Evailton Arantes de Oliveira

Avaliação da Utilização de Aditivos em Betão Permeável Modificado, Estado do Amazonas, Brasil

Universidade Fernando Pessoa
Porto 2021

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Tese apresentada à Universidade Fernando Pessoa como parte dos requisitos para obtenção do grau de Doutor em Ecologia e Saúde Ambiental, sob a orientação da Professora Doutora Maria Alzira Pimenta Dinis e sob a coorientação da Professora Doutora Maria João Correia de Simas Guerreiro.

RESUMO

EVAILTON ARANTES DE OLIVEIRA: Avaliação da Utilização de Aditivos em Betão Permeável Modificado, Estado do Amazonas, Brasil.
(Sob orientação da Professora Doutora Maria Alzira Pimenta Dinis e sob a coorientação da Professora Doutora Maria João Correia de Simas Guerreiro)

A extensa malha de vias urbanas e interurbanas do Brasil tem aproximadamente 1.600.000 km, das quais cerca de 86 % apresentam a pista de circulação de veículos em solo natural, sem pavimentação. Esta ausência de pavimentação pode ser verificada também na Região Norte do Brasil, principalmente no estado do Amazonas, onde 70 % das vias urbanas e interurbanas da região não têm revestimento na zona de circulação de veículos. O transporte de pessoas, veículos e mercadorias torna-se difícil e, por vezes, até impossível, com consequentes impactes negativos ao meio ambiente e ao desenvolvimento económico.

O Governo do Brasil projetou a realização de obras de melhoramento de infraestruturas de transporte no estado do Amazonas, que incluem pavimentação nas vias urbanas e interurbanas para promover um transporte terrestre mais seguro e fiável. No entanto, os projetos de infraestrutura e de pavimentação utilizados atualmente são do tipo betão ou asfalto convencionais e não apresentam inovações tecnológicas que possam ir de encontro aos objetivos de desenvolvimento sustentável (ODS) preconizados pela Organização das Nações Unidas (ONU) na sua Agenda 2030.

O objetivo geral desta tese é apresentar uma alternativa ao pavimento convencional a ser aplicado em vias urbanas e/ou interurbanas no Amazonas, Brasil, de modo a contribuir para a proteção do meio ambiente de forma sustentável, perseguindo as propostas da ONU relativamente aos ODS, em particular o 9º ODS, i.e., desenvolver infraestruturas de qualidade, de confiança, sustentáveis e resilientes às alterações climáticas, incluindo infraestruturas regionais e transfronteiriças, para apoiar o desenvolvimento económico e o bem-estar humano, focando-se no acesso equitativo e a preços acessíveis para todos, e o 13º ODS, i.e., reforçar a sustentabilidade e a capacidade de adaptação a riscos relacionados com o clima e as catástrofes naturais no mundo.

Os objetivos específicos desta tese estão associados à avaliação das características do material proposto, tais como, permeabilidade, densidade, porosidade, resistência à compressão, deformação e captação de dióxido de carbono (CO_2). O material proposto é o betão permeável, composto por seixos rolados da região do Amazonas, em detrimento de brita importada e/ou com adição de borracha reciclada de pneus e/ou com inclusão de aditivos para eventual captura de CO_2 e/ou adição de agentes microbianos para controlo de macroinvertebrados transmissores de doenças tropicais comuns nesta região do mundo, como sejam a malária, febre amarela e dengue.

A metodologia utilizada para atingir os objetivos propostos residiu na produção de provetes de betão poroso com inclusão de diferentes aditivos com diferentes concentrações e/ou inclusão de resíduos de borracha de pneus. Os provetes foram submetidos a ensaios de compressão, avaliação de porosidade, densidade, permeabilidade, deformação e sequestração de CO_2. Os resultados destes ensaios foram objeto de análises estatísticas para determinação da melhor concentração e tipo de aditivo face ao objetivo de utilização do material para pavimentação.

Atingiu-se o objetivo geral e os específicos deste estudo, demonstrando uma contribuição para o aperfeiçoamento dos projetos de infraestrutura de pavimentação no Amazonas, Brasil, em harmonia com o 9º e 13º ODS da Agenda 2030 anteriormente mencionados, através da proposta de um novo material que atua como uma inovação tecnológica em infraestrutura face à sustentabilidade global, contribuindo ainda para a mitigação das emissões de CO_2 e apresentando ainda propriedades antimicrobianas, devido à utilização de aditivos como o hidróxido de cálcio ($Ca(OH)_2$).

Assim, o material proposto é considerado promissor quanto ao uso prático em vias urbanas, podendo também ser utilizado em acostamentos de tráfego leve de vias interurbanas, como demonstrado pela manifestação favorável do Departamento Nacional de Infraestrutura de Transportes (DNIT), que reconheceu a importância desta pesquisa como proposta que contribuirá para o êxito do licenciamento ambiental da obra de pavimentação da via interurbana BR-319, a principal via interurbana do estado do Amazonas, no Brasil.

ABSTRACT

EVAILTON ARANTES DE OLIVEIRA: Assessment of the Use of Additives in Modified Pervious Concrete, State of Amazonas, Brazil
(Under the supervision of Professor Maria Alzira Pimenta Dinis and under the co-supervision of Professor Maria João Correia de Simas Guerreiro)

The extensive network of urban and interurban roads in Brazil has approximately 1,600,000 km, of which around 86 % have a lane for vehicles on natural soil, without pavement. This lack of paving can also be seen in the Northern Region of Brazil, particularly in the state of Amazonas, where 70 % of urban and interurban roads in the region do not have paving in the vehicle circulation area. Transporting people, vehicles and goods becomes difficult and sometimes even impossible, with consequent negative impacts on the environment and economic development.

The Government of Brazil has planned to carry out transport infrastructure improvement works in the state of Amazonas, which include paving on urban and interurban roads to promote safer and more reliable land transport. However, the infrastructure and paving projects currently used are of the conventional concrete or asphalt type and do not present technological innovations that can meet the Goals of Sustainable Development (SDG) recommended by the United Nations (UN) in its Agenda 2030.

The general objective of this thesis is to present an alternative to conventional pavement to be applied on urban and/or interurban roads in Amazonas, Brazil, in order to contribute to the protection of the environment in a sustainable way, pursuing the UN proposals regarding the SDGs, in particular SDG 9, i.e., developing quality, reliable, sustainable and climate-resilient infrastructure, including regional and cross-border infrastructure, to support economic development and human well-being, focusing on equitable and affordable access accessible for all, and the SDG 13, i.e., strengthen sustainability and adaptability to climate-related risks and natural disasters in the world.

The specific objectives of this thesis are associated with the assessment of the characteristics of the proposed material, such as permeability, density, porosity, compressive strength, deformation and carbon dioxide (CO_2) uptake. The proposed material is pervious concrete, composed of rolled pebbles from the Amazon region, to the detriment of imported gravel and/or with the addition of recycled tire rubber and/or with the inclusion of additives for eventual CO_2 capture and/or addition of agents microbials to control macroinvertebrates that transmit tropical diseases common in this region of the world, such as malaria, yellow fever and dengue.

The methodology used to achieve the proposed objectives resided in the production of porous concrete specimens with the inclusion of different additives with different concentrations and/or inclusion of tire rubber residues. The specimens were submitted to compression tests, evaluation of porosity, density, permeability, deformation and CO_2 sequestration. The results of these tests were subject to statistical analysis to determine the best concentration and type of additive in view of the purpose of using the material for paving.

The general and specific objectives of this study were achieved, demonstrating a contribution to the improvement of paving infrastructure projects in Amazonas, Brazil, in harmony with the SDGs 9 and 13 of Agenda 2030 mentioned above, through the proposal of a new material that acts as a technological innovation in infrastructure in view of global sustainability, also contributing to the mitigation of CO_2 emissions and also presenting antimicrobial properties, due to the use of additives such as calcium hydroxide ($Ca(OH)_2$).

Thus, the proposed material is considered promising for practical use on urban roads, and it can also be used on the shoulders of light traffic on interurban roads, as demonstrated by the favorable opinion of the Department National of Transport Infrastructure (DNIT), which recognized the importance of this research as a proposal that will contribute to the success of the environmental licensing of the paving work on the interurban road BR-319, the main interurban road in the state of Amazonas, in Brazil.

RÉSUMÉ

EVAILTON ARANTES DE OLIVEIRA: Évaluation de l'Utilisation d'Additifs dans le Béton Perméable Modifié, État d'Amazonas, Brésil
(Sous la direction du Professeur Maria Alzira Pimenta Dinis et sous la Professeur Maria João Correia de Simas Guerreiro)

Le vaste réseau de routes urbaines et interurbaines du Brésil compte environ 1.600.000 km, dont environ 86 % ont une voie pour les véhicules sur sol naturel, sans chaussée. Ce manque de pavage peut également être observé dans la région nord du Brésil, en particulier dans l'État d'Amazonas, où 70 % des routes urbaines et interurbaines de la région n'ont pas de pavage dans la zone de circulation des véhicules. Le transport de personnes, de véhicules et de marchandises devient difficile et parfois même impossible, avec des impacts négatifs conséquents sur l'environnement et le développement économique.

Le gouvernement du Brésil a prévu de réaliser des travaux d'amélioration des infrastructures de transport dans l'État d'Amazonas, notamment le pavage des routes urbaines et interurbaines pour promouvoir des transports terrestres plus sûrs et plus fiables. Cependant, les projets d'infrastructures et de pavage sont actuellement utilisés du type conventionnel béton ou asphalte et des innovations technologiques non présentes pouvant répondre aux Objectifs de Développement Durable (ODD) recommandés par les Nations Unies (NU) dans son Agenda 2030.

L'objectif général de cette thèse est de présenter une alternative aux chaussées conventionnelles à appliquer sur les routes urbaines et/ou interurbaines en Amazonas, au Brésil, afin de contribuer à la protection de l'environnement de manière durable, en poursuivant les propositions de l'NU concernant la Les ODD, en particulier le 9^{e} ODD, c'est-à-dire le développement d'infrastructures de qualité, fiables, durables et résilientes au changement climatique, y compris les infrastructures régionales et transfrontalières, pour soutenir le développement économique et le bien-être humain, en mettant l'accent sur un accès équitable et abordable accessible aux tous, et le 13^{e} ODD, renforcer la durabilité et l'adaptabilité aux risques liés au climat et aux catastrophes naturelles dans le monde.

Les objectifs spécifiques de cette thèse sont associés à l'évaluation des caractéristiques du matériau proposé, telles que la perméabilité, la densité, la porosité, la résistance à la compression, la déformation et l'absorption de dioxyde de carbone (CO_2). Les matériaux proposés sont du béton perméable, composé de galets roulés de la région amazonienne, au détriment des graviers importés et/ou avec ajout de caoutchouc de pneu recyclé et/ou avec inclusion d'additifs pour un éventuel captage du CO_2 et/ou ajout d'agents microbiens pour lutter contre les macroinvertébrés qui transmettent des maladies tropicales courantes dans cette région du monde, comme le paludisme, la fièvre jaune et la dengue.

La méthodologie utilisée pour atteindre les objectifs proposés résidait dans la production d'éprouvettes de béton poreux avec l'inclusion de différents additifs avec différentes concentrations et/ou l'inclusion de résidus de caoutchouc de pneu. Les éprouvettes ont été soumises à des tests de compression, d'évaluation de la porosité, de la densité, de la perméabilité, de la déformation et de la séquestration du CO_2. Les résultats de ces tests ont été soumis à une analyse statistique pour déterminer la meilleure concentration et le meilleur type d'additif en vue de l'utilisation du matériau pour le pavage.

Les objectifs généraux et spécifiques de cette étude ont été atteints, démontrant une contribution à l'amélioration des projets d'infrastructure de pavage en Amazonas, au Brésil, en harmonie avec les 9^{e} et 13^{e} ODD de l'Agenda 2030 mentionnés précédemment, à travers la proposition d'un nouveau matériau qui agit comme un innovation dans les infrastructures dans une perspective de durabilité globale, contribuant également à l'atténuation des émissions de CO_2 et présentant également des propriétés antimicrobiennes, grâce à l'utilisation d'additifs tels que l'hydroxyde de calcium ($Ca(OH)_2$).

Ainsi, le matériel proposé est considéré comme prometteur pour une utilisation pratique sur les routes urbaines, et il peut également être utilisé sur les accotements de trafic léger sur les routes interurbaines, comme en témoigne l'avis favorable de la Département Nationale des Infrastructures de Transport (DNIT), l'importance de cette recherche en tant que proposition qui contribuera au succès de l'autorisation environnementale des travaux de pavage de la route interurbaine BR-319, la principale route interurbaine de l'État d'Amazonas, au Brésil.

DEDICATÓRIA

“A fé é o instinto da ação”
Fernando Pessoa

Dedico esta Tese ao meu pai Rosalvo e a minha mãe Maria que me deram a primeira educação e primeira fagulha de fé que me possibilitou alcançar este sonho.

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A

ASTM – *American **S**ociety for **T**esting and **M**aterials* (USA)

B

BPC – Betão **P**ermeável **C**onvencional

BPM – Betão **P**ermeável **M**odificado

C

CNT – **C**onfederação **N**acional de **T**ransportes (Brasil)

D

DNIT – **D**epartamento **N**acional de **I**nfraestrutura de **T**ransportes (Brasil)

IBGE – Instituto **B**rasileiro de **G**eografia **e E**statística (Brasil)

IPCC – ***I**ntergovernmental **P**anel on **C**limate **C**hange* (ONU)

IPAAM – **I**nstituto de **P**roteção **A**mbiental do **A**mazonas (Brasil)

O

ONU – Organização das **N**ações **U**nidas

OPAS – **O**rganização **P**an-**A**mericana da **S**aúde

U

UFP – Universidade **F**ernando **P**essoa (Portugal)

INTRODUÇÃO

A necessidade de investimentos em infraestrutura de pavimentação nas vias urbanas e interurbanas afeta principalmente os países menos desenvolvidos. A capacidade de realização de investimentos em infraestrutura de pavimentação é importante porque indica o nível de riqueza e desenvolvimento dos países, de acordo com o cálculo do produto interno bruto das nações (ONU, 2021b). A Figura 1 ilustra que 88 % das nações do mundo ainda necessitam de investimentos na infraestrutura de pavimentação.

