0239	95.26	73.48	0.02
	VCP=1725+1.02*VIL	0.0237	93.57	85.61	0.02
	VCP=1790+0.93*VIT	0.0093	98.15	45.92	0.01
General	**VCP=1166+0.74*VDL**	**0.0040**	**99.20**	**37.04**	**0.99**
	VCP=1103+0.79*VDT	**0.0011**	**99.78**	**19.78**	**0.53**
	VCP=499+1.64*VIL	**0.0290**	**99.41**	**31.61**	**0.85**
	VCP=752+1.38*VIT	**0.0380**	**92.52**	**113.22**	**3.03**

Table 4. Linear correlations between ultrasound velocities in specimens and velocities obtained from the panels by the direct method, in longitudinal (VDL) and transverse (VDT) directions, and by the indirect method, in longitudinal (VIL) and transverse (VIT) directions.
*Ratio between the estimation error and the average value.

3.3 Evaluation of hits and errors of stiffness and strength inference based on ultrasound tests in panels and counterforts

In the case of counterforts, we verified that the use of the specific model was more appropriate to infer both stiffness (Figure 2) and strength (Figure 3), since there were no errors associated with safety. Considering criteria used in standards for sorting structural elements, the general model was suitable for stiffness inference (Figure 2), but not for strength (Figure 3), although it only exceeded by 1% the limit used in standards for the structural elements classification, which is 5% of safety-related error.

For panels, the measurements, direct or indirect, in the longitudinal direction (Figures 4 and 5) or in the transverse direction (Figures 6 and 7), featured suitable Eci inferences (zero safety-related errors) when using a specific model. For the general model, safety-related errors accounted for 6% to 12% (Figures 4 to 7).

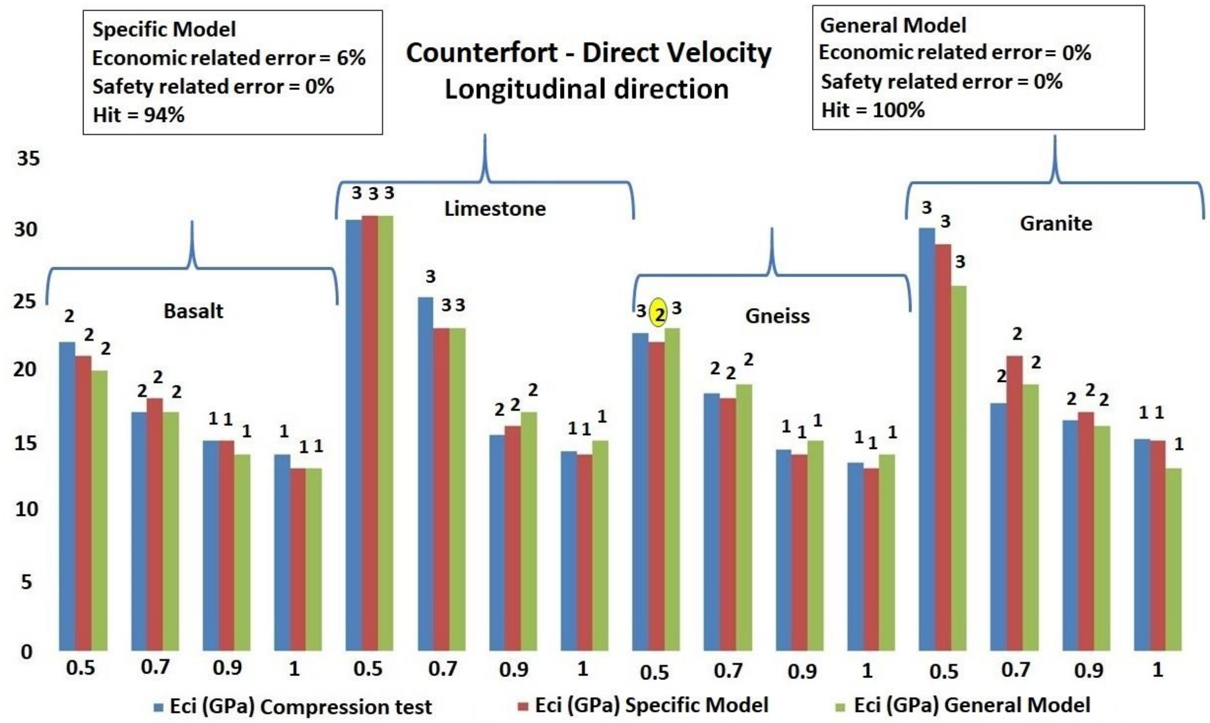


Figure 2. Initial Elasticity Modulus (Eci in GPa) obtained from the compression test and inferred by ultrasound testing (specific model and general model) in counterforts produced with different water-cement ratios (0.5; 0.7; 0.9; and 1.0) and coarse aggregates of different types of mineralogy, with the referred classes related to Eci ranges.

Eci classes = 1: up to 15.3 GPa; = 2: from 15.4 to 22 GPa; and = 3: over 22 GPa.
Values of classes without prominence: classification range hit (Category A - inferred range = reference range); highlight in yellow: economic-related error (Category B - inferred range lower than the reference range); and highlight in red: safety-related error (Category C - inferred range higher than the reference range).

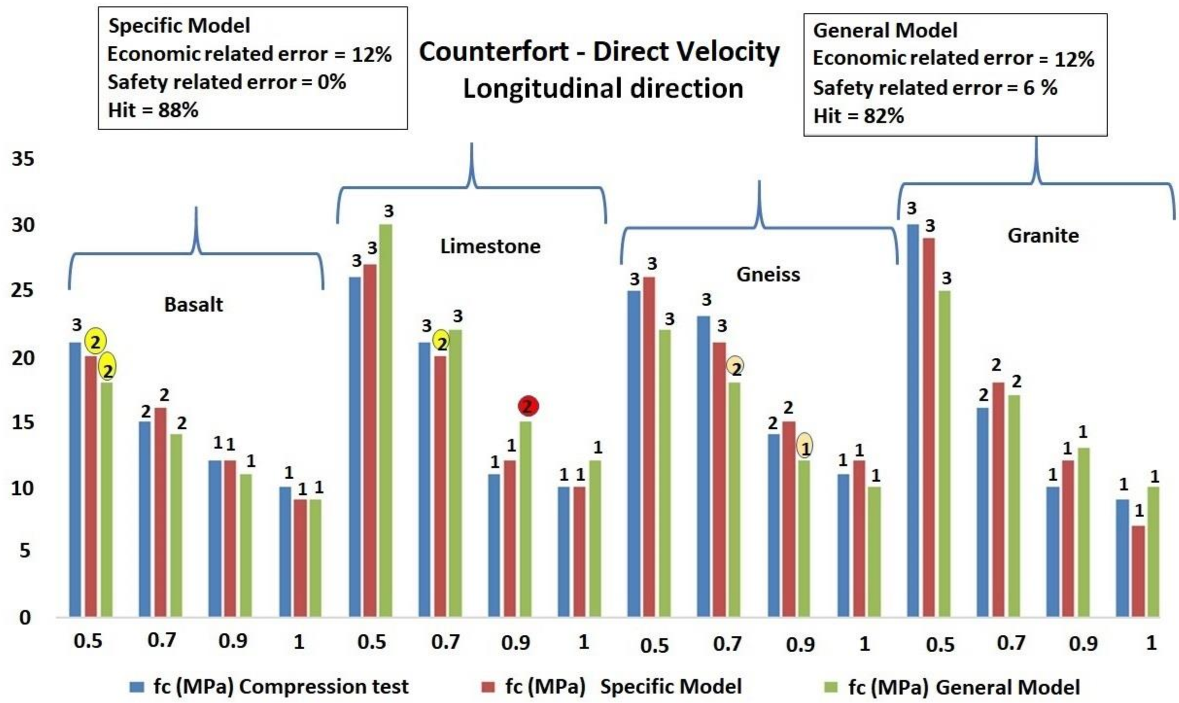


Figure 3. Compressive strength (fc in MPa) obtained from the compression test and inferred by ultrasound testing (specific model and general model) in counterforts produced with different water-cement ratios (0.5; 0.7; 0.9; and 1.0) and coarse aggregates of different types of mineralogy, with the referred classes related to fc ranges.

fc classes = 1: up to 13.3 MPa; 2: from 13.4 to 20 MPa; and 3: over 20 MPa.
Values of classes without prominence: classification range hit (Category A - inferred range = reference range); highlight in yellow: economic-related error (Category B - inferred range lower than the reference range); and highlight in red: safety-related error (Category C - inferred range higher than the reference range).

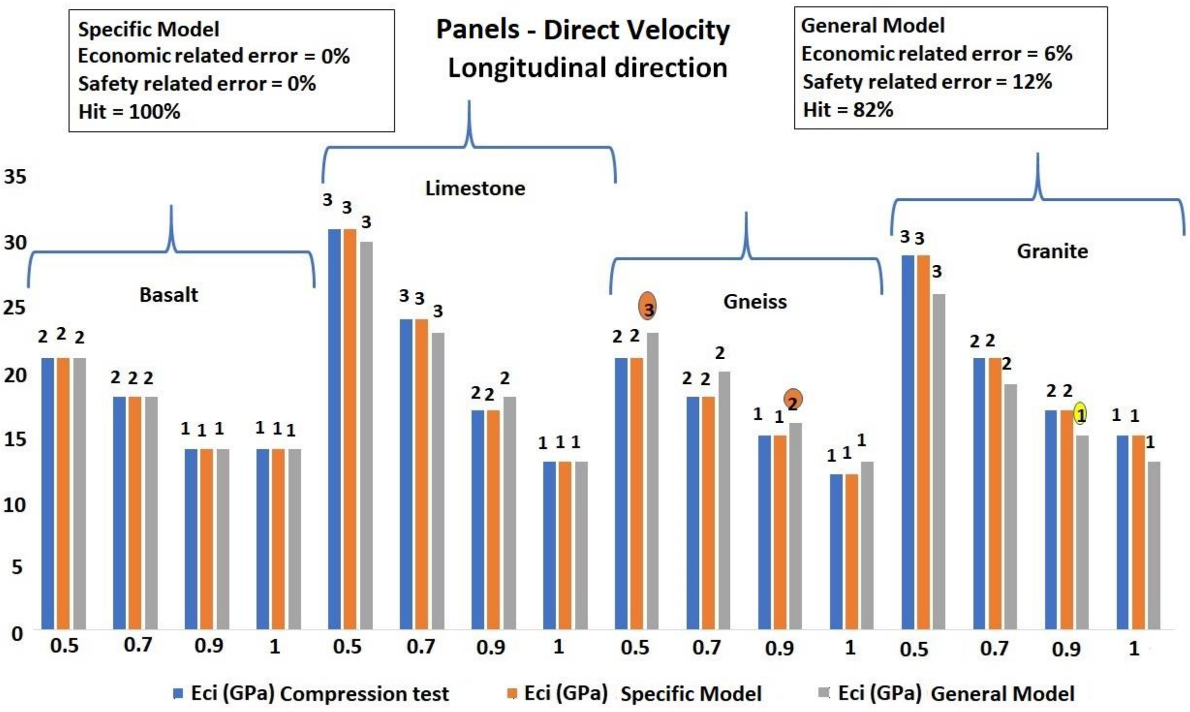


Figure 4. Initial Elasticity Modulus (Eci in GPa) obtained from the compression test and inferred by ultrasound testing (specific model and general model) in panels produced with different water-cement ratios (0.5; 0.7; 0.9; and 1.0) and coarse aggregates of different types of mineralogy, with the referred classes related to Eci ranges.

Eci classes = 1: up to 15.3 GPa; = 2: from 15.4 to 22 GPa; and = 3: over 22 GPa.
Values of classes without prominence: classification range hit (Category A - inferred range = reference range); highlight in yellow: economic-related error (Category B - inferred range lower than the reference range); and highlight in red: safety-related error (Category C - inferred range higher than the reference range).