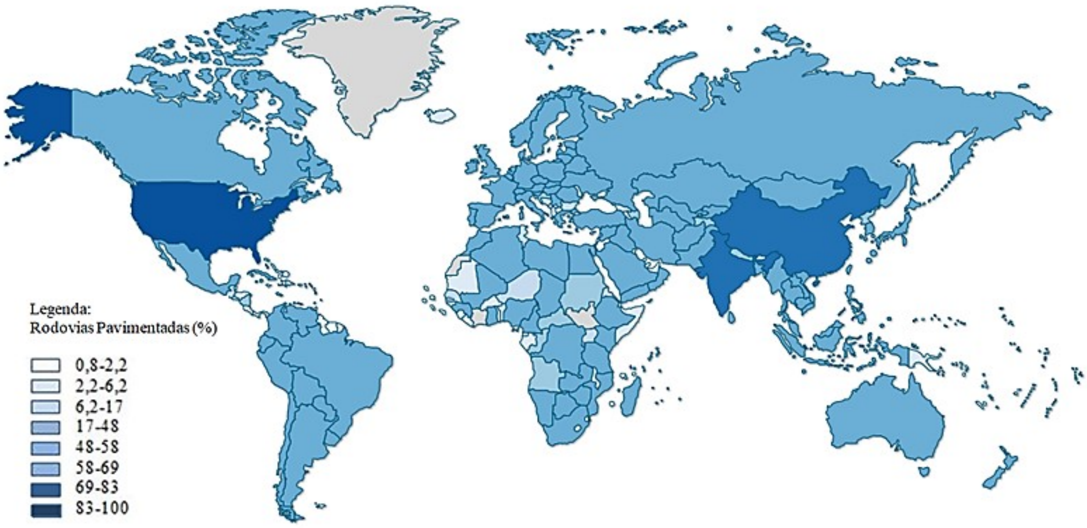


Figura 1. Extensão de pavimentação das vias urbanas e interurbanas dos países nos cinco continentes, adaptado de Nations Encyclopedia (2021).

Apenas 12 % das nações possuem mais de 83 % das vias urbanas e interurbanas pavimentadas, o restante dos países necessita da realização de obras de infraestrutura desta natureza. A União Europeia e América do Norte são locais que possuem a melhor qualidade de pavimentação, enquanto que África, Ásia, América Central, América do

Sul e Oceânia incluem países com a maior deficiência em pavimentação (Nations Encyclopedia, 2021). A área territorial de um país também influencia a qualidade da infraestrutura da pavimentação das vias urbanas e interurbanas, porque quanto maior é o território de um país mais investimentos deverão ser despendidos para obras de infraestrutura de pavimentação. Considere-se o exemplo da China, Canadá, Austrália e Brasil. Destaca-se que estas obras de infraestrutura de pavimentação devem conter inovações tecnológicas que tornem as infraestruturas ambientalmente sustentáveis, conforme acordado na Conferência das Nações Unidas, realizada em Nova York de 25 a 27 de setembro de 2015, durante a comemoração do septuagésimo aniversário da ONU, no qual foram anunciados os 17 Objetivos de Desenvolvimento Sustentável (ODS) da Agenda 2030 (2015) apresentados na Figura 2. Esta Conferência das Nações Unidas contou com a participação colaborativa de 193 representantes de países signatários para implementação da Agenda 2030, facto notório que demonstrou a importância mundial do evento. Nesta Conferência definiu-se o plano de ações para mitigação dos problemas socioambientais que afetam o planeta, nomeadamente a poluição atmosférica, extração abusiva dos recursos naturais não renováveis, geração desenfreada de resíduos que contaminam o meio ambiente, como a borracha dos pneus descartados da indústria automobilística, e a ausência de inovação nas infraestruturas que beneficiam o meio ambiente.

Figura 2. Os 17 Objetivos de Desenvolvimento Sustentável da Agenda 2030 (2015).

A ONU lançou um desafio para os representantes dos países signatários da Agenda 2030, relacionado ao cumprimento de 17 ODS. Os ODS encontram-se assim relacionados ao conceito de sustentabilidade que foi apresentado na Conferência das Nações Unidas sobre o Meio Ambiente Humano, em Estocolmo, no ano de 1972, como uma solução socioeconômica e ambiental que rege estratégias e ações em prol de suprir as demandas atuais da sociedade, sem comprometer as gerações futuras e o meio ambiente (ONU, 2021a). As boas práticas para sustentabilidade abrangem a adoção de modelos da Economia Circular que visam uma produção através da reutilização, reaproveitamento e reciclagem dos resíduos de outros materiais. A economia circular é uma economia que requer investimentos estratégicos em infraestrutura, através de uma política bem coordenada entre as partes interessadas em todos os setores privados e governamentais, visando essencialmente à integração de ciclos de redução, reutilização e reciclagem de materiais, com a finalidade de aumentar a vida útil dos materiais para preservação do meio ambiente de forma sustentável, sem o desperdício de preciosos recursos naturais não renováveis (Ddiba *et al.,* 2020, Boulding, 1966, Pearce e Turner, 1990, ECO, 2021).

Com a meta de cumprir os ODS traçados na Agenda 2030, o Brasil tem vindo a apoiar o desenvolvimento de inovações tecnológicas de infraestrutura de pavimentação que beneficiam o meio ambiente, através de investimentos no setor de infraestrutura de transportes. A importância destas inovações prende-se com a extensa malha de transporte terrestre, da ordem dos 1.600.000 km (Tabela 1), e a vasta frota de veículos de transporte de carga, composta por 2.879.080 caminhões que circulam nas vias urbanas e interurbanas do Brasil (CNT, 2021).

Tabela 1. Extensão da malha rodoviária no Brasil abrangendo vias pavimentadas e não pavimentadas, adaptado de CNT (2021).

Via Rodoviária	Via pavimentada (km)	Via não pavimentada (km)	Total (km)
Federal	64.177	9.307	73.484
Estaduais e Municipais	148.073	1.339.100	1.487.173
Total	212.250	1.348.407	1.560.657

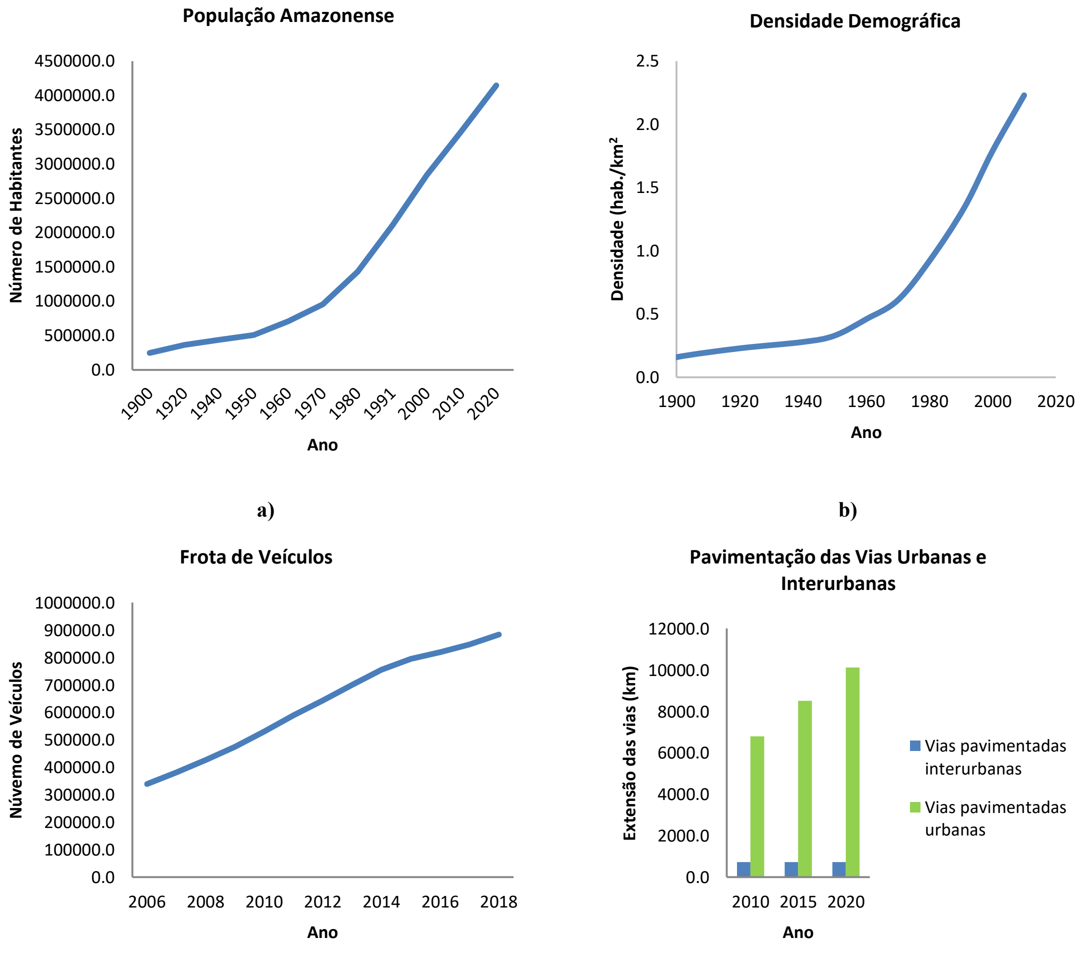
Os materiais privilegiados para pavimentação das infraestruturas rodoviárias são o asfalto e o betão. A fabricação destes materiais produz gases tóxicos poluentes e potencialmente cancerígenos, dióxido de azoto (NO_2) e o dióxido de enxofre (SO_2), no caso das usinas de asfalto (EPA, 2021a, EPA, 2021b). Se por um lado existem riscos potenciais para a saúde dos trabalhadores, para composição do asfalto ainda é utilizado o agregado de pedra calcária, denominada brita, escassa em certas regiões, como é o caso do estado do Amazonas (Maia *et al*., 2010).

Os pavimentos de betão ou asfalto convencionais contribuem para a impermeabilização do solo e, por consequência, para uma maior intensidade e frequência das inundações sazonais (Perrone e Souza, 2019). A produção do asfalto ou betão utiliza a areia como material agregado, um recurso natural não renovável. A extração desordenada de areia de rios compromete a disponibilidade deste recurso no futuro e causa impactes ambientais negativos, como a supressão da vegetação, alteração da qualidade das águas, alteração topográfica, alteração da rede hidrográfica, geração de resíduos sólidos, geração de efluentes líquidos, emissão de CO_2, geração de poeira, geração de ruídos, vibrações, aumento da erosão do solo, assoreamento, deslocamento da fauna, alteração do ecossistema aquático e impacte visual (Silva, 2005, Oliveira, 2020, Ramadon, 2016). A produção de asfalto afeta a qualidade do ar porque as usinas de fabricação de asfalto emitem até 96 t CO_2/mês para a atmosfera (Toledo *et al.*, 2017). Estas emissões das usinas de asfalto são preocupantes e tornam cada vez mais importante a inovação tecnológica de infraestrutura de pavimentação que envolvem processos de sequestração do CO_2 da atmosfera, em linha com as recomendações do IPCC (2020), para minimização da emissão do CO_2 (Vieira *et al.*, 2020).

O Amazonas é um estado com uma área de 1,57 milhões de km², com acesso geográfico terrestre dificultado pela Floresta Amazônica. O estado do Amazonas é conectado ao restante do Brasil através de uma única rodovia, a BR-319, que interliga a cidade de Manaus à cidade de Porto Velho, não pavimentada e com difícil trânsito de veículos durante o inverno amazônico, devido às constantes precipitações. Com uma população estimada de 4.144.597 habitantes (IBGE, 2019), o estado do Amazonas está totalmente inserido na Área Protegida da Amazônia (Figura 3), com restrições quanto à implantação de novas infraestruturas através do controlo do licenciamento ambiental (Lei 3219, 2007).

Figura 3. Localização do estado do Amazonas, Brasil, com coordenadas geográficas na Latitude de 2º08’30”N e 9º49’00’S e na Longitude 56º04’50” e 73º48’46”, adaptado do Google Maps (2021).

No ano de 1960 a população do estado do Amazonas, Brasil, era de 708.459 habitantes e representava uma densidade de 0,5 habitantes/km^2 (IBGE, 2019). Desde então, a população aumentou 585 % e a densidade demográfica cresceu 446 % (IBGE, 2019), devido a uma política de ocupação que vem sendo realizada pelo Governo Brasileiro, que foi intensificada na década de 1960 (Becker, 2001), conforme Figura 4b).



a) b)

c) d)

Figura 4. Pavimentação das vias urbanas e interurbanas *versus* a evolução da população, densidade demográfica e frota de veículos no estado do Amazonas, Brasil. **a)** Crescimento populacional entre 1900 a 2020, adaptado do IBGE (2019); **b)** Aumento da densidade demográfica entre 1900 a 2010, adaptado do IBGE (2019); **c)** Evolução da frota de veículos entre 2006 a 2018, adaptado do IBGE (2018); **d)** Estagnação da pavimentação das vias interurbanas e o aumento a uma taxa de 4,8 % ao ano da pavimentação urbana no estado do Amazonas, Brasil, entre 2010 a 2020, adaptado do DNIT (2021a) e da SEINFRA (2021).

A Figura 4a) apresenta o crescimento populacional no estado do Amazonas, Brasil, no período de 2000 a 2010, de 22 % (IBGE, 2019). A densidade demográfica ilustrada na Figura 4b), também, demonstra um aumento em torno de 22 % no mesmo período de 2000 a 2010 (IBGE, 2019). A consequência direta do aumento da população e da densidade demográfica está demonstrada na Figura 4c), o qual se traduz na evolução da frota de veículos motorizados em 56 %, no período de 2006 a 2010 (IBGE, 2018). Observa-se esta tendência progressiva de aumento gradual da população, densidade demográfica e frota de veículos, sendo que as obras de infraestrutura de pavimentação interurbanas estão estagnadas nos últimos 10 anos, período de 2010 a

2020 (Figura 4d) (DNIT, 2021a). A pavimentação da infraestrutura urbana aumentou 4,8 % ao ano, no período de 2010 a 2020 (SEINFRA, 2021), mas este aumento da pavimentação da infraestrutura urbana não supre a necessidade da população, em constante crescimento no estado do Amazonas, Brasil.

A principal obra de infraestrutura de pavimentação no estado do Amazonas, Brasil, é a execução da primeira etapa da pavimentação da rodovia federal BR-319, no trecho compreendido do km 250,0 até o km 655,7 com o custo de € 230.556.929,00, aprovado na Lei de Diretrizes Orçamentárias para o ano de 2021 (LDO, 2021). A via interurbana BR-319 está ilustrada no mapa da Figura 5.

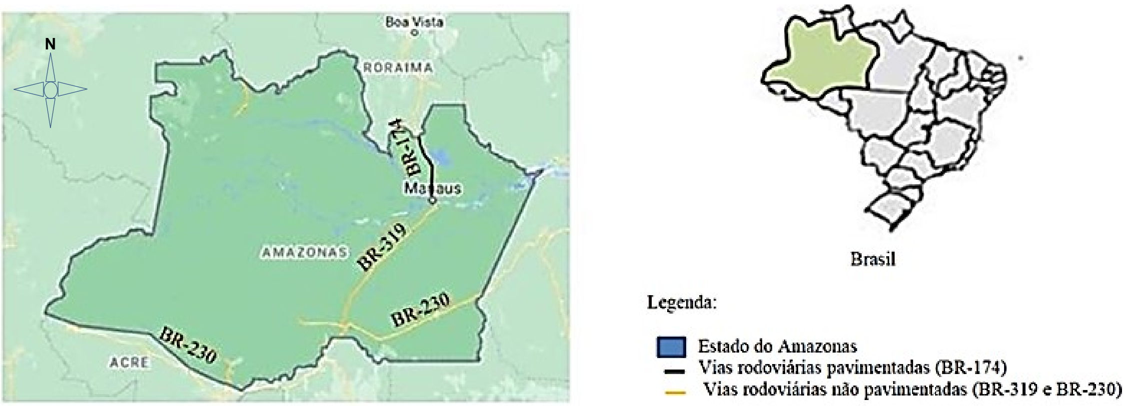


Figura 5. Vias rodoviárias do estado do Amazonas, Brasil, do ano de 2020, com 1.644 km de vias rodoviárias não pavimentadas na BR-319 e BR-230, adaptado do DNIT (2021a).

Na última década, o Governo brasileiro contratou projetos de infraestrutura de pavimentação para atender à procura no estado do Amazonas para o progresso no setor de transportes de pessoas e mercadorias, com o intuito de alavancar o desenvolvimento económico da região através da melhoria da qualidade do trânsito de veículos nas vias urbanas e interurbanas (DNIT, 2020). Entretanto, o problema reside no facto destes projetos de infraestrutura de pavimentação utilizarem equipamentos de produção de asfalto que podem emitir até 3,2 t CO_2/dia (Toledo *et al.*, 2017) e operarem com extração de recursos naturais de forma contrária à economia circular, isto é, uma extração contínua, que não faz uso ou reutilização de resíduos, sem possibilidade de reciclagem da matéria-prima, devido a um consumo descontrolado de recursos que prejudica a natureza e compromete as gerações futuras (Lin, 2020). Os projetos de infraestrutura de pavimentação que foram contratados pelo Governo do Brasil não levam em consideração a meta de limitação de emissão de CO_2 até o ano de

2030, o que dificulta o Brasil a alcançar os objetivos previstos de redução de emissões de CO_2 em relação à Agenda 2030 (Agenda 2030, 2015), inclusive a redução de 37 % das emissões de gases do efeito estufa até o ano 2025 (UNFCCC, 2020), definidos no Acordo de Paris (2015). O Brasil possui uma meta para limitar a emissão em 1.208 milhões de t CO_2 até o ano de 2030, atendendo ao 13º ODS, o que corresponde a uma redução de 58 % das emissões do ano de 2020, cerca de 2.068 milhões t CO_2. Destas emissões de CO_2 no ano de 2020, os processos industriais correspondem a 7 % do total de emissões, estando inseridas nestes processos as usinas de asfalto e betão do Brasil (IPEA, 2019), utilizadas nos atuais projetos de infraestrutura de pavimentação. Estes projetos de infraestrutura de pavimentação não trazem inovações tecnológicas que contribuam para a sustentabilidade, porque ainda utilizam as técnicas arcaicas de pavimentação com os tradicionais pavimentos betuminosos. Assim, os projetos de infraestrutura de pavimentação contratados pelo Governo Brasileiro precisam ser atualizados, para que se enquadrem nas boas práticas dos modelos vigentes de economia circular, quanto à reciclagem, reutilização e reaproveitamento dos resíduos de outros materiais.

O objetivo geral desta tese é apresentar uma alternativa ao pavimento convencional, a ser aplicado em vias urbanas e/ou interurbanas, de modo a contribuir para a proteção do meio ambiente de modo sustentável, perseguindo as propostas da ONU quanto à melhoria da qualidade do ar previstas nos ODS 9º e 13º, e ilustrado na Figura 6.

Figura 6. Sequestração do CO_2 pelo betão permeável modificado (BPM), constituído por seixos nativos que podem ser reciclados, adaptado da Plataforma Agenda 2030 Brasil (2021).

O BPM utiliza agregados de seixos e brita nativos da região, um facto que contribui para facilitação da rastreabilidade destes materiais pela fiscalização da extração no meio ambiente destes recursos naturais (Silva, 2005, Oliveira, 2020). Este material é produzido a partir do Betão Permeável Convencional (BPC). Os conceitos de betão permeável coincidem quanto à composição básica do material, conjunto de agregados aglutinados pelo cimento com uma estrutura interna porosa (Taheri *et. al*., 2020, Hu *et al*., 2020, Lederle *et al*., 2020). Alguns estudos consideram o betão permeável um material ecológico (Shen *et al*., 2020, Liu *et al*., 2020) e outros estudos consideram o betão permeável sustentável (Ibrahim *et al*., 2020), ou um material concomitantemente ecológico e sustentável (Barisic *et al*., 2020). O BPC pode ser modificado através de aditivos que alteram as suas propriedades de resistência mecânica à compressão, porosidade, densidade, permeabilidade, deformação e sequestração de CO_2 (**de Oliveira** *et al*., 2020), sem comprometer, contudo, a sua aplicabilidade prática.

O BPM pode incluir diferentes tipos de aditivos combinados de formas diferentes, como superplastificantes (Ghafoori e Dutta, 1995), pó de sílica ativa, acetato de vinil, formaldeído (Yang e Jiang, 2003), látex, fibra de polipropileno (Huang *et al*., 2010), pó de sílica ativa (Lian e Zhuge, 2010), pó de sílica ativa (Chandrappa e Biligiri, 2016), óxido de titânio (TiO_2) (Barnhouse e Srubar III, 2016), fibra de cloreto de magnésio (Zhong e Wille, 2018), fibra de polipropileno, borracha, pó de sílica ativa e látex (Aliabdo *et al*., 2018). Os aditivos óxido de cálcio (CaO) e hidróxido de cálcio ($Ca(OH)_2$) foram escolhidos para estudo nesta pesquisa porque integram a reação química da carbonatação (Haselbach e Thomle, 2014). A carbonatação realiza sequestração de CO_2, durante a produção do carbonato de cálcio ($CaCO_3$), conforme os estudos de Florin e Fennel (2011), Benitez-Guerrero *et al.* (2018), Jamrunroj *et al.* (2019) e Gao *et al.* (2020). O BPM com aditivo de $Ca(OH)_2$ possui capacidade de sequestração de CO_2 ao longo do tempo (Rahmani e Montazer, 2019).

Os estudos apresentados por **de Oliveira** *et al.* (2019b) demonstraram que o BPM é promissor para utilização de aditivos de resíduos de borracha de pneus descartados, na proporção de até 5 % na mistura de fabricação do BPM. A reutilização de resíduos de materiais de difícil degradação na natureza, como a borracha de pneus, contribui para a sustentabilidade BPM, conforme os estudos de Boon *et al.* (2017) e de Onuaguluchi e Banthia (2019). As experiências realizadas permitiram avaliar o comportamento do BPM quanto ao uso dos aditivos CaO, $Ca(OH)_2$ e resíduos de borracha de pneus descartados, na busca pelos quatro objetivos específicos justificados e enquadrados a seguir.

i. Contribuição do BPM para a mitigação das emissões de CO_2

A porosidade do BPM favorece a penetração de CO_2 na estrutura interna do mesmo, o que favorece a reação química de carbonatação do cimento existente no BPM (Haselbach e Thomle, 2014). A carbonatação do cimento (EN 16757/2017) é um fenômeno químico que absorve CO_2 para produção de $CaCO_3$ (Andrade, 2020). Esta sequestração de CO_2 pela carbonatação no interior da estrutura do BPM está em harmonia com o 13º ODS (Agenda 2030, 2015). Este fenômeno químico de sequestração de CO_2 pela carbonatação do cimento no interior do betão permeável está em estudo na China quanto a utilização em uma futura cidade esponja que absorve CO_2 da atmosfera (Shen *et al.,* 2020). No Reino Unido as pesquisas sobre a carbonatação e a calcinação do CaO e sua forma hidratada $Ca(OH)_2$ foram promissoras quanto à sequestração de CO_2 pela tecnologia *Direct Air Capture* (Erans *et al*., 2020, Erans *et al.*, 2019). Na União Europeia, especificamente na Espanha, estudos determinaram graus de carbonatação e sequestração de CO_2 pelo cimento (Andrade, 2020, Wang *et al.*, 2019, Huntzinger *et al*., 2009), componente ligante dos agregados do BPM.

ii. Contribuição da permeabilidade do BPM para redução do volume das inundações

O BPM é um pavimento permeável que permite a passagem de água da sua superfície para o lençol freático. Esta permeabilidade reduz o volume de inundações provocadas por intensas precipitações pluviais que escoam na superfície do pavimento de vias urbanas. Além disso, também mitiga o escoamento superficial nos acostamentos e dispositivos de drenagem das vias interurbanas (Xie *et al*., 2020). A porosidade do BPM contribui para a redução do escoamento superficial responsável por inundações (Vieira *et al*., 2020, **de Oliveira** *et al*., 2018a, **de Oliveira** *et al*., 2018b, **de Oliveira** *et al*., 2019c).

iii. Utilização de materiais reciclados de borracha de pneus descartados no BMP

O pavimento de BPM é poroso e pode ser fabricado com agregados de resíduos da construção civil reciclados, mantendo suas propriedades hidráulicas de permeabilidade e de porosidade (Ibrahim *et al*., 2020). O BPM proposto neste estudo utiliza materiais originados no próprio estado do Amazonas, ao custo médio de €130,00/m^3, valores de 2019, enquanto que ao se utilizar brita importada o custo pode triplicar (SINAPI, 2020). Este aumento no custo de produção do BPM é provocado pelo valor do frete de transporte de mercadorias no estado do Amazonas, que alcançou em 2015 valores até 546 % mais elevados que em outras regiões do Brasil, devido à dificuldade no transporte terrestre no estado do Amazonas, causada pela precariedade na zona de circulação de veículos das vias interurbanas sem pavimentação (GuiaTRC, 2021). O BPM pode utilizar resíduos de borracha de pneus descartados da indústria automobilística. A produção de pneus é preocupante no contexto ecológico e ambiental, porque o tempo de decomposição na produção de um resíduo de borracha da indústria automobilística pode chegar a 600 anos e a produção de pneus está a aumentar gradualmente ao longo dos anos em todo o mundo (Hejna *et al*., 2020). Os estudos para reutilização de borracha de pneus descartados como aditivo no BPM apontaram para uma promissora aplicação prática futura do BPM como um novo material que poderá a vir ser utilizado num modelo de economia circular que utiliza o ciclo utilização-reciclagem-utilização para geração de emprego e desenvolvimento de uma economia sustentável (Parchomenko *et al*., 2020, Xu *et al*., 2020, Nandi *et al*., 2020).

iv. Contribuição do BMP para o controlo da reprodução de insetos transmissores de doenças tropicais

O estado da arte na pesquisa de novos materiais de construção para estruturas e pavimentos abrange a avaliação de impactes destes novos materiais em organismos vivos, considerando as propriedades antimicrobianas e toxicológicas de aditivos utilizados na produção de novos materiais (Augustyniak et al., 2020). Os agentes biocidas adicionados na mistura do cimento possibilitam a fabricação de edifícios e pavimentos com propriedades antimicrobianas (Travush *et al*., 2017). Materiais biocidas aditivados ao cimento contribuem para a desinfeção de estruturas afetadas por agentes microbianos, típicos de climas quentes e húmidos, que prejudicam a saúde humana e causam a deterioração precoce do betão (Grishina, 2020). Estudos demonstraram que o $Ca(OH)_2$ em contato com a água causa efeitos antimicrobianos que contribuem para a esterilização do ambiente (Mori *et al.*, 2019). A utilização de aditivos de CaO e $Ca(OH)_2$ na mistura de fabricação do BPM tem como finalidade um pavimento antimicrobiano que contribua para o controlo das larvas de macroinvertebrados transmissores de doenças tropicais, depositadas por estes insetos em superfícies húmidas durante o período das precipitações pluviais (**de Oliveira** *et al.*, 2021). Destaca-se a importância do controlo das larvas de macroinvertebrados transmissores de doenças tropicais, como é o caso do Amazonas, no Brasil. Em 2017, as fêmeas do gênero *Anopheles*, que transmitem a malária, afetaram 90 países e territórios, com 70 % dos óbitos representados por crianças com menos de 5 anos de idade (OPAS, 2021).

Além da proposta de utilização do BPM como contribuição para a redução dos macroinvertebrados, procurou-se ao longo dos estudos a criação de uma inovação tecnológica na área de infraestrutura de pavimentação no Amazonas, Brasil, através da realização dos experimentos apresentados nos capítulos desta tese.

A organização desta tese contemplou assim cinco capítulos, respeitantes a parte das publicações alcançadas ao longo do doutoramento, visando atender ao objetivo geral e aos objetivos específicos estabelecidos.

O primeiro capítulo integra a investigação com o título "*New Pervious Concrete Construction Material for Carbon Dioxide Sequestration*", publicado na revista *Encyclopedia of the UN Sustainable Development Goals*, *Sustainable Cities and Communities, 6(3), 2019, 473-482*. Este estudo contemplou a pesquisa para alcançar os objetivos específicos **i** e **ii**, os quais se relacionam com um novo material que pode ser utilizado nos projetos de pavimentação de vias urbanas, com benefício ambiental de sequestração de CO_2.

O segundo capítulo contempla o artigo com o título "*Environmental Implications of pH in a Pervious Concrete Pavement on Highway BR-319, Amazonas, Brazil*", publicado na revista *Current World Environment, 13(2), 2018, 187-193.* Este artigo apresentou a investigação para atingir os objetivos específicos **i** e **ii**, porém, desta vez, os estudos avançaram para a possibilidade de uma utilização prática material proposto em uma via interurbana, a rodovia BR-319. O Departamento Nacional de Infraestrutura de Transportes (DNIT) aprovou a utilização do material proposto na pavimentação de acostamentos para tráfego leve, em substituição do pavimento tradicional de betão ou asfalto convencionais da BR-319, nos trechos do km 250,0 até o km 655,7, localizada no estado do Amazonas, Brasil. A validação foi oficializada na manifestação favorável do DNIT contida no OFÍCIO Nº 145346/2020/NAA - AM/SRE - AM, datado de 02/12/2020, da Superintendência Regional do DNIT no estado do Amazonas, Brasil (DNIT, 2021b).