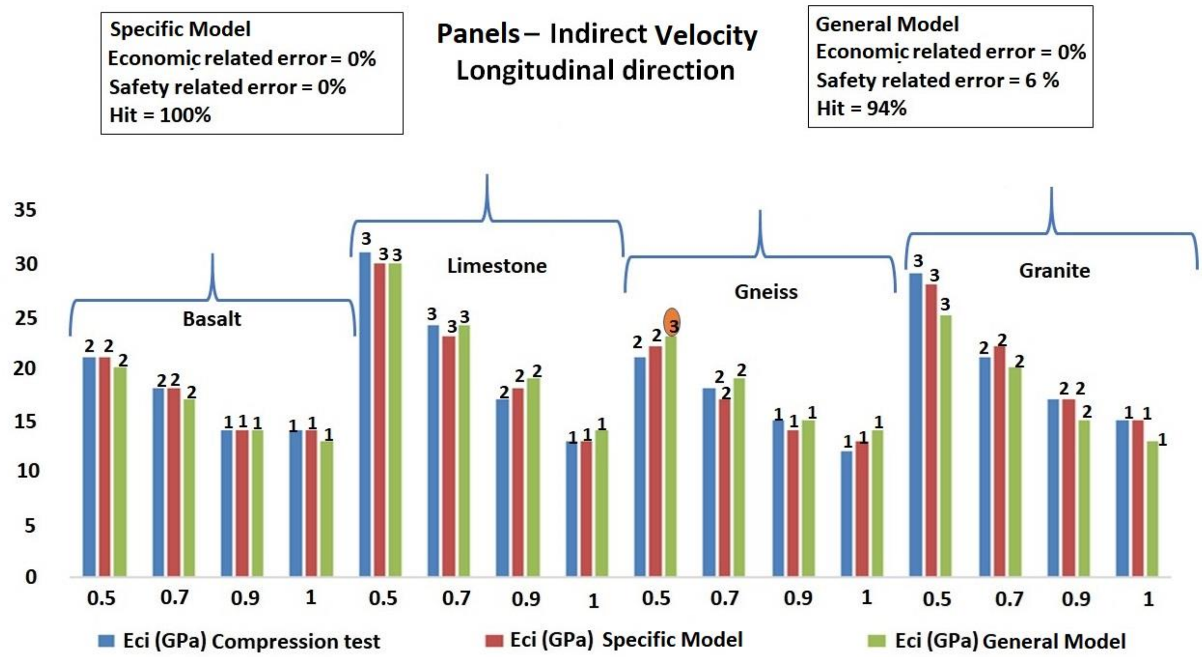


Figure 5. Initial Elasticity Modulus (Eci in GPa) obtained from the compression test and inferred by ultrasound testing (specific model and general model) in panels produced with different water-cement ratios (0.5; 0.7; 0.9; and 1.0) and coarse aggregates of different types of mineralogy, with the referred classes related to Eci ranges.

Eci classes = 1: up to 15.3 GPa; = 2: from 15.4 to 22 GPa; and = 3: over 22 GPa.
Values of classes without prominence: classification range hit (Category A - inferred range = reference range); highlight in yellow: economic-related error (Category B - inferred range lower than the reference range); and highlight in red: safety-related error (Category C - inferred range higher than the reference range).

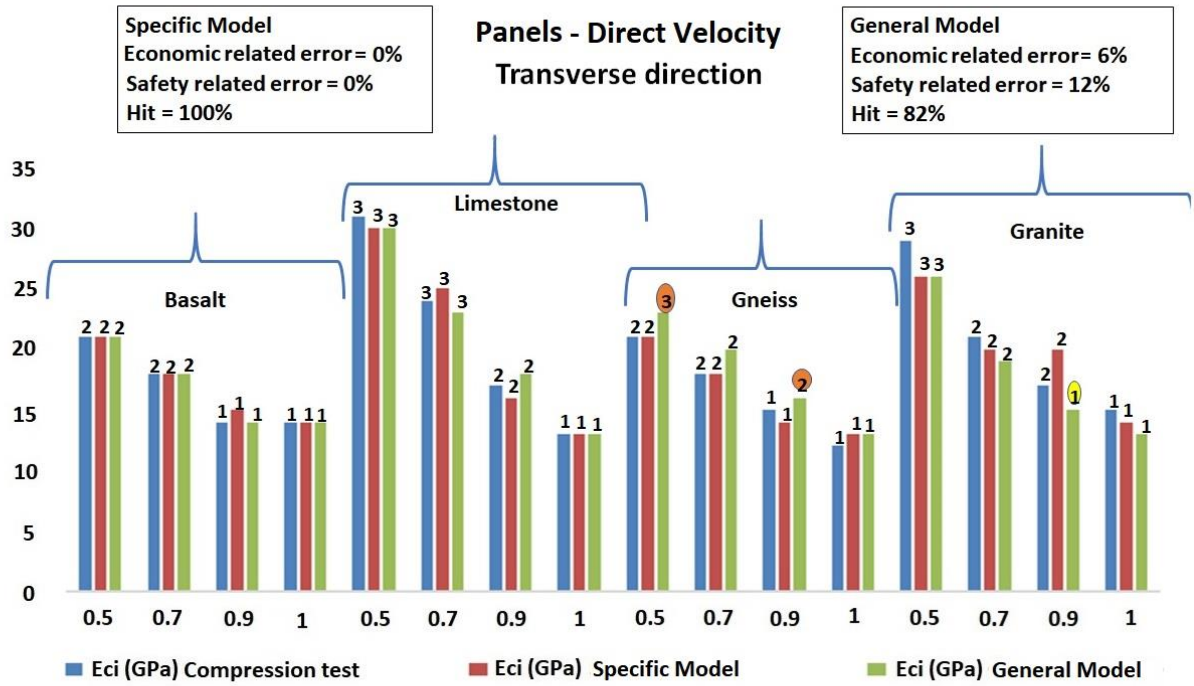


Figure 6. Initial Elasticity Modulus (Eci in GPa) obtained from the compression test and inferred by ultrasound testing (specific model and general model) in panels produced with different water-cement ratios (0.5; 0.7; 0.9; and 1.0) and coarse aggregates of different types of mineralogy, with the referred classes related to Eci ranges.

Eci classes = 1: up to 15.3 GPa; = 2: from 15.4 to 22 GPa; and = 3: over 22 GPa.
Values of classes without prominence: classification range hit (Category A - inferred range = reference range); highlight in yellow: economic-related error (Category B - inferred range lower than the reference range); and highlight in red: safety-related error (Category C - inferred range higher than the reference range).

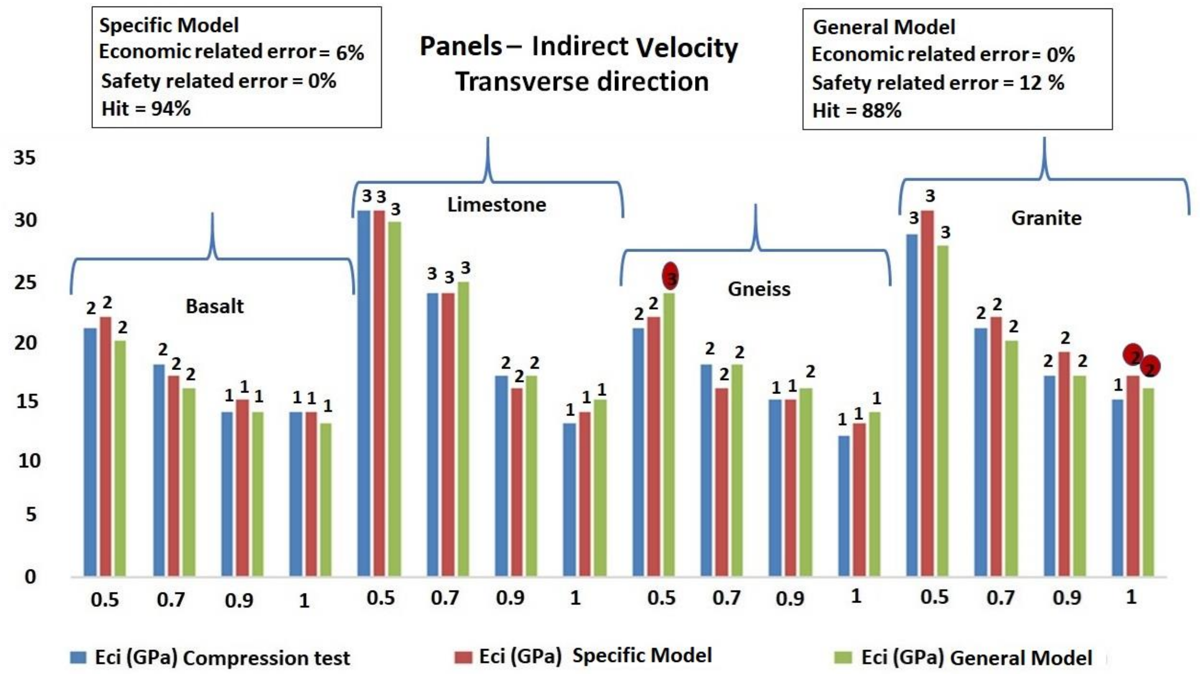


Figure 7. Initial Elasticity Modulus (Eci in GPa) obtained from the compression test and inferred by ultrasound testing (specific model and general model) in panels produced with different water-cement ratios (0.5; 0.7; 0.9; and 1.0) and coarse aggregates of different types of mineralogy, with the referred classes related to Eci ranges.

Eci classes = 1: up to 15.3 GPa; = 2: from 15.4 to 22 GPa; and = 3: over 22 GPa.
Values of classes without prominence: classification range hit (Category A - inferred range = reference range); highlight in yellow: economic-related error (Category B - inferred range lower than the reference range); and highlight in red: safety-related error (Category C - inferred range higher than the reference range).

For strength (fc) inference only velocities obtained in the longitudinal direction (direct – Figure 8 or indirect – Figure 9) and the use of the specific model allowed achieving safety-related errors below 5%. For this inference (fc), the general model accounted for safety-related errors from 0 to 19% (Figures 8 to 11).

The transverse, direct and indirect measurements, presented the highest safety-related errors in the compressive strength (fc) inference, either with the specific or general model (Figures 10 and 11).

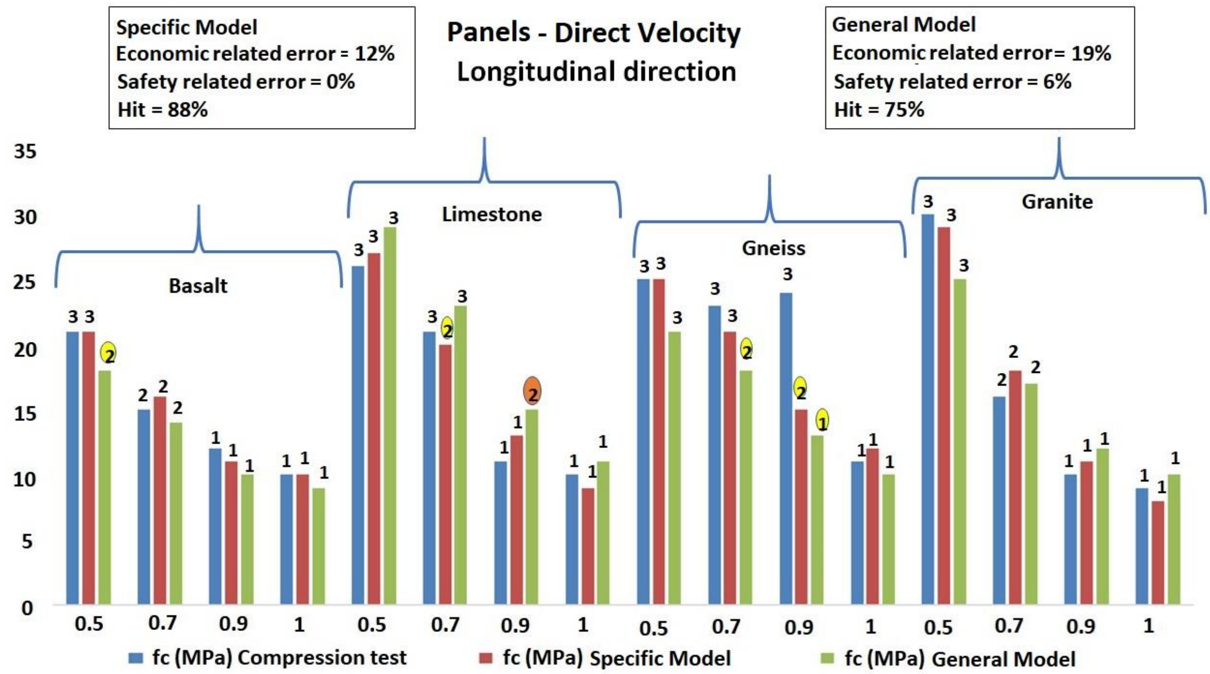


Figure 8. Compressive strength (fc in MPa) obtained from the compression test and inferred by ultrasound testing (specific model and general model) in panels produced with different water-cement ratios (0.5; 0.7; 0.9; and 1.0) and coarse aggregates of different types of mineralogy, with the referred classes related to fc ranges.

fc classes = 1: up to 13.3 MPa; 2: from 13.4 to 20 MPa; and 3: over 20 MPa.
Values of classes without prominence: classification range hit (Category A - inferred range = reference range); highlight in yellow: economic-related error (Category B - inferred range lower than the reference range); and highlight in red: safety-related error (Category C - inferred range higher than the reference range).