O terceiro capítulo abrange o artigo com o título "*Comparative Statistical Analysis New Urban Road Pavement versus Conventional Pavement of Pervious Concrete*", apresentado na *1ª Conference Environmental Innovations: Advances in Engineering, Technology and Management, EIAETM, 23th-27rd September,* publicado na revista *Procedia Environmental Science, Engineering and Management, 6(3), 2019, 473-482,* e contempla os estudos realizados na investigação para alcançar do objetivo específico **iii**, assentando nas comparações estatísticas entre as amostras de dois grupos de pavimentos porosos, o novo material e o betão permeável convencional.

O quarto capítulo engloba o artigo com o título "*Environmental Implications of CO_2 Absorption by Pervious Concrete Pavement in Urban Roads*", publicado nos anuários do *XIII International Conference on Virtual City and Territory: "Challenges and paradigms of the contemporary city". UPC, Barcelona, 2th-4rd October, 2019*, CPSV, p. 8425. Este artigo compila os estudos realizados na busca contínua pelo alcance dos objetivos específicos **i**, **ii** e **iii**, com ênfase da utilização do novo material em vias urbanas, devido aos benefícios ambientais da mitigação das emissões de CO_2. O capítulo quarto, também, inclui os estudos para adição de resíduos de borracha de pneus descartados na mistura do novo material, através da reciclagem.

O quinto capítulo inclui o artigo intitulado "*A new microbicidal pervious concrete pavement for hospital parking lots: assesment of the modulus of elasticity*", apresentado na *2ª Conference Environmental Innovations: Advances in Engineering,* *Technology and Management, EIAETM, 23th-27rd September, 2020,* publicado na revista *Procedia Environmental Science, Engineering and Management, 8(2), 2021, 335-345,* o qual diz respeito à investigação para alcançar o objetivo específico **iv**, através dos estudos da avaliação do comportamento do material proposto, BPM com aditivo $Ca(OH)_2$, como pavimento de estacionamento de hospitais, considerando as propriedades físicas de resistência à compressão, densidade e módulo de Young.

Os estudos englobados nos cinco capítulos desta tese demonstraram uma contribuição para o aperfeiçoamento dos projetos de infraestrutura de pavimentação no Amazonas, Brasil, através da proposta de utilização do BPM como uma inovação tecnológica em infraestrutura, contribuindo para a mitigação das emissões de CO_2. Este novo pavimento poroso contribui para a sustentabilidade por meio da reutilização da borracha de pneus descartados e reciclagem de agregados podendo ainda ter propriedades microbianas.

Deve realçar-se que os estudos para uso em vias interurbanas propostos no segundo capítulo obtiveram uma manifestação favorável pelo DNIT, para uso em acostamentos de tráfego leve, reconhecendo assim a importância dos estudos realizados nesta tese, como uma proposta viável que contribuirá para o licenciamento ambiental da obra de pavimentação da via interurbana BR-319, no estado do Amazonas, Brasil (DNIT, 2021b). Este reconhecimento constitui uma validação do trabalho realizado nesta tese de doutoramento, o qual sempre perseguiu a criação de um material alternativo para os pavimentos convencionais de vias urbanas, estacionamentos e acostamentos de vias interurbanas com baixa capacidade de tráfego. O novo pavimento desenvolvido nesta pesquisa pode ser utilizado numa futura economia circular a ser implantada no Brasil, integrando os ciclos de pavimentação de vias urbanas e interurbanas a materiais sustentáveis, através da criação de uma cadeia de produção que utilize resíduos de borracha de pneus descartados na fabricação de pavimentos sustentáveis de vias urbanas.

CAPÍTULO I – Novo Material de Construção de Betão Permeável para Sequestração de Dióxido de Carbono

Este capítulo trata dos ensaios de densidade (ASTM C-127, 2015), de compressão axial (ASTM C-39, 2018) e monitoramento de volume de CO_2, metodologia proposta em **de Oliveira *et al*.** (2019b), realizados em 30 corpos de prova do BPM com aditivo de $Ca(OH)_2$, com fator água/cimento de 0,3, divididos em 3 grupos com as composições 1:0,3:4 (cimento:$Ca(OH)_2$:seixo), 1:0,5:4 (cimento:$Ca(OH)_2$:seixo) e 1:0,8:4 (cimento: $Ca(OH)_2$:seixo). Os resultados foram utilizados na elaboração de 9 protótipos virtuais no *software* de elementos finitos ANSYS R1 2019, para realização de simulações virtuais do comportamento estrutural com cargas dinâmicas de 5.000 N. A avaliação dos resultados da inclusão do aditivo $Ca(OH)_2$ através da análise estatística de inferência, permitiu concluir que este novo material pode ser utilizado em pavimentos de vias urbanas de baixo tráfego, estacionamentos, calçadas e parques, com benefício ambiental de sequestro de CO_2.

Nesta publicação, o primeiro autor participou no desenvolvimento da metodologia, investigação, recolha de dados e na escrita do manuscrito. A citação completa da publicação encontra-se apresentada a seguir:

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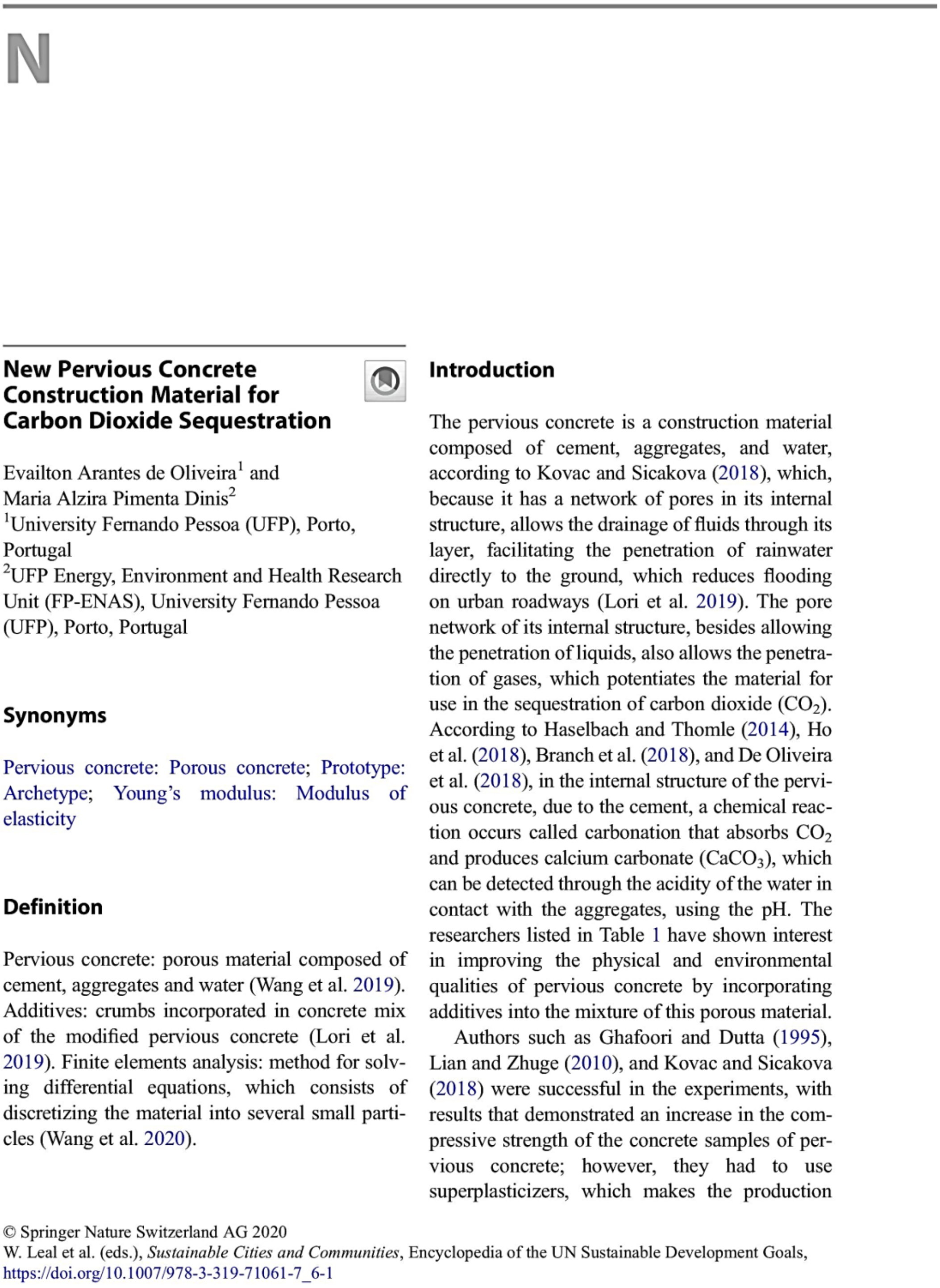

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New Pervious Concrete Construction Material for Carbon Dioxide Sequestration

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Synonyms

Pervious concrete: Porous concrete; Prototype: Archetype; Young's modulus: Modulus of elasticity

Definition

Pervious concrete: porous material composed of cement, aggregates and water (Wang et al. 2019). Additives: crumbs incorporated in concrete mix of the modified pervious concrete (Lori et al. 2019). Finite elements analysis: method for solving differential equations, which consists of discretizing the material into several small particles (Wang et al. 2020).

Introduction

The pervious concrete is a construction material composed of cement, aggregates, and water, according to Kovac and Sicakova (2018), which, because it has a network of pores in its internal structure, allows the drainage of fluids through its layer, facilitating the penetration of rainwater directly to the ground, which reduces flooding on urban roadways (Lori et al. 2019). The pore network of its internal structure, besides allowing the penetration of liquids, also allows the penetration of gases, which potentiates the material for use in the sequestration of carbon dioxide (CO_2). According to Haselbach and Thomle (2014), Ho et al. (2018), Branch et al. (2018), and De Oliveira et al. (2018), in the internal structure of the pervious concrete, due to the cement, a chemical reaction occurs called carbonation that absorbs CO_2 and produces calcium carbonate ($CaCO_3$), which can be detected through the acidity of the water in contact with the aggregates, using the pH. The researchers listed in Table 1 have shown interest in improving the physical and environmental qualities of pervious concrete by incorporating additives into the mixture of this porous material.

Authors such as Ghafoori and Dutta (1995), Lian and Zhuge (2010), and Kovac and Sicakova (2018) were successful in the experiments, with results that demonstrated an increase in the compressive strength of the concrete samples of pervious concrete; however, they had to use superplasticizers, which makes the production