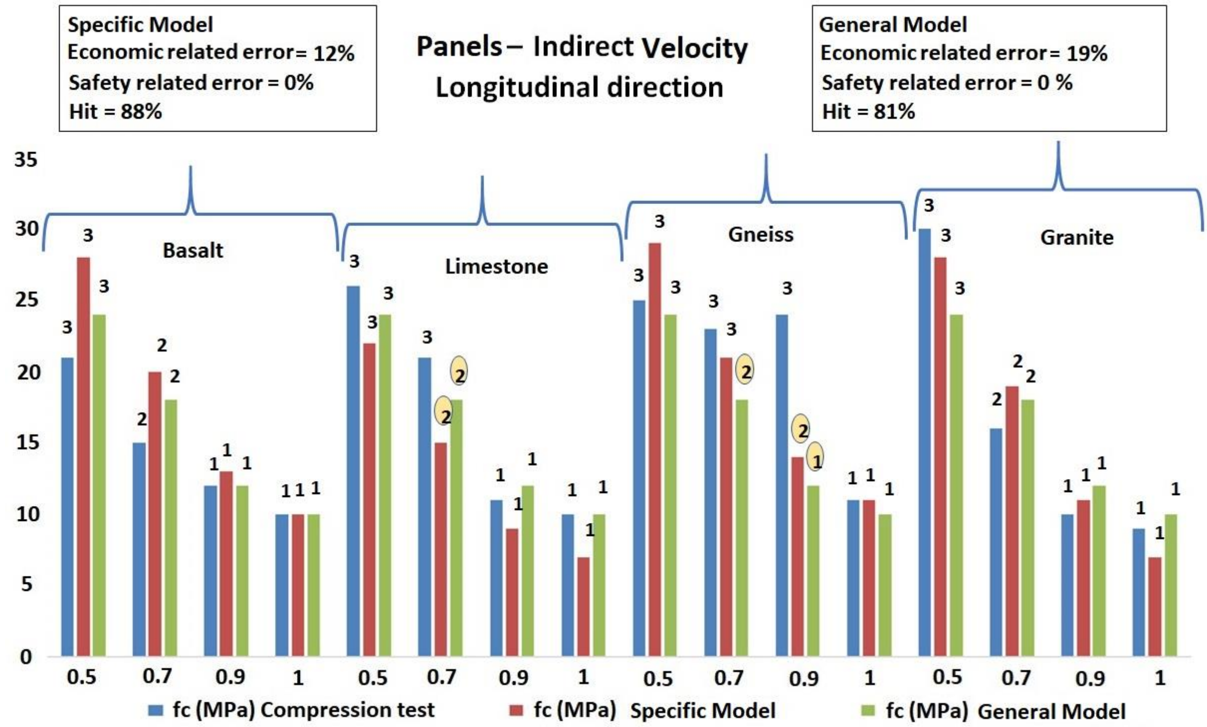


Figure 9. Compressive strength (fc in MPa) obtained from the compression test and inferred by ultrasound testing (specific model and general model) in panels produced with different water-cement ratios (0.5; 0.7; 0.9; and 1.0) and coarse aggregates of different types of mineralogy, with the referred classes related to fc ranges.

fc classes = 1: up to 13.3 MPa; 2: from 13.4 to 20 MPa; and 3: over 20 MPa.
Values of classes without prominence: classification range hit (Category A - inferred range = reference range); highlight in yellow: economic-related error (Category B - inferred range lower than the reference range); and highlight in red: safety-related error (Category C - inferred range higher than the reference range).

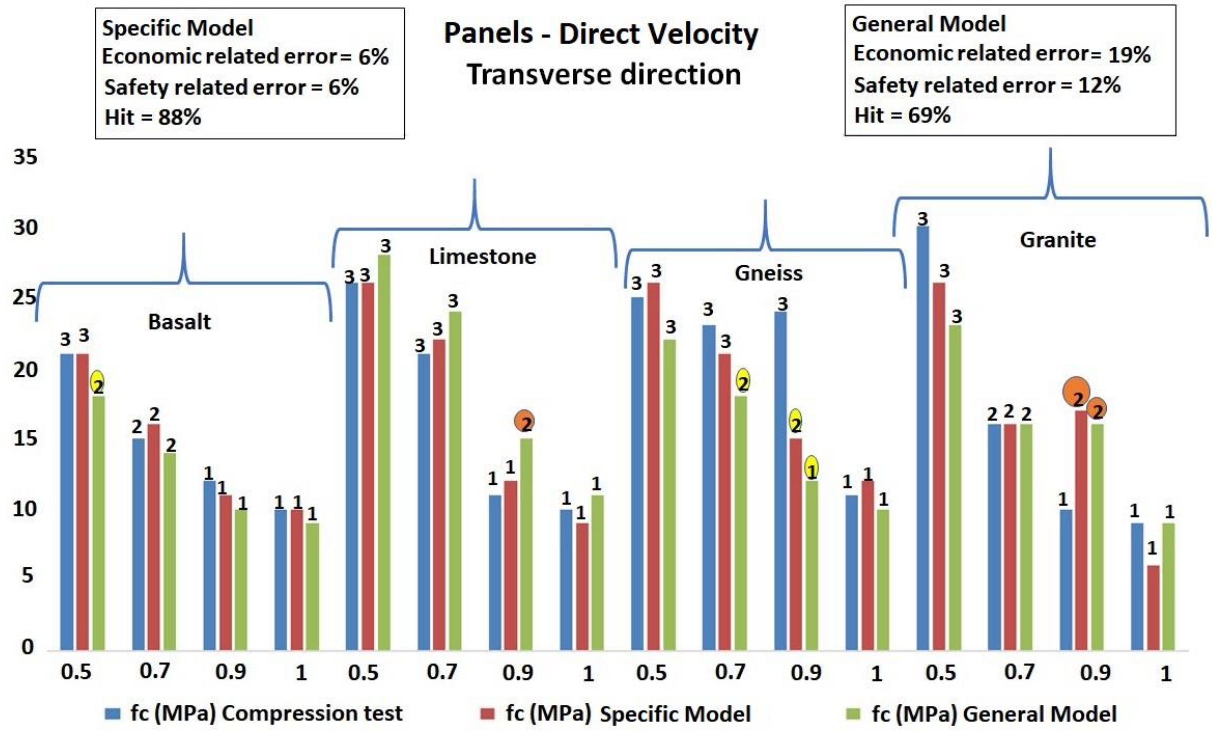


Figure 10. Compressive strength (fc in MPa) obtained from the compression test and inferred by ultrasound testing (specific model and general model) in panels produced with different water-cement ratios (0.5; 0.7; 0.9; and 1.0) and coarse aggregates of different types of mineralogy, with the referred classes related to fc ranges.

fc classes = 1: up to 13.3 MPa; 2: from 13.4 to 20 MPa; and 3: over 20 MPa.
Values of classes without prominence: classification range hit (Category A - inferred range = reference range); highlight in yellow: economic-related error (Category B - inferred range lower than the reference range); and highlight in red: safety-related error (Category C - inferred range higher than the reference range).

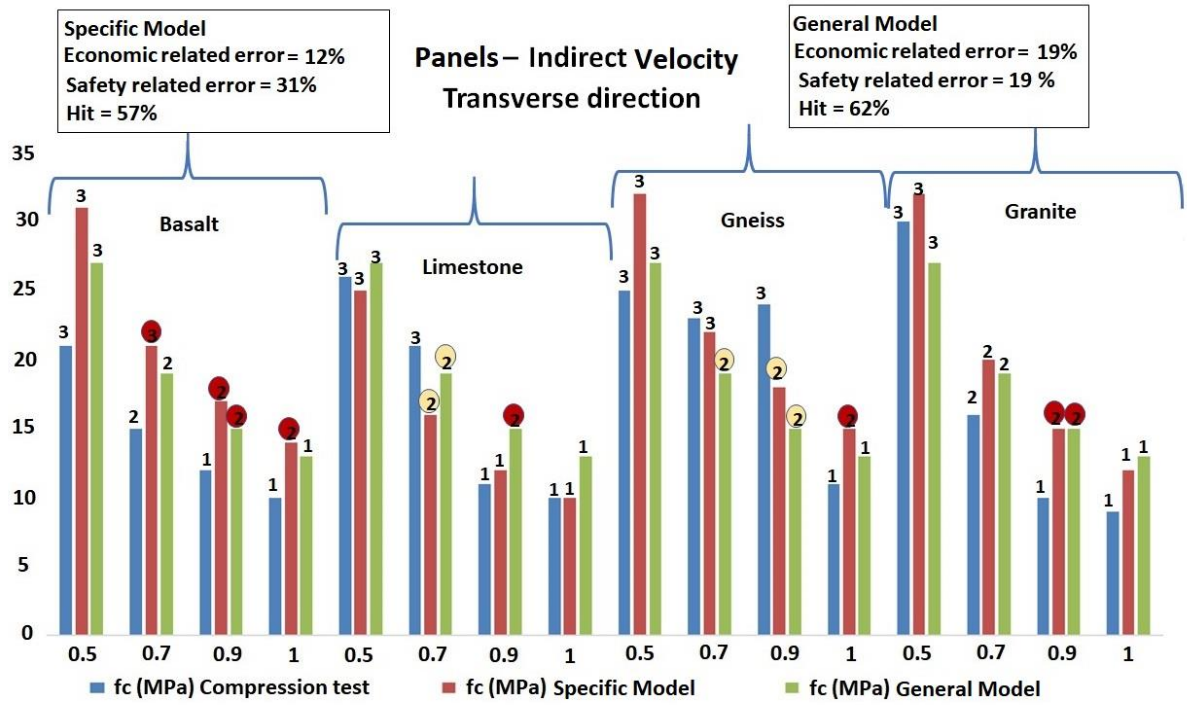


Figure 11. Compressive strength (fc in MPa) obtained from the compression test and inferred by ultrasound testing (specific model and general model) in panels produced with different water-cement ratios (0.5; 0.7; 0.9; and 1.0) and coarse aggregates of different types of mineralogy, with the referred classes related to fc ranges.

fc classes = 1: up to 13.3 MPa; 2: from 13.4 to 20 MPa; and 3: over 20 MPa.
Values of classes without prominence: classification range hit (Category A - inferred range = reference range); highlight in yellow: economic-related error (Category B - inferred range lower than the reference range); and highlight in red: safety-related error (Category C - inferred range higher than the reference range).

CONCLUSIONS

– Assuming 5% as the maximum safety-related error limit (property prediction higher than the actual value of the property), the ultrasound test using direct measurement in the counterfort is suitable for sorting elements of the system by stiffness, both for the aggregate specific model and for the general model (regardless of the aggregate). Sorting of the system elements by strength is only suitable with the use of the specific model. Economic-related errors (property prediction below the actual value of the property) are higher when inference was carried out with the general model;

– Assuming the same maximum safety-related error limit (5%), the classification of panels by stiffness using a direct ultrasound testing is only suitable with the use of the specific model, both for propagation in the longitudinal and transverse directions. For sorting by strength, only the direct testing in the longitudinal direction using the specific model is suitable;

– Inspection of panels using indirect ultrasound testing for stiffness inference is suitable (maximum of 5% safety-related error), in the longitudinal and transverse directions, and only with the use of the specific model. For strength, inference in the inspection is suitable only with the indirect testing in the longitudinal direction and using the specific model. Testing in the transverse direction is not suitable for the inference of strength with any of the models.

ACKNOWLEDGEMENTS

The authors would like to thank the Sao Paulo Research Foundation (FAPESP), São Paulo for the financing of several projects of the research group, which allowed the facilities used in this research and Geosoluções for the logistic support, materials and permission to use the Lock and Load forms.

REFERENCES

[1] Reunion internationale de laboratoires d’essais et materiaux. RILEM NDT 1. Testing of Concrete by the Ultrasonic Pulse Method. Paris, 1972.

[2] British standards institution. BS 1881 - PART 203: Recommendations for measurement of velocity pulses in concrete. London: p.20. 1988.

[3] American concrete institute. ACI 228. 2R. Report On Nondestructive Test Methods For Evaluation Of Concrete In Structures, Detroit, 2013.

[4] European commitee for standardization, BS EN 12504:4, Testing Concrete. Determination of ultrasonic pulse velocity, Brussels, 2004.