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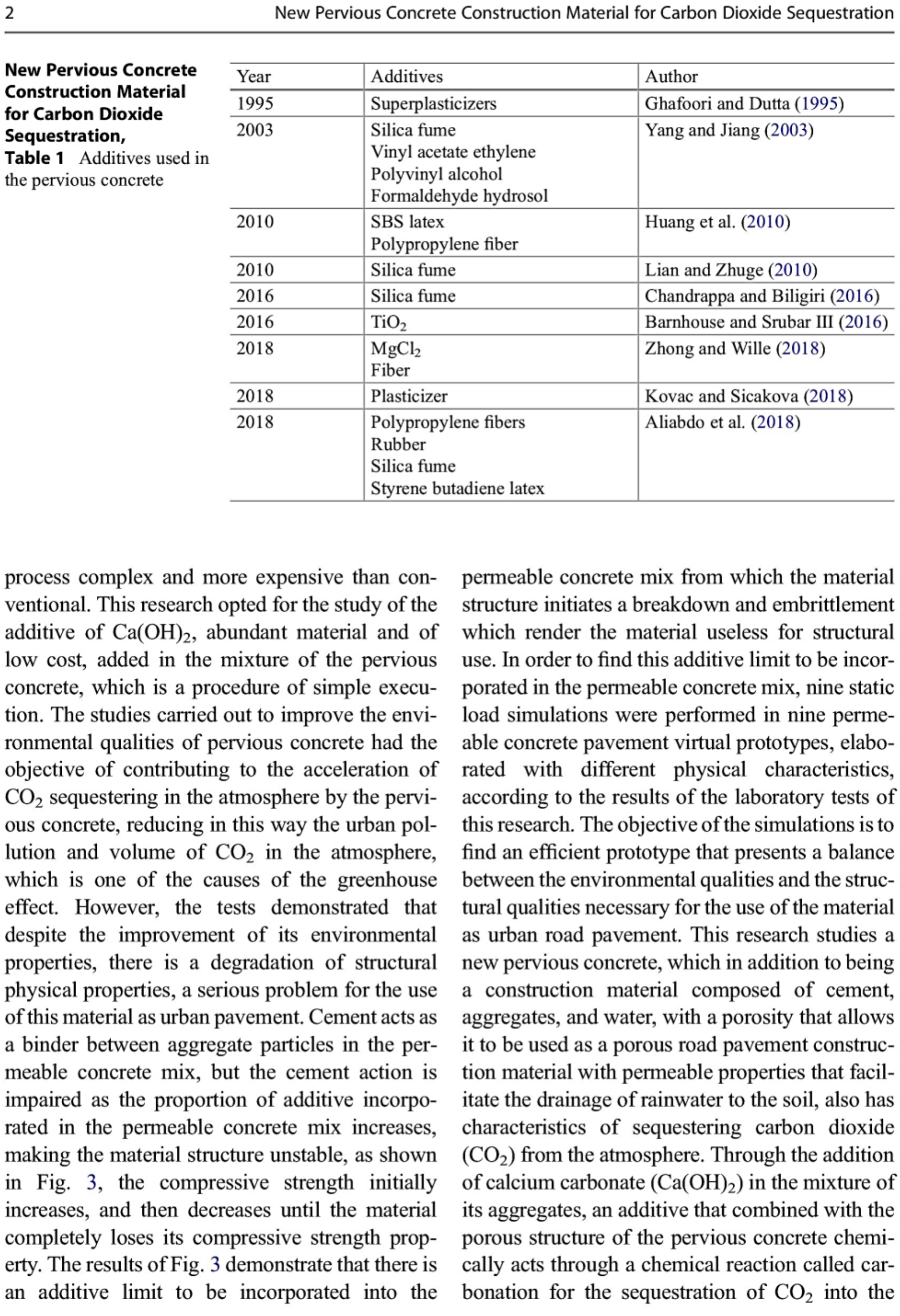
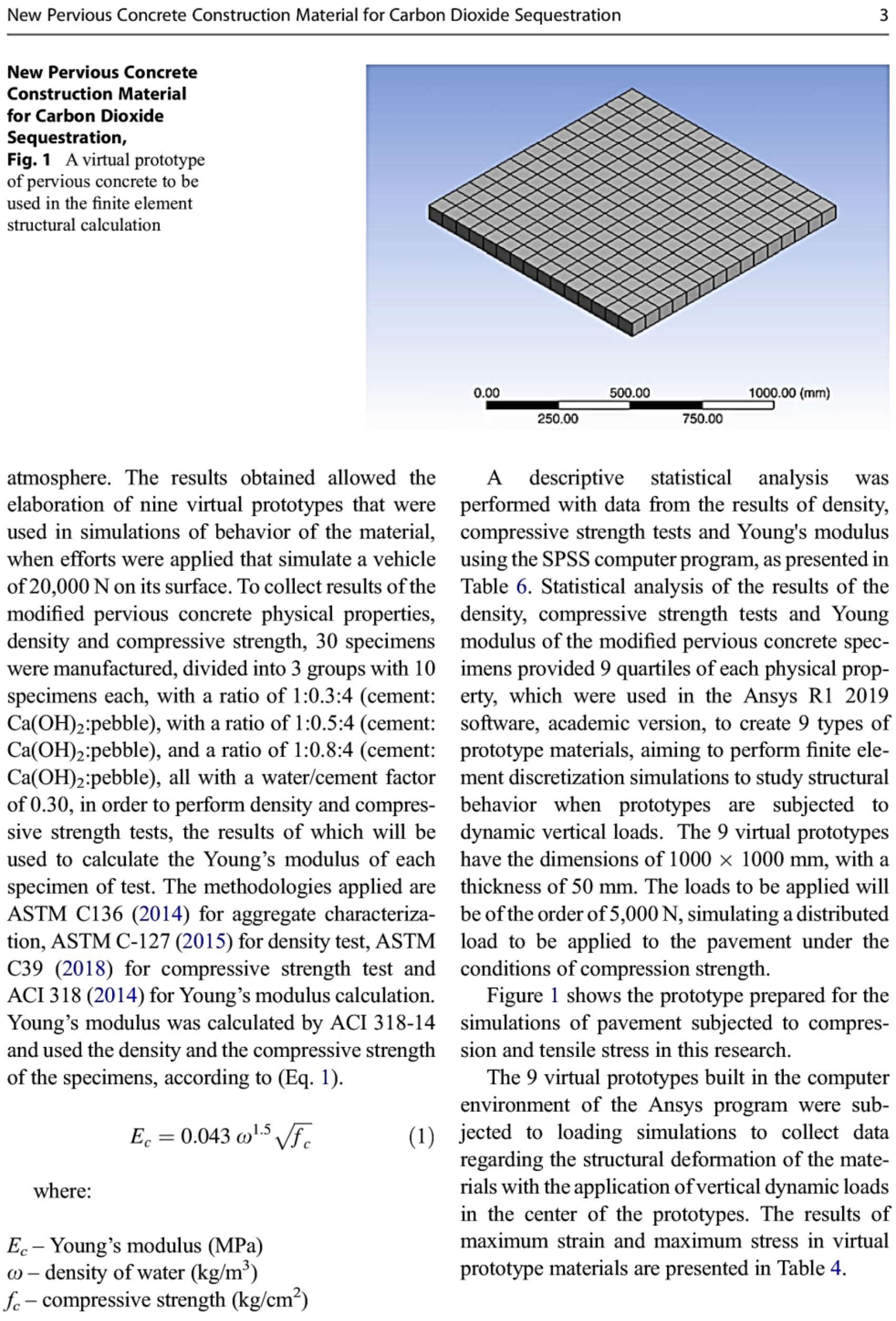
https://doi.org/10.1007/978-3-319-71061-7_6-1



New Pervious Concrete Construction Material for Carbon Dioxide Sequestration, Table 1 Additives used in the pervious concrete

Year	Additives	Author
1995	Superplasticizers	Ghafoori and Dutta (1995)
2003	Silica fume Vinyl acetate ethylene Polyvinyl alcohol Formaldehyde hydrosol	Yang and Jiang (2003)
2010	SBS latex Polypropylene fiber	Huang et al. (2010)
2010	Silica fume	Lian and Zhuge (2010)
2016	Silica fume	Chandrappa and Biligiri (2016)
2016	TiO_2	Barnhouse and Srubar III (2016)
2018	$MgCl_2$ Fiber	Zhong and Wille (2018)
2018	Plasticizer	Kovac and Sicakova (2018)
2018	Polypropylene fibers Rubber Silica fume Styrene butadiene latex	Aliabdo et al. (2018)

process complex and more expensive than conventional. This research opted for the study of the additive of $Ca(OH)_2$, abundant material and of low cost, added in the mixture of the pervious concrete, which is a procedure of simple execution. The studies carried out to improve the environmental qualities of pervious concrete had the objective of contributing to the acceleration of CO_2 sequestering in the atmosphere by the pervious concrete, reducing in this way the urban pollution and volume of CO_2 in the atmosphere, which is one of the causes of the greenhouse effect. However, the tests demonstrated that despite the improvement of its environmental properties, there is a degradation of structural physical properties, a serious problem for the use of this material as urban pavement. Cement acts as a binder between aggregate particles in the permeable concrete mix, but the cement action is impaired as the proportion of additive incorporated in the permeable concrete mix increases, making the material structure unstable, as shown in Fig. 3, the compressive strength initially increases, and then decreases until the material completely loses its compressive strength property. The results of Fig. 3 demonstrate that there is an additive limit to be incorporated into the permeable concrete mix from which the material structure initiates a breakdown and embrittlement which render the material useless for structural use. In order to find this additive limit to be incorporated in the permeable concrete mix, nine static load simulations were performed in nine permeable concrete pavement virtual prototypes, elaborated with different physical characteristics, according to the results of the laboratory tests of this research. The objective of the simulations is to find an efficient prototype that presents a balance between the environmental qualities and the structural qualities necessary for the use of the material as urban road pavement. This research studies a new pervious concrete, which in addition to being a construction material composed of cement, aggregates, and water, with a porosity that allows it to be used as a porous road pavement construction material with permeable properties that facilitate the drainage of rainwater to the soil, also has characteristics of sequestering carbon dioxide (CO_2) from the atmosphere. Through the addition of calcium carbonate ($Ca(OH)_2$) in the mixture of its aggregates, an additive that combined with the porous structure of the pervious concrete chemically acts through a chemical reaction called carbonation for the sequestration of CO_2 into the



New Pervious Concrete Construction Material for Carbon Dioxide Sequestration,
Fig. 1 A virtual prototype of pervious concrete to be used in the finite element structural calculation

atmosphere. The results obtained allowed the elaboration of nine virtual prototypes that were used in simulations of behavior of the material, when efforts were applied that simulate a vehicle of 20,000 N on its surface. To collect results of the modified pervious concrete physical properties, density and compressive strength, 30 specimens were manufactured, divided into 3 groups with 10 specimens each, with a ratio of 1:0.3:4 (cement: $Ca(OH)_2$:pebble), with a ratio of 1:0.5:4 (cement: $Ca(OH)_2$:pebble), and a ratio of 1:0.8:4 (cement: $Ca(OH)_2$:pebble), all with a water/cement factor of 0.30, in order to perform density and compressive strength tests, the results of which will be used to calculate the Young's modulus of each specimen of test. The methodologies applied are ASTM C136 (2014) for aggregate characterization, ASTM C-127 (2015) for density test, ASTM C39 (2018) for compressive strength test and ACI 318 (2014) for Young's modulus calculation. Young's modulus was calculated by ACI 318-14 and used the density and the compressive strength of the specimens, according to (Eq. 1).

$$E_c = 0.043\,\omega^{1.5}\sqrt{f_c} \tag{1}$$

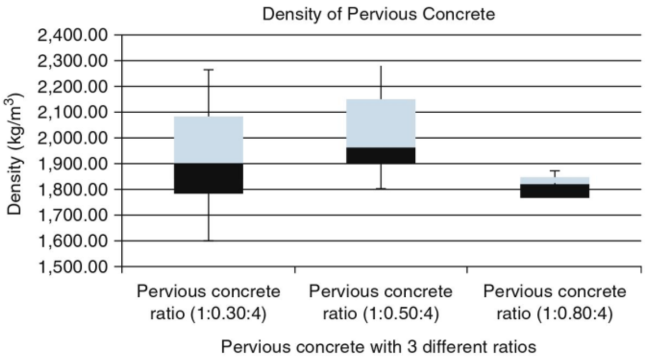
where:

E_c – Young's modulus (MPa)
ω – density of water (kg/m^3)
f_c – compressive strength (kg/cm^2)

A descriptive statistical analysis was performed with data from the results of density, compressive strength tests and Young's modulus using the SPSS computer program, as presented in Table 6. Statistical analysis of the results of the density, compressive strength tests and Young modulus of the modified pervious concrete specimens provided 9 quartiles of each physical property, which were used in the Ansys R1 2019 software, academic version, to create 9 types of prototype materials, aiming to perform finite element discretization simulations to study structural behavior when prototypes are subjected to dynamic vertical loads. The 9 virtual prototypes have the dimensions of 1000 × 1000 mm, with a thickness of 50 mm. The loads to be applied will be of the order of 5,000 N, simulating a distributed load to be applied to the pavement under the conditions of compression strength.

Figure 1 shows the prototype prepared for the simulations of pavement subjected to compression and tensile stress in this research.

The 9 virtual prototypes built in the computer environment of the Ansys program were subjected to loading simulations to collect data regarding the structural deformation of the materials with the application of vertical dynamic loads in the center of the prototypes. The results of maximum strain and maximum stress in virtual prototype materials are presented in Table 4.



New Pervious Concrete Construction Material for Carbon Dioxide Sequestration, Fig. 2 The ratio 1:0.30:4 with lower amount of additive presents a greater variation of density

Findings

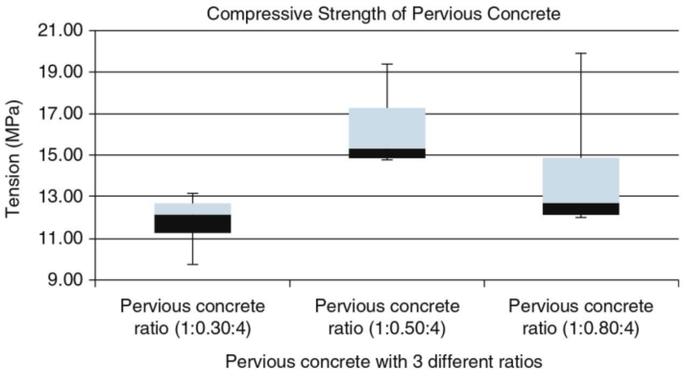
The results of the tests of density, compression strength, and test of monitoring of CO_2 volume sequestered will be presented next. The addition of $Ca(OH)_2$ additive in the pervious concrete mixture fills the voids of the pore network of the internal structure, leaving the material more compact, with a lower density variation, according to Figure 2.

Figure 2 presents the results of the density tests performed with the three groups of specimens with the proportions of 1:0.3:4 (cement:Ca $(OH)_2$:pebble), 1:0.5:4 (cement:$Ca(OH)_2$:pebble), and 1:0.8:4 (cement:$Ca(OH)_2$:pebble), all with a water/cement factor of 0.30, which show an increase in resistance when the additive ratio goes from 0.3 to 0.5 and a reduction when an increase in additive increase to 0.8 occurs. This is because with the addition of additive in the mixture, the material becomes more compact, with an increase in density, but the excess of additive makes the material fragile and weak, with disintegration of its structure 0.8. Excessive additive impairs cement adhesion between aggregate particles, causing material disintegration. However, a reduced amount of additive improves the material's environmental properties as it absorbs CO_2 from the atmosphere as shown in the CO_2 volume monitoring tests; this way you should find an optimal additive value to be added to the new material mix so as not to impair the density properties. Figure 2 shows the results of an initial 3% density increase, which is natural as the additive fills the pores of the new material, and an 8% reduction in density demonstrating the disintegration of the new material's internal structure, because the additive impairs the action of cement as a bonding element between aggregate particles.

As the additive fills the voids of the internal pore network of the pervious concrete, the material becomes more compact and exhibits a false resistance to compression, as in Figure 3.

Figure 3 presents results of the compressive strength of the specimens of the proportion of 1:0.3:4 (cement:$Ca(OH)_2$:pebble), 1:0.5:4 (cement:$Ca(OH)_2$:pebble), and 1:0.8:4 (cement:$Ca(OH)_2$:pebble), all with a water/cement factor of 0.30, consistent with the results of the density tests performed on the specimens shown in Figure 2, because initially there is an increase in compressive strength and subsequently a reduction in this property. The addition of the additive makes the new material more compact; however, the excess additive ultimately makes the material brittle with little compressive strength. This phenomenon occurs because initially the additive fills the pores of the new material, making the material more compact, but excess additive impairs the cement which disintegrates the internal structure of the new material, rendering the material without compressive strength as it is added more additive to your mix. A material with low compressive strength cannot be used as a pavement or structural part, as it compromises the safety of the

New Pervious Concrete Construction Material for Carbon Dioxide Sequestration,
Fig. 3 The material gains resistance with the $Ca(OH)_2$ additive because the carbonation produces $CaCO_3$, but the material becomes brittle



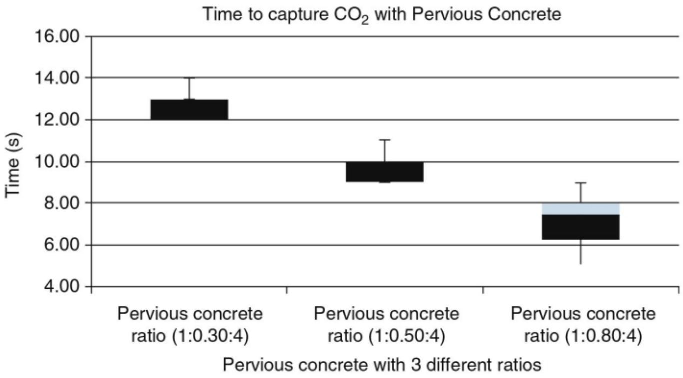
work, so the results of Fig. 3 demonstrate the need for strict control on the amount of additive to be added to the mix in the new material. The results demonstrate the need for further testing with specimens in order to find an optimized proportion of additive that allows the new material to be used as urban road pavement and maintains its CO_2 sequestration properties. However, this negative feature of the new material of loss of density and loss of compressive strength does not predict its use as a sidewalk for pedestrians and garden floors that do not require structural strength of the material. Figure 3 initially shows an average 20% increase in compressive strength from 12.00 MPa to 15.10 MPa, but this 15.10 MPa is reduced to 12.90 MPa followed by a 14.5% reduction, indicating that excess additive contributes for the disintegration of the modified pervious concrete material, as it affects the binder action of the cement next to the aggregates. From that point on, the material loses compressive strength as the addition of additive to the mixture is increased, such that the internal structure of the new material becomes unstable and the new material cannot be used as urban road pavement or structural parts because it is very fragile. This loss of physical properties of the modified pervious concrete, with additive incorporated into the mixture, starts from a limit that configures the excess additive to be incorporated into the material. Tests shall be carried out to strike a balance between the additive limit and the maintenance of physical properties allowing the structural use of modified pervious road pavement concrete capable of absorbing CO_2 into the atmosphere. An economical solution found in this research is a virtual simulation of nine prototypes of the new material being used as urban pavement and subjected to 5,000 N dinamic loads through the finite element calculation. The simulation is built using the modulus of elasticity data found in the test results of the density and compressive strength specimens performed in the laboratory.