[5] ______. NBR 8802. Concreto Endurecido – Determinação da velocidade de propagação da onda ultra-sônica. Rio de Janeiro, 2019

[6] American society for testing and materials. C597-16. Standard Test Method for Pulse Velocity Through Concrete. West Conshohocken, 2016.

[7] Kaplan, M. F. The relation between ultrasonic pulse velocity and the compressive strength of concretes having the same workability but different mix proportions. Magazine of Concrete Research, v. 12, n. 34, p. 3-8, 1960.

[8] Popovics, S. Analysis of the concrete strength versus ultrasonic pulse velocity relationship. Materials Evaluation (USA), v. 59, n. 2, p. 123-124, 2001.

[9] Abo-Qudais, S. A. Effect of concrete mixing parameters on propagation of ultrasonic waves". Construction and building materials, v.19, n.4, p. 257-263, maio 2005.

[10] Lin, Y.; Shih-Fang, K., Hsiao, C.; Chao-Peng, L. Investigation of pulse velocity-strength relationship of hardened concrete. ACI Materials Journal, v. 104, n. 4, p. 344, 2007.

[11] Mahure, N. V.; Vijh, G. K.; Sharma, P. Sivakumar, N. Ratnam, M. Correlation between pulse velocity and compressive strength of concrete. International Journal of Earth Sciences and Engineering, v. 4, n. 6, p. 871-874, 2011.

[12] Bucur, Voichita, Acoustics of Wood. Editora Springer Verlage – N.Y. 393p. 2006.

[13] Yaman, I. O.; Inci, G.; Yesiller, N.; Aktan, H. M. Ultrasonic pulse velocity in concrete using direct and indirect transmission. ACI Materials Journal, v. 98, n. 6, p. 450, 2001.

[14] Turgut, P.; Kucuk, O. F. Comparative relationships of direct, indirect, and semi-direct ultrasonic pulse velocity measurements in concrete. Russian Journal of Nondestructive Testing, v. 42, n. 11, p. 745, 2006.

[15] Savaliya, K. D.; Thaker, K. K.; Dave, U. V. Comparison between different methods of ultrasonic pulse velocity tests on concrete. International Journal of Engineering Research and Applications (IJERA), ISSN, p. 2248-9622, 2014.

[16] Benaicha, M.; Jalbaud, O.; Alaoui, A. H.; Burtschell, Y. Correlation between the mechanical behavior and the ultrasonic velocity of fiber-reinforced concrete. Construction and Building Materials, v. 101, p. 702-709, 2015.

[17] Azreen, M. N.; Pauzi, I. M.; Nasharuddin, I.; Haniza, M. M.; Akasyah, J.; Karsono, A. D.; Lei, V. Y. Prediction of concrete compression strength using ultrasonic pulse velocity. In: AIP Conference Proceedings. AIP Publishing, 2016. Vol. 1704, No. 1, p. 040006. 2016.

[18] Carcaño, R. S; Moreno, E. I. Evaluation of concrete made with crushed limestone aggregate based on ultrasonic pulse velocity. Construction and Building Materials, v. 22, n. 6, p. 1225-1231, 2008.

[19] Uddin, M. T.; Hasan, A. M. Effects of maximum aggregate size on UPV of brick aggregate concrete. Ultrasonics, v.69, p. 129–136, 2016.

[20] Kiliç, A.; Teym, A.; Özdemir, O.; Atis, C. D. Estimation of Compressive Strength of Concrete Using Physico-Mechanical Properties of Aggregate Rock. Iranian Journal of Science and Technology, Transactions of Civil Engineering, p. 1-8, 2018.

[21] Mlakar, P. F.; Trone, J.; Madden, J. Ultrasonics in the heart of darkness. Concrete international, v. 20, n. 10, p. 36-38, 1998.

[22] Shiotani, T.; Aggelis, D. G.; Makishima, O. Global monitoring of large concrete structures using acoustic emission and ultrasonic techniques: case study. Journal of Bridge Engineering, v. 14, n. 3, p. 188-192, 2009.

[23] Sahuinco, M. H. C. Utilização de métodos não destrutivos e semi-destrutivos na avaliação de pontes de concreto. 2011. Tese de Doutorado. Universidade de São Paulo.

[24] Saint-Pierre, F.; Philibert, A.; Giroux, B.; Rivard, P. Concrete quality designation based on ultrasonic pulse velocity. Construction and Building Materials, v. 125, p. 1022-1027, 2016.

[25] Haach, V. G., Juliani, L. M. (2017). Possibilities of using ultrasound for the technological 532 control of concrete of hollow-core slabs. Construction and Building Materials, v. 133, p. 533 409-415.

[26] Villain, G.; Garnier, V.; Sbartai, Z. M.; Derobert, X.; Balayssac, J. P. Development of a calibration methodology to improve the on-site non-destructive evaluation of concrete durability indicators. Materials and Structures, v. 51, n. 2, p. 40, 2018.

[27] Sahmaran, M.; Yaman, I. O. Hybrid fiber reinforced self-compacting concrete with a high-volume coarse fly ash. Construction and Building Materials, v. 21, n. 1, p. 150-156, 2007.

[28] Topcu, I. B.; Canbaz, M. Effect of different fibers on the mechanical properties of concrete containing fly ash. Construction and Building Materials, v. 21, n. 7, p. 1486-1491, 2007.

[29] Acebes, M.; Molero, M.; Segura, I.; Moragues, A.; Hernandez, M. G. Study of the influence of microstructural parameters on the ultrasonic velocity in steel–fiber-reinforced cementitious materials. Construction and Building Materials, v. 25, n. 7, p. 3066-3072, 2011.

[30] Gencel, O.; Brostow, W.; Datashvili, T.; Thedford, M. Workability and mechanical performance of steel fiber-reinforced self-compacting concrete with fly ash. Composite interfaces, v. 18, n. 2, p. 169-184, 2011.

[31] Nik, A. S.; Omran, O. L. Estimation of compressive strength of self-compacted concrete with fibers consisting nano-SiO2 using ultrasonic pulse velocity. Construction and Building Materials, v. 44, p. 654-662, 2013.

[32] Silva, R. R. C. da; Bonfim, L. H. S. Análise do comportamento mecânico em concreto com diferentes adições de fibras através de propagação de onda de ultrassom. Exatas e Engenharia, v. 9, n. 25, 2019.

[33] Associação brasileira de normas tecnicas. NBR 11578: Cimento Portland Composto. Rio de Janeiro, 1997.

[34] Silva, R. R. C. da. Propagação de ondas de ultrassom em sistemas de contenção par obras de terra. Tese de Doutoradao. UNICAMP - Universidade Estadual de Campinas. p.114. 2020.

[35] Bungey, J. H.; Millard, S. G.; Grantham, M. G. Ultrasonic pulse velocity methods. Testing of Concrete in Structures, Taylor & Francis, New York, 2006.

[36] Nepomuceno, M. C. Ensaios não destrutivos em betão. Provas de Aptidão Pedagógica e Capacidade Científica, p. 469, 1999.

[37] Ferrari, V. J; Padaratz, I. J. Aplicação de ondas ultra-sônicas na detecção das primeiras fissuras em vigas de concreto armado e na avaliação da resistência à compressão. Acta Scientiarum. Technology, v. 25, n. 2, p. 185-191, 2003.

[38] Malhotra V. M.; Carino N. J. Nondestructive Testing of Concrete. 2. ed. London: American Society for Testing and Materials, 2004.

[39] Câmara, E. Avaliação da resistência à compressão do concreto utilizado usualmente na grande Florianópolis através de métodos de ensaios não destrutivos. 152f. Dissertação (Mestrado Engenharia Civil) – Universidade Federal de Santa Catarina, Florianópolis, 2006.

[40] Hadlich, A. R.; Pinto, R. C. A.; Padaratz, I. J., Análise comparativa do uso do ultra-som em concreto com adição de fibra de aço. 48º Congresso Brasileiro do Concreto, Rio de Janeiro, IBRACON, 2006.

[41] Palacios, M.P.G. Emprego de Ensaios Não Destrutivos e de Extração de Testemunhos na Avaliação da Resistência à Compressão do Concreto. Dissertação de Mestrado em Estruturas e Construção Civil, Publicação E.DM-007A/12, Departamento de Engenharia Civil e Ambiental, Universidade de Brasília, Brasília, DF, p. 165, 2012.

[42] Soares, D.; Brito, J., Ferreira, J., Pacheco, J. In situ materials characterization of full-scale recycled aggregates concrete structures. Construction and Building Materials, v. 71, p. 237-245, 2014.

[43] European committee for standardization, EN-ISO 8047: Testing concrete – Determination of ultrasonic pulse velocity, Brussels, 1994.

[44] Kretschmann, D.; Hernandez, R. Grading timber and glued structural members. Primary wood processing : principles and practice. Dordrecht, Springer, pages 339-390, 2006.

[45] Chung, H. W. Effects of embedded steel bars upon ultrasonic testing of concrete. Magazine of Concrete Research, v. 30, n. 102, p. 19-25, 1978.

[46] Bungey, J. H. A. Influência do reforço no teste de velocidade de pulso ultrassônico. Publicação Especial , v. 82, p. 229-246, 1984.

[47] Naik, T. R.; Malhotra, V. M.; Popovics, J. S. The ultrasonic pulse velocity method. In: Handbook on nondestructive testing of concrete. CRC Press. p. 182-200. 2003.

[48] Andrade, P. B. Estimativa da profundidade de fendas no concreto através da utilização do ultra-som e eco-impacto. Dissertação de Mestrado. Universidade Federal de Santa Cataria. P.167. 2006.

[49] Medeiros, A. Aplicação do ultra-som na estimativa da profundidade de fendas superficiais e na avaliação da eficácia de injeções em elementos de concreto armado. Dissertação de Mestrado. Universidade Federal de Santa Catarina, p. 200. 2007.

[50] Pardo, F.; Perez, E. Evaluación del efecto de las barras de refuerzo del concreto sobre las medidas de velocidad de pulso ultrasónico. Bucaramanga, Colombia, Universidad Industrial de Santander, p. 123, 2010.

[51] Cruz, R.; Quintero, L. A.; Herrera, J. Evaluación del efecto de barras de refuerzo en concreto sobre las medidas de velocidad de pulso ultrasónico (VPU). Revista Colombiana de Materiales, n. 5, p. 107-113, 2014.

[52] Chies, J.; A. Ensaios não destrutivos em concreto: detecção de falhas no interior de estruturas de concreto com o uso de ultrassom. Dissertação de Mestrado. Universidade Federal do Rio Grande do Sul, RS, p.133, 2014.

[53] Chung, H. W.; LAW, K. S., Diagnosing in situ concrete by ultrasonic pulse technique, Concrete International, October, p. 42-49, 1983.

[54] Dornelles, F. L.; Pinto, R. C. A.; Padaratz, I. J, Influência do Posicionamento da Armadura em Medições de Ultra-Som para Avaliação da Resistência à Compressão do Concreto, Encontro Nacional Betão Estrutural 2004, Actas, Porto, Portugal, p. 1015-1022, 2004.

[55] Puncinoti, R.; Hinterholz, L.; D'elia, A.; De Loenzo, R. A. (Influence of steel reinforcement on ultrasonic pulses velocity. In: 4 th International Conference on NDT (11–14 octubre, Chania, Crete-Grecia), Italy. 2007.

[56] Giacon Jr, M. Propagação de ondas de ultra-som em prototipos de postes tubulares de concreto armado. Dissertação de Mestrado. Universidade Estadual de Campinas. 2009.

[57] Ferreira, G. Estudo sobre fatores influentes nos resultados de ensaios não destrutivos em concreto endurecido. Dissertação (Mestrado em Engenharias) - Universidade Federal de Uberlândia, Uberlândia, p.199. 2011.

[58] Robles, O. J. C.; Ziegler, A. J. F. Evaluación de la influencia del acero de refuerzo en la aplicación de ensayo de velocidade de pulso ultrasónico en elementos de concreto armado. Trabajo Especial de Grado. Universidad Central de Venezuela. 2015.

[59] Ramírez, F. C. Detecção de danos em estruturas de concreto por meio de tomografia ultrassônica. Tese de Doutorado. Universidade de São Paulo. p.169, 2015.

[60] Adamatti, D. S.; Lorenzi, A.; Chies, J. A.; da Silva Filho, L. C. P. Análise de estruturas de concreto armado através da velocidade de propagação do pulso ultrassônico: estudo de parâmetros tecnológicos intervenientes. RIEM-IBRACON Structures and Materials Journal, v. 10, n. 2, 2016.

[61] Paiva, M. A. D. C. Análise das propriedades mecânicas nas primeiras idades do concreto de lajes alveolares utilizando o ensaio de ultrassom. Tese de Doutorado. Universidade de São Paulo. p.161, 2017.