As expected, the more the additive in the mixture of pervious concrete, the more CO_2 sequestration occurs and the shorter the time, according to Figure 4.

Figure 4 shows the CO_2 absorption results of the specimens of the proportions of 1:0.3:4 (cement:$Ca(OH)_2$:pebble), 1:0.5:4 (cement:$Ca(OH)_2$:pebble), and 1:0.8:4 (cement:$Ca(OH)_2$:pebble), all with a water/cement factor of 0.30, demonstrating a reduction in CO_2 absorption time as we add additive to the new material mix, with an acceleration in CO_2 sequestration time of about 25% from one ratio to another. This reduction in CO_2 absorption time occurs as we increase the additive due to a chemical reaction called carbonation (Eq. 2), according to Haselbach and Thomle (2014).

$$\mathrm{Ca(OH)_2(s) + CO_2(g) \rightleftarrows CaCO_3(s) + H_2OH} = -178\mathrm{kJ/mol} \tag{2}$$

The stoichiometric chemical calculation for

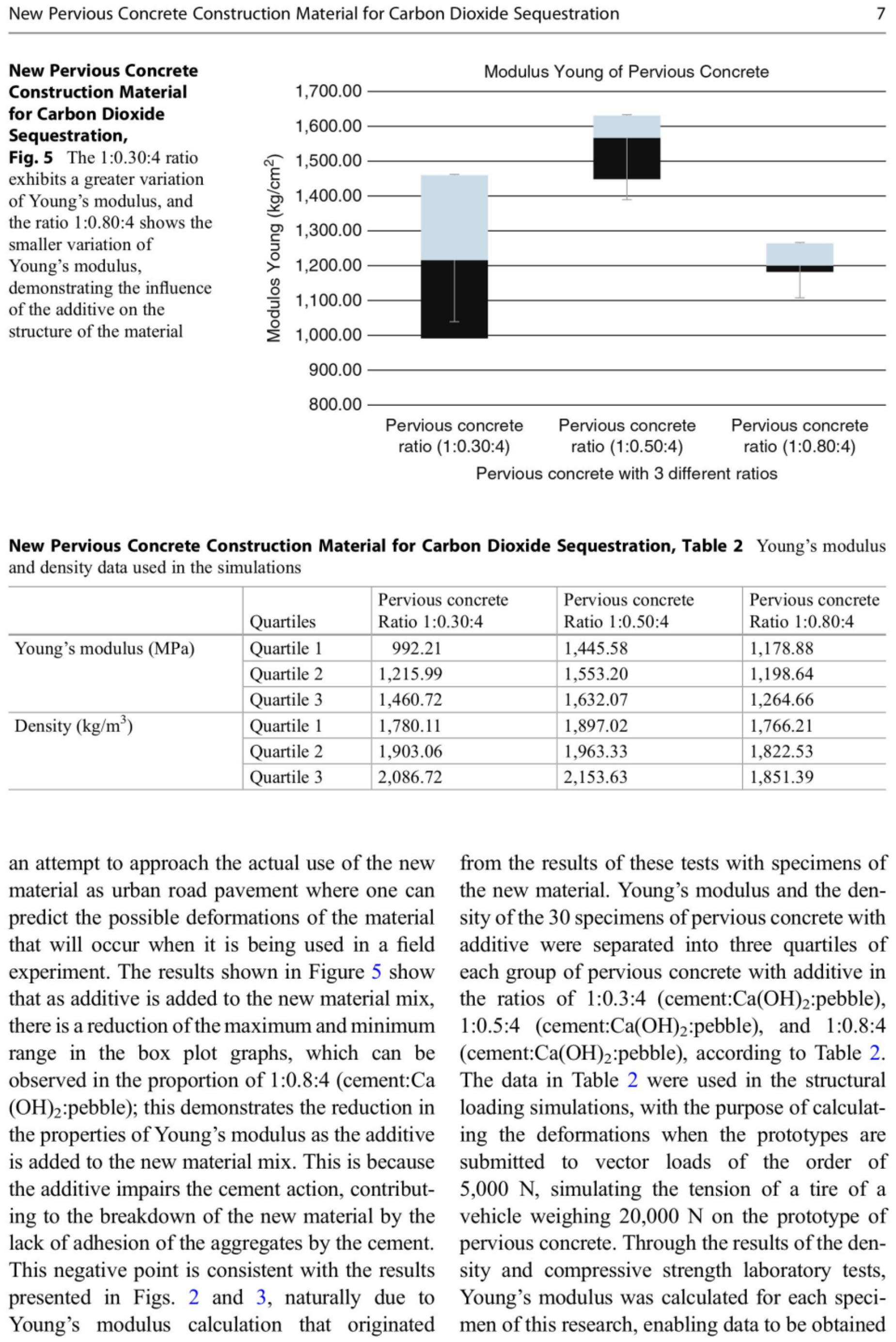


New Pervious Concrete Construction Material for Carbon Dioxide Sequestration, Fig. 4 The 1:0.80:4 ratio was the most efficient because it took less time to capture the same amount of CO_2

calculating the $Ca(OH)_2$ mass required to capture 1,000 L of CO_2 from the atmosphere at an ambient temperature of 27 ° C (300 K) and atmospheric pressure of 0.20 atm is performed with $n = 8{,}333$ moles of CO_2, as the molar ratio is 1: 1: 1, we have $Ca(OH)_2 = 8.33 \times (40 + 2 \times 16 + 2 \times 1) = 616.42$ g to be incorporated into the mixture of modified permeable concrete on each specimen. This CO_2 sequestration property of the new material is very important for the environment, especially in climate control, air quality, and reduction of athermic pollution. Therefore this environmental benefit cannot be neglected, despite the negative points of reduction of density and compressive strength properties presented in the results of Figs. 2 and 3. The absorption of CO_2 is accelerated with the addition of additive in the new material, but the results show that the material completely loses its physical properties, eventually disintegrating due to the lack of adhesion of cement to aggregates. An optimal ratio must be found so that there is a balance between CO_2 absorption by the new material and its ability to be used as a building material, such as urban road pavement. The use of this new material as urban road pavement is important because it would cover an area of the city that would absorb toxic gases emanating from urban transport vehicles, which justifies the continuity of the research and laboratory tests being carried out. The results shown in Figure 4 have a positive environmental benefit that should be balanced against the negative results in density, Figure 2, and compressive strength, Figure 3, in such a way that the environmental and physical properties of the new material can be maximized. This equilibrium can be found with further research through laboratory testing with a larger number of specimens and new mixing ratios within the additive range without the destruction of the structure of the new material, manufactured from conventional pervious concrete with changes in the mix made in the laboratory.

With the addition of additive in the mixture of pervious concrete, the internal structure becomes more compact and varies less in Young's modulus, according to Figure 5.

Young's modulus results of the specimens are shown in Figure 5 and demonstrate consistency with the results of Figures 2 and 3, a false perception of improved qualities accompanied by a reduction in these properties to disintegration of the material's internal structure. This coherence is justified because Young's modulus calculation is performed with the results of the density and compressive strength tests presented in Figures 2 and 3. Young's modulus was calculated to be used in the construction of nine virtual prototypes of the new material, which will be modeled by finite elements throughout its structure. The importance of Young's modulus calculation of the specimens that were used in this research lies in its use for structural calculations of the new material, which requires Young's modulus of the material to perform finite element calculations. The simulation of the structural behavior of virtual prototypes is



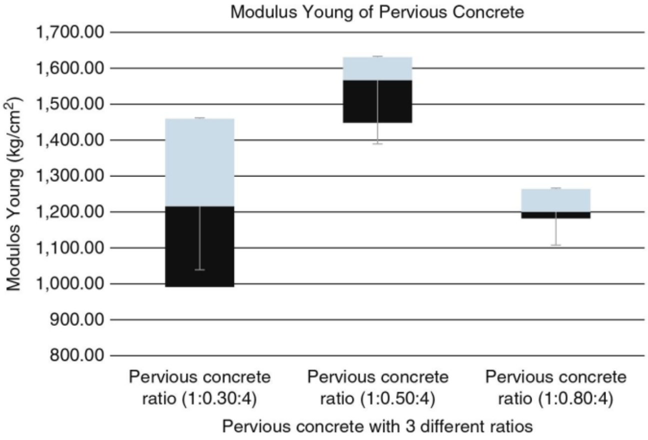
New Pervious Concrete Construction Material for Carbon Dioxide Sequestration 7

New Pervious Concrete Construction Material for Carbon Dioxide Sequestration, Fig. 5 The 1:0.30:4 ratio exhibits a greater variation of Young's modulus, and the ratio 1:0.80:4 shows the smaller variation of Young's modulus, demonstrating the influence of the additive on the structure of the material

New Pervious Concrete Construction Material for Carbon Dioxide Sequestration, Table 2 Young's modulus and density data used in the simulations

	Quartiles	Pervious concrete Ratio 1:0.30:4	Pervious concrete Ratio 1:0.50:4	Pervious concrete Ratio 1:0.80:4
Young's modulus (MPa)	Quartile 1	992.21	1,445.58	1,178.88
	Quartile 2	1,215.99	1,553.20	1,198.64
	Quartile 3	1,460.72	1,632.07	1,264.66
Density (kg/m^3)	Quartile 1	1,780.11	1,897.02	1,766.21
	Quartile 2	1,903.06	1,963.33	1,822.53
	Quartile 3	2,086.72	2,153.63	1,851.39

an attempt to approach the actual use of the new material as urban road pavement where one can predict the possible deformations of the material that will occur when it is being used in a field experiment. The results shown in Figure 5 show that as additive is added to the new material mix, there is a reduction of the maximum and minimum range in the box plot graphs, which can be observed in the proportion of 1:0.8:4 (cement:Ca(OH)$_2$:pebble); this demonstrates the reduction in the properties of Young's modulus as the additive is added to the new material mix. This is because the additive impairs the cement action, contributing to the breakdown of the new material by the lack of adhesion of the aggregates by the cement. This negative point is consistent with the results presented in Figs. 2 and 3, naturally due to Young's modulus calculation that originated from the results of these tests with specimens of the new material. Young's modulus and the density of the 30 specimens of pervious concrete with additive were separated into three quartiles of each group of pervious concrete with additive in the ratios of 1:0.3:4 (cement:Ca(OH)$_2$:pebble), 1:0.5:4 (cement:Ca(OH)$_2$:pebble), and 1:0.8:4 (cement:Ca(OH)$_2$:pebble), according to Table 2. The data in Table 2 were used in the structural loading simulations, with the purpose of calculating the deformations when the prototypes are submitted to vector loads of the order of 5,000 N, simulating the tension of a tire of a vehicle weighing 20,000 N on the prototype of pervious concrete. Through the results of the density and compressive strength laboratory tests, Young's modulus was calculated for each specimen of this research, enabling data to be obtained



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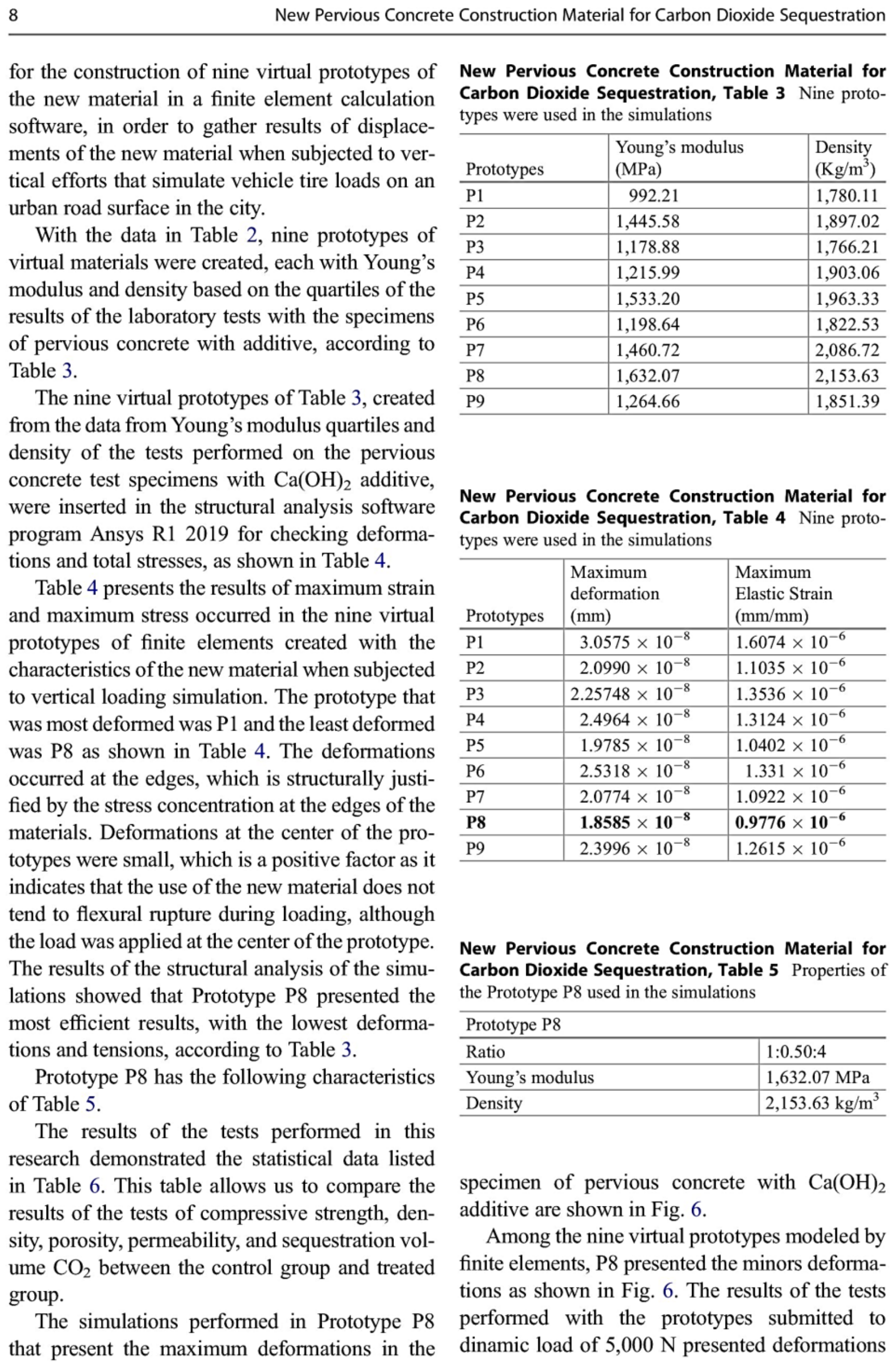


for the construction of nine virtual prototypes of the new material in a finite element calculation software, in order to gather results of displacements of the new material when subjected to vertical efforts that simulate vehicle tire loads on an urban road surface in the city.