[62] Popovics, J. S.; Song, W.; Achenbach, J. D.; Lee, J. H.; Andre, R. F. One-sided stress wave velocity measurement in concrete. Journal of Engineering Mechanics, v. 124, n. 12, p. 1346-1353, 1998.

[63] Haach, V. G.; Ramirez, F. C. Qualitative assessment of concrete by ultrasound tomography. Construction and Building Materials, v. 119, p. 61-70, 2016.

[64] Rheinheimer, V. Utilização de ensaios não destrutivos no controle tecnológico de execução de pavimentos de concreto tipo Fast Track. Dissertação de Mestrado em Engenharia Civil, Universidade Federal de Santa Catarina – UFSC. p. 258, 2007.

3 DISCUSSÃO GERAL

Neste capítulo serão apresentados e discutidos os principais resultados obtidos a partir dos objetivos específicos abordados pelos 3 artigos apresentados no corpo da tese, os quais estão interligados e se completam para que o objetivo geral seja alcançado.

3.1 Aspectos Metodológicos

3.1.1 Ensaio direto – controle de qualidade dos painéis e dos contrafortes antes da instalação

Através da metodologia de arranjo e tipo dos transdutores e tipo de ensaio, avaliada por meio de análises estatísticas de comparação de médias e regressões, foi possível verificar que a frequência de 45 KHz é a mais adequada para inspeções visando o controle de qualidade das placas do sistema *Lock and Load* antes da instalação.

A frequência de 45 KHz atende as bases teóricas de propagação de ondas, permitindo diferenciar placas e contrafortes em função da resistência e/ou rigidez. Além disso, os valores de velocidades foram menos afetados por fatores tais como as distâncias entre transdutores e o posicionamento dos mesmos nas placas. Nesta frequência a velocidade obtida foi superior às demais, possivelmente em função da não adequação da frequência de 25 kHz em relação à dimensão transversal da placa e da não adequação da frequência de 80 kHz em relação à dimensão da brita (agregado graúdo). Assim, verifica-se que a frequência dos transdutores é de grande relevância, pois está diretamente relacionado com aspecto teórico importante envolvido no ensaio, que é a propagação em meios infinitos e a perda de energia do sinal em função da estrutura do material.

Para o contraforte as frequências de 25 kHz e de 45 kHz tiveram resultados estatisticamente equivalentes, mas tendo em vista a melhor adequação da frequência de 45 kHz nas placas, torna-se mais adequado o uso da mesma frequência em ambas peças. Importante destacar que também ficou demonstrada a sensibilidade de detecção de diferenças entre as placas utilizando-se ensaios diretos com transdutores de 45 kHz de frequência.

Considerando os resultados obtidos foi possível observar que, mesmo com controle do processo de fabricação, todos os elementos produzidos não possuem as mesmas características, e que o uso do ensaio de ultrassom no controle de qualidade das peças pré-moldadas teve sensibilidade paera detectar essas diferenças.

O tipo e a dimensão do agregado e a presença da armadura são aspectos destacados em normas e em pesquisas como fatores que interferem nas relações entre parâmetros de qualidade e de resistência do concreto inferidos pelo ensaio de propagação de ondas. No entanto, tendo em vista que a proposta desta pesquisa é a aplicação do ensaio em um sistema que utiliza sempre a mesma composição de traço para o concreto e mesmo tipo e posicionamento de armadura, é esperado que o uso do ensaio direto de ultrassom antes da aplicação na obra permita inferir, com acurácia e reprodutibilidade, a qualidade das placas e dos contrafortes.

3.1.2 Ensaio indireto – controle de qualidade das placas após a instalação

No caso do ensaio indireto verificou-se que o transdutor de faces exponenciais sem furos para acoplamento foi o único que permitiu distinguir as placas por velocidade e a distinção foi a mesma obtida para o ensaio direto. Esse resultado é de extrema importância, uma vez que o foco desta pesquisa é a utilização da metodologia para inspeção das placas após a instalação. Neste caso não é viável o uso dos ensaios diretos, uma vez que não se tem acesso às extremidades das peças.

Em relação às diferenças numéricas entre os resultados de velocidade obtidos de forma direta e indireta, o ensaio com transdutores de faces exponenciais com furação foi o que apresentou os menores valores. Na prática, no entanto, a furação das placas para os ensaios de campo não seria adequado em inspeções, tendo sido realizado somente com o objetivo de analisar erros no uso deste tipo de transdutor apenas com contato na peça (sem furação). Apesar da irregularidade superficial das placas, a utilização de acoplamento através de gel medicinal, proporcionou a melhor correlação entre as velocidades obtidas de forma direta e indireta para o transdutor de faces planas distanciados de 300 mm.

A obtenção de velocidades inferiores no ensaio superficial já é esperada, mas é muito importante conhecer a diferença para que o ensaio possa ser utilizado em inspeções. Para os ensaios mais adequados para serem realizados em campo (transdutores de faces planas e de faces exponenciais sem furação) a relação entre a velocidade obtida de forma indireta e direta foi da ordem de 0,60. Esta tendência pode ser justificada tanto pelo próprio ensaio, que afeta o modo de propagação da onda, quanto pela alteração da matriz do concreto. O processo de vibração e aumento do fator (a/c) durante a fabricação das placas contribui para a segregação do agregado graúdo, formando-se na superfície uma camada mais porosa, menos densa e menos resistente, resultando na perda de homogeneidade do concreto devido a falta de coesão entre o agregado graúdo e argamassa.

Em relação a distância entre os transdutores para o ensaio superficial, estatisticamente os valores de velocidade são equivalentes à partir de 300 mm. Dados da literatura para medições indiretas em amostras de concreto também indicam resultados mais consistentes e de menor variabilidade para as leituras com transdutores distanciados de cerca de 300 mm.

3.2 Determinação de modelos de predição da resistência e da rigidez do concreto por meio do ensaio de ultrassom – Calibração dos modelos de predição

Foram obtidas correlações estatisticamente significativas (nível de significância de 95%) e com ajuste adequado (coeficiente de correlação) entre os parâmetros obtidos por ultrassom (velocidades de propagação das ondas e coeficiente de rigidez) e a resistência (fc) e rigidez (Ec) do concreto. Esse resultado ficou evidenciado tanto para os modelos obtidos para cada tipo de agregado graúdo (específicos) quanto para aqueles envolvendo todos agregados (geral), e para ambas as frequências de 45 e 80 KHz de transdutores (face plana).

O módulo de elasticidade é uma das propriedades elásticas mais importantes dos compósitos cimentícios e está relacionado diretamente com as propriedades da pasta de cimento, a rigidez dos agregados selecionados e com o método utilizado para sua determinação. A resistência a compressão está mais relacionada à relação água-cimento do que ao tipo de agregados utilizados.

Em geral a inferência do módulo de elasticidade do concreto é realizada por meio de relações empíricas com a resistência, obtida em ensaios destrutivos, ou com a massa específica. No entanto, a literatura indica que essas relações nem sempre representam, com acurácia, a rigidez do concreto, uma vez que há vários fatores de influência, sendo a natureza dos agregados o mais representativo.

Os modelos de predição do módulo de elasticidade (Eci) do concreto utilizando a velocidade de propagação de ondas de ultrassom apresentaram melhores correlações do que os modelos de predição da resistência (fc). O coeficiente de rigidez obtido por ultrassom (C) apresentou melhor correlação com os parâmetros de rigidez (Eci) e de resistência (fc) do concreto do que a velocidade de propagação das ondas (V) utilizada de forma isolada, resultado esperado uma vez que o coeficiente de rigidez inclui parâmetro físico do concreto (densidade).

Observou-se que a velocidade de pulsos ultrassônicos é influenciada pela composição do concreto com agregados graúdos de diferentes origens mineralógicas. Velocidades mais baixas foram obtidas em agregados graúdos com maior porosidade, confirmando achados da literatura.

3.3 Uso do ultrassom no controle de qualidade dos contrafortes antes da instalação e das placas antes e depois da instalação

Para essa parte da pesquisa foi feito um grid XY de medição nas placas e nos contrafortes. A análise estatística de comparação múltipla mostrou que, para nenhum tipo de rocha utilizada na confecção das placas e dos contrafortes e nenhum tipo (direto e indireto) e forma de medição (longitudinal e transversal) há uma linha de medição que se diferencie, de forma consistente, das demais. Esse resultado é importante pois permite concluir que se pode escolher uma linha de medição já que, na prática, não é viável usar o grid. Apesar disso, as linhas de medição que ficavam mais próximas das extremidades da peça foram as que apresentaram maior variabilidade sendo, portanto, as que devem ser evitadas. Nesta região as placas estão mais suscetiveis a patologias durante a desforma, o transporte e o empilhamento.

As peças pré-moldadas se comportaram de forma isotrópica quando se consideram as propagações longitudinal e transversal, indicando não haver influência da armadura, presente em apenas uma das direções. Os resultados da análise estatística também mostraram que a variabilidade da velocidade, explicada pela presenca da armadura, não foi significativa. Esses resultados permitiram confirmar dados da literatura e de normas que indicam que armaduras com diâmetro de 6,3 mm, como as utilizadas no sistema *Lock and Load*, não afetam as velocidades de propagação das ondas.

As velocidades obtidas diretamente nas placas e nos contrafortes foram estatisticamente diferentes das velocidades obtidas nos corpos de prova, mas os valores são estatisticamente correlacionados, de forma que foi possível obter modelos de inferência das velocidades nos corpos de prova à partir de velocidades nas peças do sistema, quer seja as obtidas de forma direta como de forma indireta. Esse resultado viabilizou utilizar os modelos de correlação obtidos nos corpos de prova nas inferências da resistência e da rigidez utilizando as velocidades mensuradas nas placas e contrafortes. Essa variação (entre corpos de prova e placas e contrafortes) está relacionada com a diferença de forma e de dimensão das peças e, também, do efeito que essas dimensões exercem na compactação do concreto durante a moldagem.

A revisão bibliográfica demonstra que é possível avaliar e estimar a resistência do concreto *in loco* através de curvas de correlação geradas a partir de ensaios de ultrassom em corpos de provas, com erros na ordem de ± 10%, em relação aos ensaios destrutivos, desde que as amostras possuam traços semelhantes as das estruturas em estudo. Tendo em vista que a os modelos propostos serão aplicados em placas de concreto com as mesmas granulometrias e composição, é de se esperar que a calibração terá efeitos positivos na redução dos erros de inferência da resistência e da rigidez do concreto.

Os resultados da inferência da resistência e da rigidez foram considerados adequados quando a faixa de valor inferido pelo ensaio de ultrassom fosse igual a faixa de real do valor obtido no ensaio estático de compressão. O resultado de inferência também é considerado adequado quando a faixa inferida indica valor infeior ao real, sendo nesse caso chamado de erro de economia, já que a classificação será realizada abaixo da capacidade do material. O resultado da inferência foi considerado erro quando a faixa inferida indica valor superior ao real, chamado erro de segurança, já que nesse caso se estaria superestimando a resistência/rigidez do material. Em normas de classificação de materiais estruturais o erro de segurança não deve ultrapassar 5%. Assim, tanto para as placas quanto para os contrafortes, o modelo adotado para cada tipo de rocha (específico) foi o que se mostrou adequado para a inferência da rigidez das placas. Para a inferência da resistência, tanto esse modelo quanto o modelo geral (todos os tipos de rocha) não foram adequados considerando a exigência de segurança (erros inferiores a 5%) quando as medições nas placas foram na direção transversal. O uso do modelo geral apresentou erros de segurança entre zero e 12% na inferência da rigidez, para propagação longitudinal ou transversal, e entre zero e 6% na inferência da resistência para propagação longitudinal. Para as medições na direção transversal na inferência da resistência os erros de segurança foram de 6 a 31% para o modelo específico e de 12 a 19% para o modelo geral.

4 CONCLUSÃO GERAL

Os resultados encontrados na pesquisa comprovam a hipótese da viabilidade do uso do ensaio de propagação de ondas de ultrassom no controle de qualidade das peças do sistema *Lock and Load*, inferidas por meio da resistência e da rigidez, desde que sejam aplicadas metodologias adequadas às especificidades do sistema, e de acordo com aspectos teóricos do ensaio.

No controle de qualidade dos painéis e dos contrafortes do sistema *Lock and Load* antes da instalação (ensaio direto), a frequência de 45 kHz é a mais adequada. Para o controle de qualidade das placas após a instalação (inspeções) o ensaio indireto também pode ser realizado com transdutores de 45 kHz de frequência, distanciados de 300 mm. Para comparações com velocidades obtidas de forma direta os valores dos ensaios indiretos devem ser corrigidos dividindo-se por 0,60.

Os modelos de inferência da resistência e da rigidez do concreto por meio dos parâmetros obtidos no ensaio de ultrassom (Velocidade e Coeficiente de Rigidez), obtidos com uso de transdutores de 45kHz de frequência, foram estatisticamente significativos (P-valor = 0,0000) para os concretos produzidos com todos os tipos de rocha estudados (Basalto, Calcário, Gnaisse e Granito). O coeficiente de rigidez é melhor preditor do que a velocidade; a predição da rigidez é sempre melhor do que da resistência e os modelos de inferência obtidos para cada tipo de brita são melhores (coeficientes de determinação superiores a 86%) do que os gerais (todos os tipos de brita juntos – coeficientes de determinação superiores a 79%).

Considerando 5% como limite máximo de erro relativo a segurança (predição da propriedade superior ao valor real da propriedade) o ensaio direto nos contrafortes foi adequado para classificar as peças por rigidez, tanto com o modelo específico para o agregado quanto com o modelo geral (independente do agregado). A classificação das peças por resistência só foi adequada com o uso do modelo específico. Os erros por economia (predição da propriedade inferior ao valor real da propriedade) foram superiores quando a inferência foi realizada com o modelo geral.

Para as placas, considerando o mesmo limite máximo de erro relativo a segurança (5%), a classificação por rigidez por meio de ensaio direto de ultrassom só foi adequado com o uso do modelo específico, tanto para a propagação na direção longitudinal quanto na transversal. Para a classificação por resistência somente o ensaio direto na direção longitudinal com uso do modelo específico foi adequado.

A inspeção das placas com uso de ensaio indireto de ultrassom para a inferência da rigidez foi adequada (máximo de 5% de erro de segurança), na direção longitudinal e transversal, somente com o uso do modelo específico. Para a resistência a inferência na inspeção foi adequada apenas com o ensaio indireto na direção longitudinal e com o modelo específico. O ensaio na direção transversal não foi adequada para a inferência da resistência com nenhum dos modelos.

5 REFERÊNCIAS BIBLIOGRÁFICAS

ABO-QUDAIS, S. A. Effect of concrete mixing parameters on propagation of ultrasonic waves". Construction and building materials, v.19, n.4, p. 257-263. 2005.

ACEBES, M.; MOLERO, M.; SEGURA, I.; MORAGUES, A.; HERNANDEZ, M. G. Study of the influence of microstructural parameters on the ultrasonic velocity in steel–fiber-reinforced cementitious materials. Construction and Building Materials, v. 25, n. 7, p. 3066-3072, 2011.

ADAMATTI, D. S.; LORENZI, A.; CHIES, J. A.; da SILVA FILHO, L. C. P. Análise de estruturas de concreto armado através da velocidade de propagação do pulso ultrassônico: estudo de parâmetros tecnológicos intervenientes. RIEM-IBRACON Structures and Materials Journal, v. 10, n. 2, 2016.

AGGELIS, D. G.; SHIOTANI, T. Repair evaluation of concrete cracks using surface and through transmission wave measurements. Cement & Concrete Composites, Vol. 29, p. 700-701, 2007.

AGGELIS, D.G.; SHIOTANI, T. Effect of inhomogeneity parameters on wave propagation in cementitious material. ACI materials journal, v. 105, n. 2, p. 187, 2008.

ALI, M.; LIU, A.; SOU, H.; CHOUW, N. Mechanical and dynamic properties of coconut fibre reinforced concrete, Construction and Building Materials, v. 30, p. 814-825, 2012.

AL-ZHARANI, T. M., DEMIRBOGA, R., KHUSHAFATI, W. H. Relationship Between Core Compressive Strength and UPV Values for Different Core Slenderness of High Strength Concrete Beam. 2016.

AMERICAN CONCRET INSTITUTE, ACI 228.1R–03. “In-Place Methods to Estimate Concrete Strength”, Detroit. 2003.

AMERICAN CONCRETE INSTITUTE. ACI 228. 2R. Report On Nondestructive Test Methods For Evaluation Of Concrete In Structures, Detroit, 2013.

AMERICAN SOCIETY FOR TESTING AND MATERIALS. ASTM C597-02. Standard test method for pulse velocity through concrete. West Conshohocken, 2016.

ANDRADE, P. B. Estimativa da profundidade de fendas no concreto através da utilização do ultra-som e eco-impacto. Dissertação de Mestrado. Universidade Federal de Santa Cataria. P.167. 2006.

ANEPAC - ASSOCIAÇÃO NACIONAL DAS ENTIDADES DE PRODUTORES DE AGREGADOS PARA A CONSTRUÇÃO CIVIL. Disponível em: www.anepac.org.br . Acesso em: 21 outubro. 2019.

ANUGONDA, P.; WIEHN, J. S.; TURNER, J. A. Diffusion of ultrasound in concrete. Ultrasonics, v. 39, n. 6, p. 429-435, 2001.

ARAÚJO, S. S.; GUIMARÃES, G. N.; GEYER, A. L. B. Influência do Tipo de Medição na Determinação do Módulo Estático de Elasticidade do Concreto. RIEM-IBRACON Structures and Materials Journal, v. 5, n. 5, 2012.

ARAÚJO, S. S.; GUIMARÃES, G. N.; GEYER, A. L. B. Influência do tipo de concreto, da dimensão do corpo de prova e do tipo de laboratório na determinação da resistência à compressão do concreto. Revista Engenharia Civil, Uminho, v. 52. Uminho, Portugal, 2016.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TECNICAS. NBR 11578: Cimento Portland Composto. Rio de Janeiro, 1997.

_______. NBR NM 67. Concreto: determinação da consistência pelo abatimento do tronco de cone. Rio de Janeiro, 1998.

_______. NBR NM 30: Agregado miúdo - Determinação da absorção de água. Rio de Janeiro, 2001.

______. NBR NM 248. Agregados: Determinação da composição granulométrica. Rio de Janeiro, 2003.

_______. NBR 9778: Argamassa e concreto endurecidos – Determinação da absorção de água por imersão – Índice de vazios e massa específica. Rio de Janeiro, 2005.

______. NBR NM 45: Agregados: Determinação da massa unitária e do volume de vazios. Rio de Janeiro. 2006.

______. NBR 7211. Agregados para concreto - Especificação. Rio de Janeiro. 2009.

______. NBR 7211. Agregados para concreto - Especificação. Rio de Janeiro. 2009.

______. NBR NM 52: Determinação da massa específica de agregados miúdos por meio de frasco Chapman. Rio de Janeiro, 2009.

______. NBR NM 53. Agregado graúdo – Determinação da massa específica, massa específica aparente e absorção de água. Rio de Janeiro. 2009.

______. NBR 12655. Concreto de cimento Portland - Preparo, controle, recebimento e aceitação - Procedimento. Rio de Janeiro, 2015.

______. NBR 5738. Concreto: Procedimento para moldagem e cura de corpos de prova. Rio de Janeiro, 2015.

______. NBR 8522 - Concreto – Determinação dos módulos estáticos de elasticidade e de deformação a compressão. Rio de Janeiro, 2017.

______. NBR 5739. Ensaio de compressão de corpos-de-prova cilíndricos de concreto. Rio de Janeiro, 2018.

______. NBR 8802. Concreto Endurecido – Determinação da velocidade de propagação da onda ultra-sônica. Rio de Janeiro, 2019.

AZREEN, M. N.; PAUZI, I. M.; NASHARUDDIN, I.; HANIZA, M. M.; AKASYAH, J.; KARSONO, A. D.; LEI, V. Y. Prediction of concrete compression strength using ultrasonic pulse velocity. In: AIP Conference Proceedings. AIP Publishing, 2016. Vol. 1704, No. 1, p. 040006. 2016.

BAUTZ, R. S.; MACIOSKI, G.; WEBER, S. L.; MOREIRA, A. R. Análise da qualidade do concreto em pilares de viadutos por meio de ensaios não destrutivos para fins de reabilitação. 1º Congresso Brasileiro de Patologia das Fundações. Foz do Iguaçu- Paraná. 2014.

BAYAN, S. A.; BESTOON, R. A., SABR, A. A., SIRWAN E. K. Effect of Aggregate Content on the Concrete Compressive Strength - Ultrasonic Pulse Velocity Relationship. American Journal of Civil Engineering and Architecture, Vol. 4, No. 1, 1-5. 2016.

BENAICHA, M.; JALBAUD, O.; ALAOUI, A. H.; BURTSCHELL, Y. Correlation between the mechanical behavior and the ultrasonic velocity of fiber-reinforced concrete. Construction and Building Materials, v. 101, p. 702-709, 2015.

BENJAMIM, C. V. S. Avaliação experimental de protótipos de estruturas de contenção em solo reforçado com geotêxtil. Tese de Doutorado. Universidade de São Paulo, 2006.

BENTUR, A.; MINDESS, S. Fibre Reinforced Cementitious Composites. Fibre reinforced cementitious composites. CRC Press, 2014.

BERODIER, E.; GIBSON II, L. R.; BURNS, E.; ROBERTS, L.; CHEUNG, J. Robust production of sustainable concrete through the use of admixtures and in-transit concrete management systems. Cement and Concrete Composites, 2018.

BEZERRA, A. C. S.; SILVA, F. M.; SOARES, M. N. S.;AGUILAR, M. T. P. Relações do módulo de elasticidade dinâmico, estático e resistência à compressão do concreto. In: Congresso Brasileiro do Concreto, 51º, Curitiba-PR. 2009.

BITA, H.; FAIZ, B.; MOUDDEN, A.; LOTFI, H.; OUACHA, E. H.; BOUTAIB, M. Evaluation of Ultrasonic Attenuation in Mortars Structures Using the Argand Diagram. International Journal of Materials Engineering, v. 6, n. 3, p. 77-84, 2016.

BLITZ, J.; SIMPSON, G. Ultrasonic methods of non-destructive testing. London: Chapman e Hall. 1996.

BOGAS, J. A.; GOMES. A. Static and dynamic modulus of elasticity of structural lightweight and modified density concrete with and without nanosilica–characterization and normalization. International Journal of Civil Engineering, Vol. 12, N. 2, p. 269-278, June 2014.

BOND, L. J.; KEPLER, W. F.; FRANGOPOL, D. M. Improved assessment of mass concrete dams using acoustic travel time tomography. Part I—theory. Construction and Building Materials, v. 14, n. 3, p. 133-146, 2000.

BRITISH STANDARDS INSTITUTION. BS 1881 - PART 203: Recommendations for measurement of velocity pulses in concrete. London: p.20. 1988.

BUCUR, V. Acoustics of Wood. Editora Springer Verlage – N.Y. p.393, 2006.

BUNGEY J.; MILLARD, S. Testing of concrete in structures. 3 ed. London: Blackie Academic e Professional, 1996.

BUNGEY, J. H. A. Influência do reforço no teste de velocidade de pulso ultrassônico. Publicação Especial , v. 82, p. 229-246, 1984.

BUNGEY, J. H.; GRANTHAM, M. G. Testing of concrete in structures. 4.ed. New Work, USA: Champan e Hall. 310p. 2006.

BUNGEY, J. H.; MILLARD, S. G.; GRANTHAM, M. G. Ultrasonic pulse velocity methods. Testing of Concrete in Structures, Taylor & Francis, New York, 2006.

CÂMARA, E. Avaliação da resistência à compressão do concreto utilizado usualmente na grande Florianópolis através de métodos de ensaios não destrutivos. 152f. Dissertação (Mestrado Engenharia Civil) – Universidade Federal de Santa Catarina, Florianópolis, 2006.

CAMARA, L.A.; WONS, M.; ESTEVES, I.C.; MEDEIROS-JUNIOR, R. A. Monitoring the Self-healing of Concrete from the Ultrasonic Pulse Velocity. Journal of Composites Science, v. 3, n. 1, p. 16, 2019.

CARBONARI, B. M. T; CAVALARO, S. H., CASTANHA, J. C. M., GUACELLI, P. A G., SILVA, C. C. Utilização do método ultra-sônico para avaliação da performance do concreto de alto desempenho. Revista Ibracon de Estrututas e Materiais, V. 3, n.4, p. 494–502, dez., 2010.

CARCAÑO, R. S; MORENO, E. I. Evaluation of concrete made with crushed limestone aggregate based on ultrasonic pulse velocity. Construction and Building Materials, v. 22, n. 6, p. 1225-1231, 2008.