With the data in Table 2, nine prototypes of virtual materials were created, each with Young's modulus and density based on the quartiles of the results of the laboratory tests with the specimens of pervious concrete with additive, according to Table 3.

The nine virtual prototypes of Table 3, created from the data from Young's modulus quartiles and density of the tests performed on the pervious concrete test specimens with $Ca(OH)_2$ additive, were inserted in the structural analysis software program Ansys R1 2019 for checking deformations and total stresses, as shown in Table 4.

Table 4 presents the results of maximum strain and maximum stress occurred in the nine virtual prototypes of finite elements created with the characteristics of the new material when subjected to vertical loading simulation. The prototype that was most deformed was P1 and the least deformed was P8 as shown in Table 4. The deformations occurred at the edges, which is structurally justified by the stress concentration at the edges of the materials. Deformations at the center of the prototypes were small, which is a positive factor as it indicates that the use of the new material does not tend to flexural rupture during loading, although the load was applied at the center of the prototype. The results of the structural analysis of the simulations showed that Prototype P8 presented the most efficient results, with the lowest deformations and tensions, according to Table 3.

Prototype P8 has the following characteristics of Table 5.

The results of the tests performed in this research demonstrated the statistical data listed in Table 6. This table allows us to compare the results of the tests of compressive strength, density, porosity, permeability, and sequestration volume CO_2 between the control group and treated group.

New Pervious Concrete Construction Material for Carbon Dioxide Sequestration, Table 3 Nine prototypes were used in the simulations

Prototypes	Young's modulus (MPa)	Density (Kg/m^3)
P1	992.21	1,780.11
P2	1,445.58	1,897.02
P3	1,178.88	1,766.21
P4	1,215.99	1,903.06
P5	1,533.20	1,963.33
P6	1,198.64	1,822.53
P7	1,460.72	2,086.72
P8	1,632.07	2,153.63
P9	1,264.66	1,851.39

New Pervious Concrete Construction Material for Carbon Dioxide Sequestration, Table 4 Nine prototypes were used in the simulations

Prototypes	Maximum deformation (mm)	Maximum Elastic Strain (mm/mm)
P1	3.0575×10^{-8}	1.6074×10^{-6}
P2	2.0990×10^{-8}	1.1035×10^{-6}
P3	2.25748×10^{-8}	1.3536×10^{-6}
P4	2.4964×10^{-8}	1.3124×10^{-6}
P5	1.9785×10^{-8}	1.0402×10^{-6}
P6	2.5318×10^{-8}	1.331×10^{-6}
P7	2.0774×10^{-8}	1.0922×10^{-6}
P8	$\mathbf{1.8585 \times 10^{-8}}$	$\mathbf{0.9776 \times 10^{-6}}$
P9	2.3996×10^{-8}	1.2615×10^{-6}

New Pervious Concrete Construction Material for Carbon Dioxide Sequestration, Table 5 Properties of the Prototype P8 used in the simulations

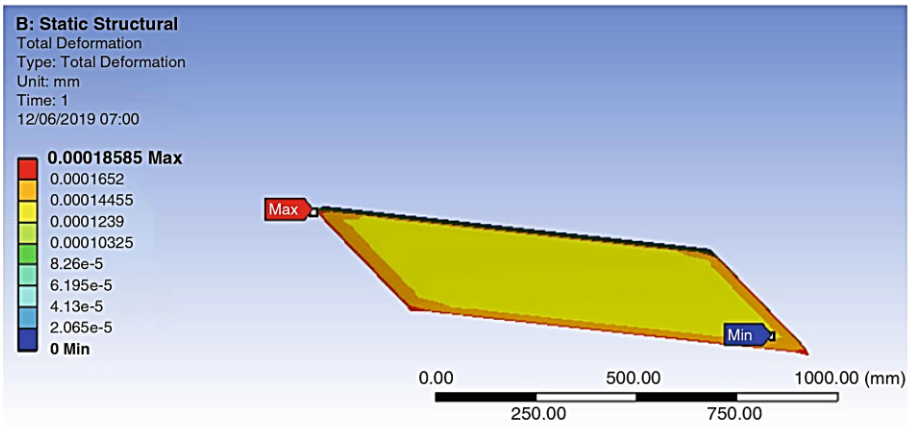
Prototype P8	
Ratio	1:0.50:4
Young's modulus	1,632.07 MPa
Density	2,153.63 kg/m^3

The simulations performed in Prototype P8 that present the maximum deformations in the specimen of pervious concrete with $Ca(OH)_2$ additive are shown in Fig. 6.

Among the nine virtual prototypes modeled by finite elements, P8 presented the minors deformations as shown in Fig. 6. The results of the tests performed with the prototypes submitted to dinamic load of 5,000 N presented deformations

New Pervious Concrete Construction Material for Carbon Dioxide Sequestration, Table 6 Descriptive statistics for the treated group (30 specimens) in the SPSS

Treated samples	Compressive strength (kg/cm^2)	Density (kg/m^3)	Sequestration volume CO_2 (ppm/s)	Young's modulus (kg/cm^2)
Mean	13.83	1911.36	9.83	1338.40
Std. deviation	2.57	193.33	2.46	246.11
Median	13.05	1873.18	10.00	1305.89
Variance	6.65	37,376	6.07	60570.85
Minimum	8.70	1475	5.00	815.47
Maximum	19.40	2284.94	14.00	1776.02
Skewness (statistic/error)	0.50/0.43	0.29/0.43	−0.08/0.43	−0.098/0.427
Kurtosis (statistic/error)	−0.05/0.83	−0.08/0.83	0.97/0.83	−0.611/0.833

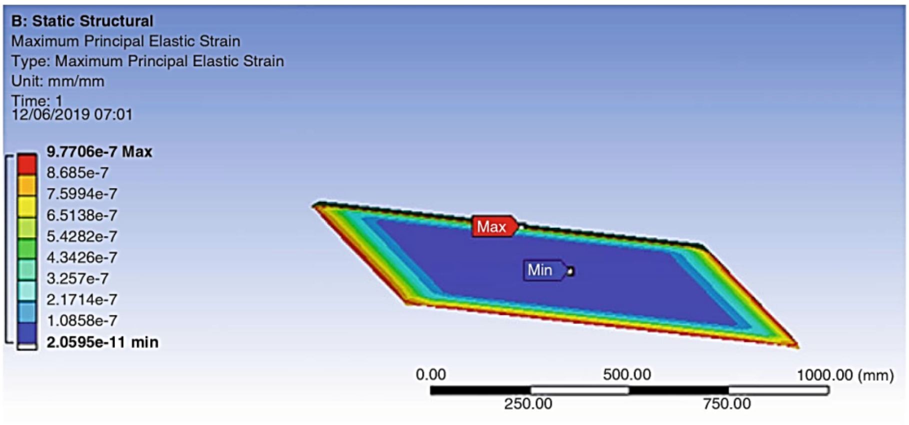


New Pervious Concrete Construction Material for Carbon Dioxide Sequestration, Fig. 6 Maximum deformations in red color and located at the ends of Prototype P8

in the order of 0.00018585 mm (maximum) represented by the red color in the caption of Fig. 6. The P8 prototype showed the lowest deformations compared to the other prototypes, as shown in Table 4, which means that the P8 prototype material presented the best deformation results. The dimensions of the deformations that emerged in prototype P8 are noticeable only at the microscopic level. These results originate from a virtual simulation performed using finite element software, which does not rule out the need for field tests to prove the theoretical results presented here in the simulations. The results presented by the finite element software are positive and point to a possibility of using the new material as urban road pavement provided that there is a strict control of the additive mixture addition of the new material under study in this research and made from normal pervious concrete.

The simulations performed in Prototype P8 that present the maximum tension in the specimen of pervious concrete with $Ca(OH)_2$ additive are shown in Fig. 7.

The displacements and deformations occurred in the prototype, through the structural loading simulations, allowed to verify the possibility of

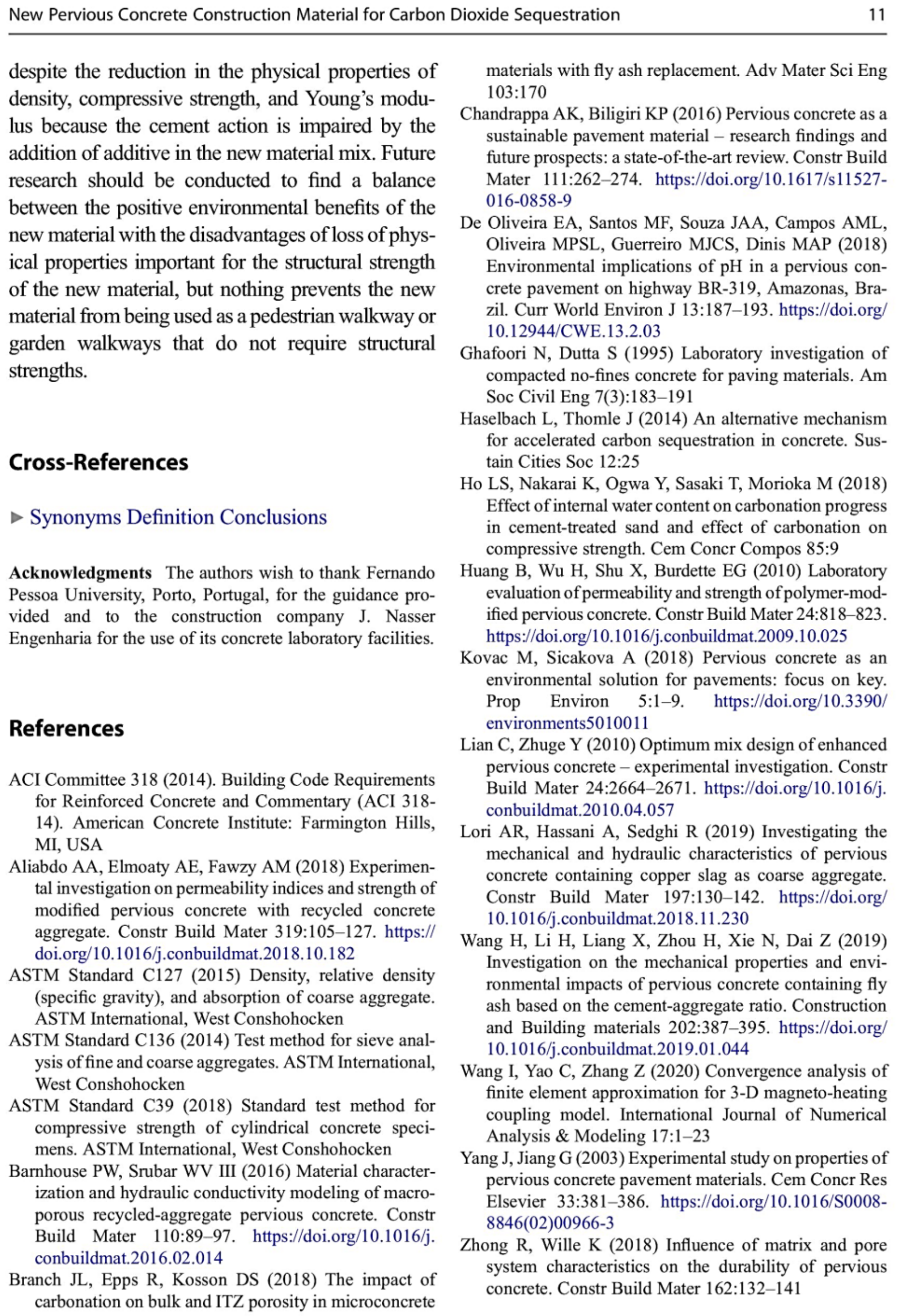


New Pervious Concrete Construction Material for Carbon Dioxide Sequestration, Fig. 7 Minimum tensions in P8 is located in the center of the prototype

using the material researched as urban porous pavement and the choice of the best mixing ratio of the pervious concrete with the additive $Ca(OH)_2$. The simulations performed in the computational program of structural analysis showed that the pervious concrete with additive, Prototype P8, supports well the loads applied in its structure, because it presented acceptable deformations and tensions in the structural field. The applied loads simulated a vehicle of 2,000 N on the surface of the pervious concrete pavement of a parking lot or urban road. For higher loads the material does not support the loading and should be replaced by a more resistant pavement. The addition of additive in the pervious concrete mixture causes an excess of deformations in its material, rendering the material unsuitable for structural use. The equilibrium between the environmental and structural qualities of the new pervious concrete with $Ca(OH)_2$ additive is possible, but it is also fragile; therefore, more laboratory and field studies are needed to improve the material. The continuity of the studies should be carried out through field experiments that prove the studies carried out in the structural analyses of loading simulations on the prototype of pervious concrete with additive.