CARCAÑO, R. S; PEREYRA, J.B. The influence of the physical properties of aggregates on the ultrasound pulse thecnique in predicting the compressive strength of concrete. Revista Técnica de la Facultad de Ingeniería Universidad del Zulia, v. 26, n. 1, 2003.

CHAIX, J. F.; ACK-BARALY, C.; GARNIERG, V.; SALIM, J. Etude de la propagation des ondes de volume et de surface dans du béton. Les Journées COFREND, 2011.

CHIES, J.; A. Ensaios não destrutivos em concreto: detecção de falhas no interior de estruturas de concreto com o uso de ultrassom. Dissertação de Mestrado. Universidade Federal do Rio Grande do Sul, RS, p.133, 2014.

CHOTARD, T.; GIMET-BREART, N.; SMITH, A.; FARGEOT, D.; BONETT, J. P.; GAULT, C. Application of ultrasonic testing to describe the hydration of calcium aluminate cement at the early age. Cement and Concrete Research, v. 31, n. 3, p. 405-412, 2001.

CHUNG, H. W. Effects of embedded steel bars upon ultrasonic testing of concrete. Magazine of Concrete Research, v. 30, n. 102, p. 19-25, 1978.

CHUNG, H. W.; LAW, K. S., Diagnosing in situ concrete by ultrasonic pulse technique, Concrete International, October, p. 42-49, 1983.

COMITÉ EURO-INTERNATIONAL DU BÉTON. “CEB-FIP Model Code 1990”. London, Thomas Telford. 1993.

CRESPO, A. A. Estatística fácil. 18ª edição. São Paulo: Editora Saraiva. p. 224, 2002.

CRUZ, R.; QUINTERO, L. A.; HERRERA, J. Evaluación del efecto de barras de refuerzo en concreto sobre las medidas de velocidad de pulso ultrasónico (VPU). Revista Colombiana de Materiales, n. 5, p. 107-113, 2014.

DER RIO, L. M.; JIMENEZ, A.; LOPEZ, F.; ROSA, F. J.; RUFO, M. M.; PANIAGUA, J. M. Characterization and hardening of concrete with ultrasonic testing. Ultrasonics, v. 42, n. 1-9, p. 527-530, 2004.

DORNELLES, F. L.; PINTO, R. C. A.; PADARATZ, I. J, Influência do Posicionamento da Armadura em Medições de Ultra-Som para Avaliação da Resistência à Compressão do Concreto, Encontro Nacional Betão Estrutural 2004, Actas, Porto, Portugal, p. 1015-1022, 2004.

EUROPEAN COMMITTEE FOR STANDARDIZATION, EN-ISO 8047: Testing concrete – Determination of ultrasonic pulse velocity, Brussels, 1994.

EUROPEAN COMMITEE FOR STANDARDIZATION, BS EN 12504:4, Testing Concrete. Determination of ultrasonic pulse velocity, Brussels, 2004.

EVANGELISTA, A. Avaliação da resistência do concreto usando diferentes ensaios não destrutivos. 239f. Tese (Doutorado em Engenharia) – Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2002.

EVANGELISTA, A. C. J.; SHEHATA, I. A. E. M. ; SHEHATA, L. C. D. . Parameter that Influence the Results of Nondestructive Methods for Concrete Strength. In: International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE), 2003.

FERRARI, V. J; PADARATZ, I. J. Aplicação de ondas ultra-sônicas na detecção das primeiras fissuras em vigas de concreto armado e na avaliação da resistência à compressão. Acta Scientiarum. Technology, v. 25, n. 2, p. 185-191, 2003.

FERREIRA, G. Estudo sobre fatores influentes nos resultados de ensaios não destrutivos em concreto endurecido. Dissertação (Mestrado em Engenharias) - Universidade Federal de Uberlândia, Uberlândia, p.199. 2011.

FORTES, R. M.; MERIGHI, J. V. Controle Tecnológico e Controle de Qualidade-Um alerta sobre sua importância. In: Congresso Brasileiro de Ensino de Engenharia. 2004.

GARNIER, V.; CHAIX, J. F.; ROSSAT, M.; PAYAN, C.; CORNELOUP, G. Caractérisation Non Destructive des bétons par propagation d'ondes ultrasonores. Mechanics & Industry, v. 10, n. 3-4, p. 299-303, 2009.

GENCEL, O.; BROSTOW, W.; DATASHVILI, T.; THEDFORD, M. Workability and mechanical performance of steel fiber-reinforced self-compacting concrete with fly ash. Composite interfaces, v. 18, n. 2, p. 169-184, 2011.

GIACON Jr, M. Propagação de ondas de ultrassom em protótipos de postes tubulares de concreto armado. Dissertação de Mestrado. UNICAMP-UNIVERSIDADE ESTADUAL DE CAMPINAS. 2009.

GIACON Jr, M., GONCALVES, R., SORIANO, J., AMALFI, G. Caracterização do concreto utilizando ultrassom. In: XXVIII CONAENDI - Congresso de Ensaios Não Destrutivos e Inspeção, Santos - SP. Anais CONAENDI. v. 1. p. 1-9, 2010.

GJORV, O. E. Quality Control and Quality Assurance for Concrete Durability. In: Key Engineering Materials. Trans Tech Publications, p. 76-83, 2016.

GONÇALVES, R.; JÚNIOR, M. G.; LOPES, I. M. Determining the concrete stiffness matrix through ultrasonic testing. ENGENHARIA AGRÍCOLA, v. 31:3, p. 427–437, 2011.

HAACH, V. G.; JULIANI, L. M. Possibilities of using ultrasound for the technological control of concrete of hollow-core slabs. Construction and Building Materials, v. 133, p. 409-415, 2017.

HAACH, V. G.; RAMIREZ, F. C. Qualitative assessment of concrete by ultrasound tomography. Construction and Building Materials, v. 119, p. 61-70, 2016.

HADLICH, A. R.; PINTO, R. C. A.; PADARATZ, I. J. Análise comparativa do uso do ultra-som em concreto com adição de fibra de aço. 48º Congresso Brasileiro do Concreto, Rio de Janeiro, IBRACON, 2006.

HAGER, I.; CARRÉ, H.; KRZEMIE, K. Damage assessment of concrete subjected to high temperature by means of the ultrasonic pulse velocity-UPV method. Studies and Researches, v. 32, n. 1, p. 197-211, 2013.

HASSANPOUR, M.; SHAFIGH, P.; MAHMUD, H.B. Lightweight aggregate concrete fiber reinforcement – a review. Construction and Building Materials, v. 37, p. 452 – 461, 2012.

HAUWAERT, A. V.; DELANNAY, F.; THIMUS, J., Cracking behavior of steel fiber reinforced concrete revealed by means of acoustic emission and ultrasonic wave propagation. ACI Materials Journal, V.96, p. 291- 296, May-June 1999.

IN, C. W.; KIM, J. Y.; KURTIS, K. E.; JACONBS, L. J. Characterization of ultrasonic Rayleigh surface waves in asphaltic concrete. NDT & E International, v. 42, n. 7, p. 610-617, 2009.

KAPLAN, M. F. The relation between ultrasonic pulse velocity and the compressive strength of concretes having the same workability but different mix proportions. Magazine of Concrete Research, v. 12, n. 34, p. 3-8, 1960.

KILIÇ, A.; TEYM, A.; ÖZDEMIR, O.; ATIS, C. D. Estimation of Compressive Strength of Concrete Using Physico-Mechanical Properties of Aggregate Rock. Iranian Journal of Science and Technology, Transactions of Civil Engineering, p. 1-8, 2018.

KIM, Y.; HU, J.; LEE, S.; YOU, B. Mechanical properties of fiber reinforced lightweight concrete containing surfactant. Advances in Civil Engineering, v. 2010, p. 8, 2010.

KRETSCHMANN, D.; HERNANDEZ, R. Grading timber and glued structural members. Primary wood processing : principles and practice. Dordrecht, Springer, p. 339-390, 2006.

LAWSON I.; DANSO K.A.; ODOI H.C.; ADJEI C.A.; QUASHIE F.K.; MUMUNI I.I.; IBRAHIM I.S. Non-Destructive Evaluation of Concrete using Ultrasonic Pulse Velocity. Research Journal of Applied Sciences, Engineering and Technology Published. p. 409-504. 2011.

LEAL, A.C.F.S. Investigação experimental do módulo de elasticidade nos concretos produzidos em Brasília. Dissertação de Mestrado em Estruturas e Construção Civil. Departamento de Engenharia Civil e Ambiental, Universidade de Brasília, Brasília-DF, 151p. 2012.

LEE, H. K.; LEE, K. M.; KIM, Y. H.; YIM, H.; BAE, D. B. Ultrasonic in-situ monitoring of setting process of high-performance concrete. Cement and Concrete Research, v. 34, n. 4, p. 631-640, 2004.

LIN, Y., SHIH-FANG, K., HSIAO, C., CHAO-PENG, L. Investigation of pulse velocity-strength relationship of hardened concrete. ACI Materials Journal, v. 104, n. 4, p. 344, 2007.

LIN, Y.; LAI, C. P.; YEN, T. Prediction of ultrasonic pulse velocity (UPV) in concrete. Materials Journal, v. 100, n. 1, p. 21-28, 2003.

LORENZI, A., TISBIEREK, F. T., SILVA, L. C. P. Ultrasonic pulse velocity analysis in concrete specimens. In: IV Conferencia Panamericana de END, Buenos Aires. 2007.

MACHADO, M. D.; SHEHATA, L. D.; SHEHATA, I. A. E. M. Curvas de correlação para caracterizar concretos usados no Rio de Janeiro por meio de ensaios não destrutivos. RIEM-IBRACON Structures and Materials Journal, v. 2, n. 2, 2009.

MAHURE, N. V., VIJH, G. K., SHARMA, P., SIVAKUMAR, N., RATNAM, M. Correlation between pulse velocity and compressive strength of concrete. International Journal of Earth Sciences and Engineering, v. 4, n. 6, p. 871-874, 2011.

MALHOTRA V. M.; CARINO N. J. Nondestructive Testing of Concrete. 2. ed. London: American Society for Testing and Materials, 2004.

MARTÍNEZ, M. W.; TORRES, A. A. A.; JÁUREGUI, J. C., CHÁVEZ, G. H. L., ALONSO, G., E. M.; GRAFF, M., ARTEAGA, A. J. C. Predicting concrete compressive strength and modulus of rupture using different NDT techniques. Advances in Materials Science and Engineering, 2014.

MARTINS, D. G. Influência do tamanho do corpo de prova nos resultados de ensaios e módulo de deformação e resistência á Compressão e suas correlações para concretos produzidos em Goiânia-Go. Dissertação de Mestrado, Departamento de Engenharia Civil, Universidade Federal de Goiás. 2008.

MASI, A.; VONA, M. Experimental and numerical evaluation of the fundamental period of undamaged and damaged RC framed buildings. Bulletin of Earthquake Engineering, v. 8, n. 3, p. 643-656, 2010.

MEDEIROS, A. Aplicação do ultra-som na estimativa da profundidade de fendas superficiais e na avaliação da eficácia de injeções em elementos de concreto armado. Dissertação de Mestrado. Universidade Federal de Santa Catarina, p. 200. 2007.

MEDEIROS, A.; PADARATZ, I. J.; PINTO, R. C. A. Influência da Presença de Armaduras na Estimativa da Profundidade de Fissuras Superficiais em Concreto Armado através do Ultra-som. CONGRESSSO BRASILEIRO DO CONCRETO (COBRACON 2009), v. 51, 2009.

MEHTA, P. K.; MONTEIRO, P. J. M. Concreto. Microestrutura, propriedades e materiais. 2 ed. São Paulo: IBRACON, p. 751, 2014.

MLAKAR, P. F.; TRONE, J.; MADDEN, J. Ultrasonics in the heart of darkness. Concrete international, v. 20, n. 10, p. 36-38, 1998.

MOHAMAD, G., OBREGON, P., OLIVEIRA, M. J. D, TEMP, A.L. Métodos combinados para a avaliação da resistência de concretos. Revista Matéria, v. 20, n. 1, pp. 86-102, 2015.

MOHAMMED, T. U.; MAHMOOD, A. H. Effects of maximum aggregate size on UPV of brick aggregate concrete. Ultrasonics, v. 69, p. 129-136, 2016.

MOHAMMED, T. U.; RAHMAN, M. N. Effect of types of aggregate and sand-to-aggregate volume ratio on UPV in concrete. Construction and Building Materials, v. 125, p. 832-841, 2016.

MURATA, O; TATEYAMA, M.; TATSUOKA, F. Steep reinforced with a planar geotextile having a rigid facing. Fourth International Conference on Geotextiles, Geomembranes and Related Products, The Hauge, Netherlandas, V.1, p.122. 1990.

NAIK, T. R.; MALHOTRA, V. M.; POPOVICS, J. S. The ultrasonic pulse velocity method. In: Handbook on nondestructive testing of concrete. CRC Press. p. 182-200. 2003.

NEPOMUCENO, M. C. Ensaios não destrutivos em betão. Provas de Aptidão Pedagógica e Capacidade Científica, p. 469, 1999.

NETO, A. A. M.; HELENE, P. R L. Módulo de elasticidade: dosagem e avaliação de modelos de previsão do módulo de elasticidade de concretos. In: Congresso Brasileiro do Concreto, 44º, Belo Horizonte - MG. 2002.

NIK, A. S.; OMRAN, O. L. Estimation of compressive strength of self-compacted concrete with fibers consisting nano-SiO2 using ultrasonic pulse velocity. Construction and Building Materials, v. 44, p. 654-662, 2013.

OHDAIRA, E.; MASUZAWA, N. Water content and its effect on ultrasound propagation in concrete-the possibility of NDE. Ultrasonics, v. 38, n. 1-8, p. 546-552, 2000.

OLLIVIER, J. P.; MASO, J. C.; BOURDETTE, B. Interfacial transition zone in concrete. Advanced Cement Based Materials, v. 2, n. 1, p. 30-38, 1995.

PAIVA, M. A. C. Análise das propriedades mecânicas nas primeiras idades do concreto de lajes alveolares utilizando o ensaio de ultrassom. Tese de Doutorado. Universidade de São Paulo. 2017.

PALACIOS, M.P.G. Emprego de Ensaios Não Destrutivos e de Extração de Testemunhos na Avaliação da Resistência à Compressão do Concreto. Dissertação de Mestrado em Estruturas e Construção Civil, Departamento de Engenharia Civil e Ambiental, Universidade de Brasília, Brasília, DF, 165p. 2012.

PARDO, F.; PEREZ, E. Evaluación del efecto de las barras de refuerzo del concreto sobre las medidas de velocidad de pulso ultrasónico. Bucaramanga, Colombia, Universidad Industrial de Santander, p. 123, 2010.

PETRO JR, J. T.; KIM, J. Detection of delamination in concrete using ultrasonic pulse velocity test. Construction and Building Materials, v. 26, n. 1, p. 574-582, 2012.

PHILIPPIDIS, T. P.; AGGELIS, D. G. Experimental study of wave dispersion and attenuation in concrete. Ultrasonics, v. 43, n. 7, p. 584-595, 2005.

PLANÈS, T.; LAROSE, E. A review of ultrasonic Coda Wave Interferometry in concrete. Cement and Concrete Research, v. 53, p. 248-255, 2013.

POLIMENO, M. R.; ROSLELLI, I.; LUPRANO, V. A.; MONGELLI, M.; TATI, A.; DE CANIO, G. A. non-destructive testing methodology for damage assessment of reinforced concrete buildings after seismic events. Engineering Structures, v. 163, p. 122-136, 2018.

POPOVICS, J. S.; SONG, W.; ACHENBACH, J. D.; LEE, J. H.; ANDRE, R. F. One-sided stress wave velocity measurement in concrete. Journal of Engineering Mechanics, v. 124, n. 12, p. 1346-1353, 1998.

POPOVICS, J. S.; SONG, W.; GHANDEHARI, M.; SUBRAMANIAM, K.V.; ACHENBACH, J. D.; SHAH, S. P., Application of surface wave transmission measurements for crack depth determination in concrete. ACI Materials Journal, V97, N2, March-April 2000.

POPOVICS, S. Analysis of the concrete strength versus ultrasonic pulse velocity relationship. Materials Evaluation (USA), v. 59, n. 2, p. 123-124, 2001.

POPOVICS, S.; POPOVICS, J. S. A critique of the ultrasonic pulse velocity method for testing concrete. NDT and E International, v. 4, n. 30, p. 260, 1997.

PRADO, L.A., Módulo de deformação estático do concreto de Baixa e alta relação a/c pelo método ultrassônico,. Dissertação (Mestrado em Engenharia Civil) – Escola de Engenharia Civil Universidade Federal de Goiás, Goiânia, p. 226, 2006.

PUNCINOTI, R.; HINTERHOLZ, L.; D'ELIA, A.; De LOENZO, R. A. (Influence of steel reinforcement on ultrasonic pulses velocity. In: 4 th International Conference on NDT (11–14 octubre, Chania, Crete-Grecia), Italy. 2007.

QIXIAN, L.; BUNGEY, J. H. Using compression wave ultrasonic transducers to measure the velocity of surface waves and hence determine dynamic modulus of elasticity for concrete. Construction and building materials, v. 10, n. 4, p. 237-242, 1996.

RAMÍREZ, F. C. Detecção de danos em estruturas de concreto por meio de tomografia ultrassônica. Tese de Doutorado. Universidade de São Paulo. p.169, 2015.

REUNION INTERNATIONALE DE LABORATOIRES D'ESSAIS ET MATERIAUX. RILEM NDT 1. Testing of Concrete by the Ultrasonic Pulse Method. Paris, 1972.

RHEINHEIMER, V. Utilização de ensaios não destrutivos no controle tecnológico de execução de pavimentos de concreto tipo Fast Track. Dissertação de Mestrado em Engenharia Civil, Universidade Federal de Santa Catarina – UFSC. p.258, 2007.

ROBLES, O. J. C.; ZIEGLER, A. J. F. Evaluación de la influencia del acero de refuerzo en la aplicación de ensayo de velocidade de pulso ultrasónico en elementos de concreto armado. Trabajo Especial de Grado. Universidad Central de Venezuela. 2015.

ROCHA, A. I. C. B. Identificação de patologias em vigas de concreto armado utilizando inspeção por ultrassom Dissertação de Mestrado. UNICAMP-Universidade Estadual de Campinas. 2017.

RODRIGUES, G. S. S.; FIGUEIREDO, E. I. P. Módulo de deformação estático do concreto pelo método ultrassônico: Estudo da correlação. In: 46º Congresso Brasileiro do Concreto, Florianópolis, 2004. Anais. IBRACON, Florianópolis, p.1309-1324, 2004.

ROYER, D.; DIEULESAINT, E. Elastic waves in solids II: generation, acousto-optic interaction, applications. Springer Science & Business Media, 1996.

SAHMARAN, M.; YAMAN, I. O. Hybrid fiber reinforced self-compacting concrete with a high-volume coarse fly ash. Construction and Building Materials, v. 21, n. 1, p. 150-156, 2007.

SAHUINCO, C.; H., M. Utilização de métodos não destrutivos e semi-destrutivos na avaliação de pontes de concreto. Tese de Doutorado. Universidade de São Paulo. p.170, 2011.

SAINT-PIERRE, F.; PHILIBERT, A.; GIROUX, B.; RIVARD, P. Concrete quality designation based on ultrasonic pulse velocity. Construction and Building Materials, v. 125, p. 1022-1027, 2016.

SANTIAGO, W. C.; BECK, A. T. Estudo da (não-) conformidade de concretos produzidos no Brasil e sua influência na confiabilidade de pilares curtos. RIEM-IBRACON Structures and Materials Journal, v. 4, n. 4, 2011.

SAVALIYA, K. D.; THAKER, K. K.; DAVE, U. V. Comparison between different methods of ultrasonic pulse velocity tests on concrete. International Journal of Engineering Research and Applications (IJERA), ISSN, p. 2248-9622, 2014.

SCHMIDT, W.; KÜHNE, H. C.; LEINITZ, S. Concrete casting robustness improvement due to active rheology. In: MATEC Web of Conferences. EDP Sciences, 2018.

SHIOTANI, T.; AGGELIS, D. G.; MAKISHIMA, O. Global monitoring of large concrete structures using acoustic emission and ultrasonic techniques: case study. Journal of Bridge Engineering, v. 14, n. 3, p. 188-192, 2009.

SILVA, R. R. C. da; BONFIM, L. H. S. Análise do comportamento mecânico em concreto com diferentes adições de fibras através de propagação de onda de ultrassom. Exatas e Engenharia, v. 9, n. 25, 2019.

SILVA, R. R. C. da. Propagação de ondas de ultrassom em sistemas de contenção par obras de terra. Tese de Doutoradao. UNICAMP - Universidade Estadual de Campinas. p.113. 2020.

SMITH, A.; CHOTARD, T.; GIMET-BREAT, N., FARGEOT, D. Correlation between hydration mechanism and ultrasonic measurements in an aluminous cement: effect of setting time and temperature on the early hydration. Journal of the European Ceramic Society, v. 22, n. 12, p. 1947-1958, 2002.

SOARES, D.; BRITO, J., FERREIRA, J., PACHECO, J. In situ materials characterization of full-scale recycled aggregates concrete structures. Construction and Building Materials, v. 71, p. 237-245, 2014.

SOLÍS, R.; PEYRA, J. B. The influence of the physical properties of aggregates on the ultrasound pulse tecnique in predicting the compressive strength of concrete. Revista Técnica Ingeniería Universidad Zulia, v. 26, n. 1. 2003.

SOLIS-CARCAÑO, R. l.; MORENO, Eric I. Evaluation of concrete made with crushed limestone aggregate based on ultrasonic pulse velocity. Construction and Building Materials, v. 22, n. 6, p. 1225-1231, 2008.

TATARINOV, A.; RUMJANCEVS, A.; MIRONOVS, V. Assessment of cracks in pre-stressed concrete railway sleepers by ultrasonic testing. Procedia Computer Science, v. 149, p. 324-330, 2019.

TATSUOKA, F. Keynote lecture: Roles of facing rigidity in soil reinforcing. In: Ochiai, Hayashi & Otani (eds), Earth Reinforcement Practice, A. A. Balkema, Rotterdam, p. 831-870, 1993.

TOPCU, I. B.; CANBAZ, M. Effect of different fibers on the mechanical properties of concrete containing fly ash. Construction and Building Materials, v. 21, n. 7, p. 1486-1491, 2007.

TORGAL, F. P.; GOMES, J. P. C. Influence of physical and geometrical properties of granite and limestone aggregates on the durability of a C20/25 strength class concrete. Construction and Building Materials, v. 20, n. 10, p. 1079-1088, 2006.

TRTNIK, G.; KAVČIČ, F.; TURK, G. Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks. Ultrasonics, v. 49, n. 1, p. 53-60, 2009.

TURGUT, P. “Research into the correlation between concrete strength and UPV values”, J. Nondestruct. Test. V. 12. 2004.

TURGUT, P.; KUCUK, O. F. Comparative relationships of direct, indirect, and semi-direct ultrasonic pulse velocity measurements in concrete. Russian Journal of Nondestructive Testing, v. 42, n. 11, p. 745, 2006.

UDDIN, M. T.; HASAN, A. M. Effects of maximum aggregate size on UPV of brick aggregate concrete. Ultrasonics, v.69, p. 129–136, 2016.

VILLAIN, G.; GARNIER, V.; SBARTAI, Z. M.; DEROBERT, X.; BALAYSSAC, J. P. Development of a calibration methodology to improve the on-site non-destructive evaluation of concrete durability indicators. Materials and Structures, v. 51, n. 2, p. 40, 2018.

WATANABE, S.; HISHIKAWA, K.; KAMAE, K.; NAMIKI, S. Study on estimation of compressive strength of concrete in structure using ultrasonic method. Japan Architectural Review, v. 1, n. 1, p. 87-95, 2018.

YAMAN, I. O.; INCI, G.; YESILLER, N.; AKTAN, H. M. Ultrasonic pulse velocity in concrete using direct and indirect transmission. ACI Materials Journal, v. 98, n. 6, p. 450, 2001.

YE, G., LURA, P., BREUGEL, K., FRAAIJ, A. L. Ultrasonic in-situ monitoring of setting process of high-performance concrete. Cement and Concrete Research, v. 34, p. 631-640. (2004).

YILDIRIM, H.; SENGUL, O. Modulus of elasticity of substandard and normal concretes. Construction and Building Materials, v. 25, n. 4, p. 1645-1652, 2011.

YU, T.; CHAIX, J. F.; AUDIBERT, L.; KOMATITSCH, D.; GARNIER, V.; HENAULT, J. M. Simulations of propagation of ultrasonic waves in concrete based on a two-dimensional numerical model validated analytically and experimentally. Ultrasonics, 92, 21-34. 2019.

ZHANG, J.; FAN, T.; MA, H.; LI, Z. Monitoring setting and hardening of concrete by active acoustic method: effects of water-to-cement ratio and pozzolanic materials. Construction and Building Materials, v. 88, p. 118-125, 2015.