Conclusions

The results obtained in the structural simulations showed that it is possible to use the new pervious concrete with $Ca(OH)_2$ additive as urban road pavement, with the most efficient performance obtained with the ratio of 1:0.50:4 (cement:$Ca(OH)_2$:pebble), with modulus of elasticity of 1,632.07 MPa, and with density of 2,153.63 kg/m^3. The results shown in Figure 2 show a 7% reduction in average density from 1,950.00 kg/m^3 to 1,810.00 kg/m^3, in Figure 3 a 15% reduction in average compressive strength from 15.10 MPa to 12.80 MPa and in Figure 5 a 22% reduction in Young's Average Module from 1,200.00 kg/cm^2 to 1,550 kg/cm^2. These reductions in the physical properties of modified pervious concrete indicate that the additive impairs the action of cement as a binder, so it is not possible to use large portions of the additive incorporated in the modified pervious concrete mixture. The CO_2 monitoring results demonstrated a positive environmental benefit with an increase in atmospheric CO_2 absorption time of around 25% on average. The use of this new material as urban road pavement is important because it would cover an area of the city that would absorb toxic gases emanating from urban transport vehicles, which justifies the continuity of the research and laboratory tests being carried out,



despite the reduction in the physical properties of density, compressive strength, and Young's modulus because the cement action is impaired by the addition of additive in the new material mix. Future research should be conducted to find a balance between the positive environmental benefits of the new material with the disadvantages of loss of physical properties important for the structural strength of the new material, but nothing prevents the new material from being used as a pedestrian walkway or garden walkways that do not require structural strengths.

Cross-References

► Synonyms Definition Conclusions

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CAPÍTULO II – Implicações Ambientais do pH em Pavimento de Betão Permeável na Rodovia BR-319, Amazonas, Brasil

Este capítulo aborda o comportamento do BPC nos ensaios de compressão axial (ASTM C-39, 2018) e permeabilidade (Batezini e Balbo, 2015) com 4 tipos diferentes de água, destilada, ionizada, carbonatada com CO_2 e água de torneira. Uma análise de inferência estatística nos resultados detetou alcalinidade registrada pelo aumento de pH, uma resistência à compressão média de 12,30 MPa e uma taxa de permeabilidade de 1,28 l/h. Os resultados demonstraram que o BPC não apresentou nenhuma anomalia decorrente da carbonatação, como manchas e eflorescências, e alterações nas propriedades físicas de permeabilidade e resistência à compressão axial.

Nesta publicação, o primeiro autor participou no desenvolvimento da metodologia, investigação e recolha de dados e na escrita do manuscrito. A citação completa da publicação encontra-se apresentada a seguir:

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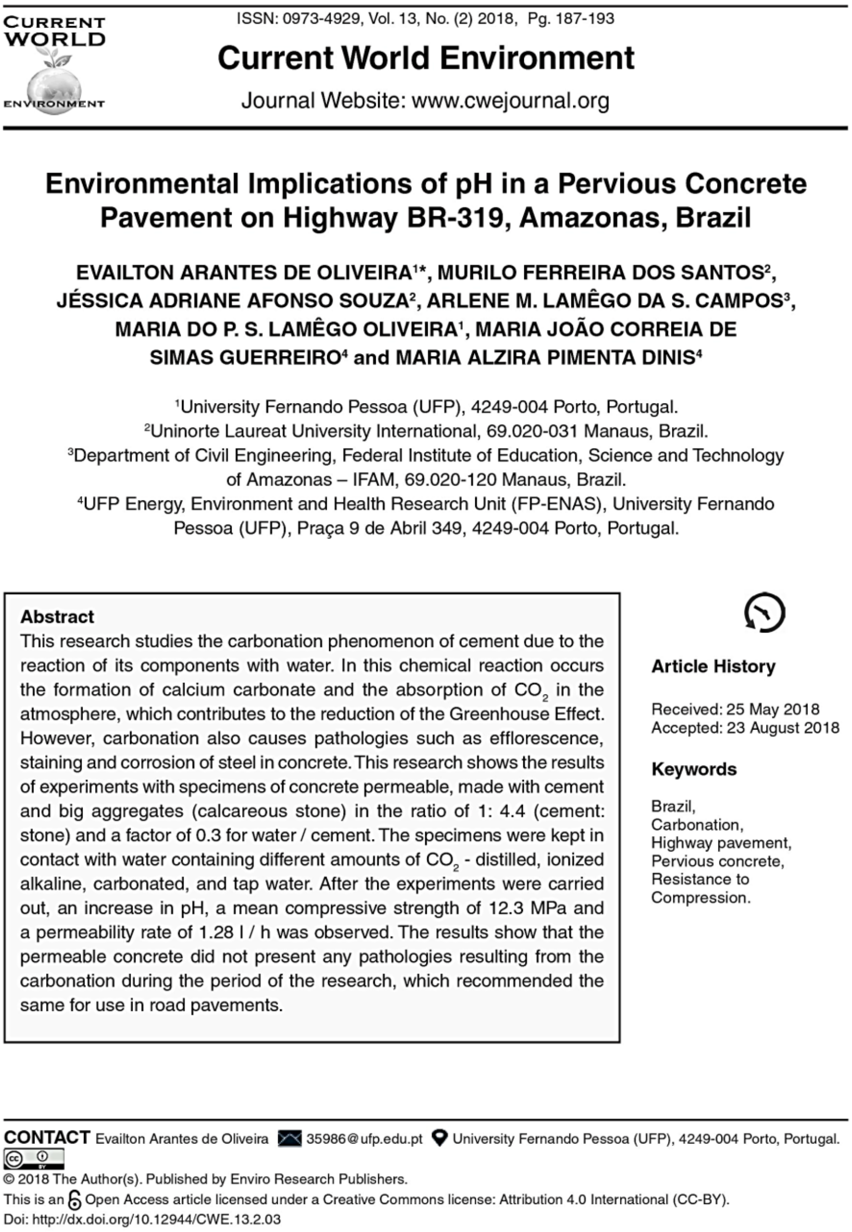

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Environmental Implications of pH in a Pervious Concrete Pavement on Highway BR-319, Amazonas, Brazil

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Abstract

This research studies the carbonation phenomenon of cement due to the reaction of its components with water. In this chemical reaction occurs the formation of calcium carbonate and the absorption of CO_2 in the atmosphere, which contributes to the reduction of the Greenhouse Effect. However, carbonation also causes pathologies such as efflorescence, staining and corrosion of steel in concrete. This research shows the results of experiments with specimens of concrete permeable, made with cement and big aggregates (calcareous stone) in the ratio of 1: 4.4 (cement: stone) and a factor of 0.3 for water / cement. The specimens were kept in contact with water containing different amounts of CO_2 - distilled, ionized alkaline, carbonated, and tap water. After the experiments were carried out, an increase in pH, a mean compressive strength of 12.3 MPa and a permeability rate of 1.28 l / h was observed. The results show that the permeable concrete did not present any pathologies resulting from the carbonation during the period of the research, which recommended the same for use in road pavements.

Article History

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Keywords

Brazil,
Carbonation,
Highway pavement,
Pervious concrete,
Resistance to Compression.

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Introduction

Concrete has cement as a binder, therefore, it is subject to two phenomena: calcination and carbonation[1]. The cement manufacturing process consumes energy and generates carbon dioxide (CO_2) due to calcination, whereas carbonation of cement, a natural process of calcium carbonate formation in the concrete hydration process, uptakes CO_2 from the environment, an interesting environmental factor that may contribute to reduction of this greenhouse gas[2,3]. In fact, cement carbonation in construction may reduce CO_2 in the environment, with a positive impact on the greenhouse effect. Nonetheless, carbonation may contribute to concrete pathology by steel corrosion in reinforced concrete[4]. The importance of investigating the environmental implications of pH variation in drainage water from porous concrete is related to cement carbonation[5]. Upon the hydrolysis reaction, an increase in the solubility of calcium carbonate, incorporates carbon dioxide, leading to an acidity in the water, once the system is in equilibrium. Sustainability requirements in today's constructions compel to investigate materials whose waste can be recycled[3]. This research work focused on the effects of carbonation in porous concrete, which may include recycling of concrete by using it as an aggregate contributing to pavements6 construction sustainability. The main objective of this study was to investigate evidence of carbonation in specimens of pervious concrete, under laboratory and field conditions of pressure and temperature, and to verify the integrity of specimens of pervious concrete subject to different types of water: distilled, alkaline ionized water, carbonated water and tap water.

Materials and Methods

This study was developed in Manaus, in the Amazon region in Brazil, and involved laboratory and field experiments.

Pervious Concrete Specimens

Pervious concrete specimens were formed based on the Brazilian standard NBR 5738[7], that defines the procedures to mold and cure concrete specimens. Based on studies of traits, preparation methods, standard quality control as well as permeability concrete optimization methods[8], ten cylindrical specimens of pervious concrete were formed, with a cement to coarse aggregate 1:4.4 ratio and a water/cement factor of 0.3 to compression (Table 1).

Table 1: Pervious concrete specimens characteristics

Material	Ratio
cement : coarse aggregate ratio	1:4.4
water / cement factor	0.3
aggregate (4.8 a 9.5 mm) (kg/m^3)	1660
cement (kg/m^3)	374

The specimens were molded into cylindrical shapes of 10 cm in diameter by 20 cm. The compaction consisted on applying 15 strokes with a shank, by layer of equal thickness. Vibration, curing and demolding were performed according to the guidelines of Brazilian standard NBR 5738, considering that the characteristics of pervious concrete differ from common concrete[9].

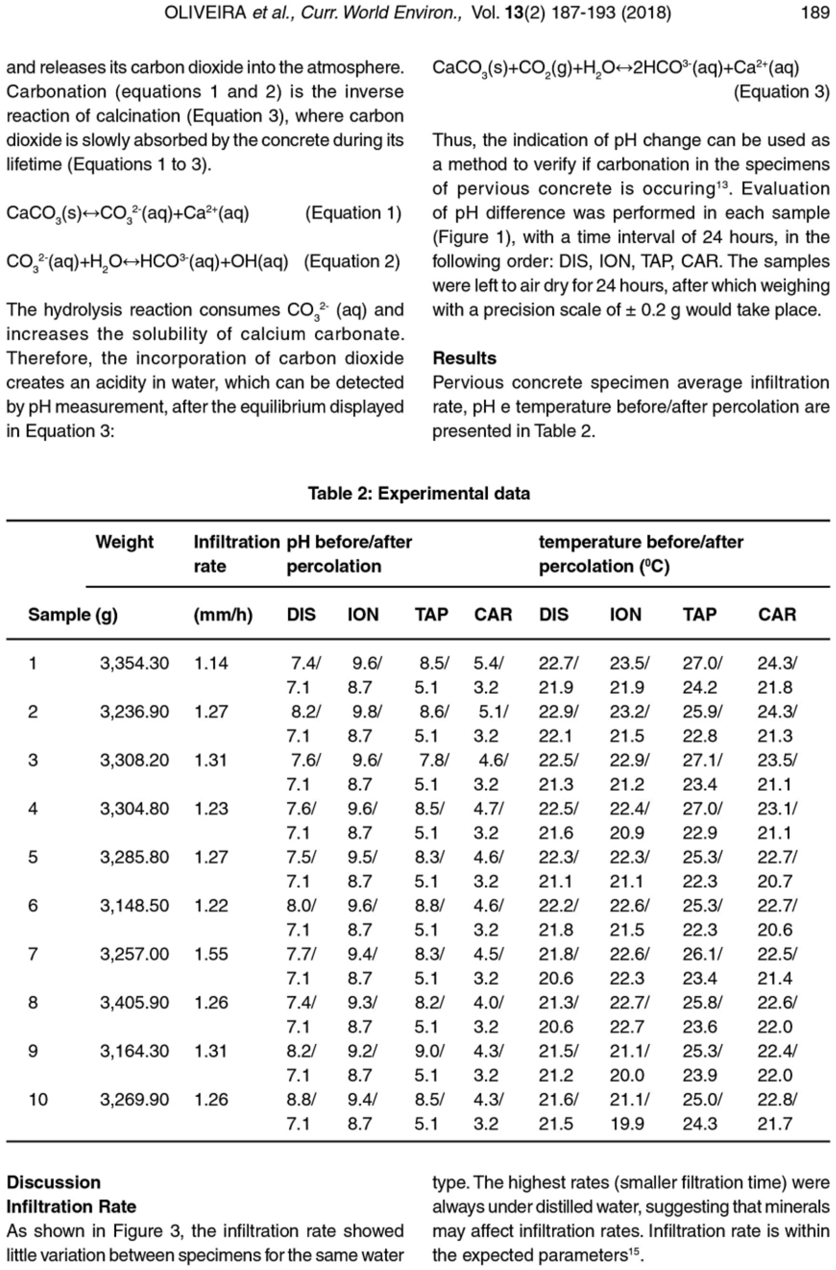
The infiltration rate was evaluated using distilled (DIS), ionized (ION), tap (TAP) and carbonated (CAR) water (Figure 1). Water adsorption was calculated by weight difference after the samples were left to air dry for 24 hours and after water (DIS, ION, TAP, and CAR) had infiltrated through the specimen.

a) b)

Fig. 1: measurement of a) pH and temperature; b) infiltration rate

The pH variation during carbonation and calcination10

The chemical reaction in cement manufacture, where calcium carbonate dissociates into carbon dioxide and calcium oxide, requires a lot of thermal energy



and releases its carbon dioxide into the atmosphere. Carbonation (equations 1 and 2) is the inverse reaction of calcination (Equation 3), where carbon dioxide is slowly absorbed by the concrete during its lifetime (Equations 1 to 3).

$CaCO_3(s) \leftrightarrow CO_3^{2-}(aq) + Ca^{2+}(aq)$ (Equation 1)

$CO_3^{2-}(aq) + H_2O \leftrightarrow HCO^{3-}(aq) + OH(aq)$ (Equation 2)

The hydrolysis reaction consumes CO_3^{2-} (aq) and increases the solubility of calcium carbonate. Therefore, the incorporation of carbon dioxide creates an acidity in water, which can be detected by pH measurement, after the equilibrium displayed in Equation 3:

$CaCO_3(s) + CO_2(g) + H_2O \leftrightarrow 2HCO^{3-}(aq) + Ca^{2+}(aq)$ (Equation 3)

Thus, the indication of pH change can be used as a method to verify if carbonation in the specimens of pervious concrete is occuring[13]. Evaluation of pH difference was performed in each sample (Figure 1), with a time interval of 24 hours, in the following order: DIS, ION, TAP, CAR. The samples were left to air dry for 24 hours, after which weighing with a precision scale of ± 0.2 g would take place.

Results

Pervious concrete specimen average infiltration rate, pH e temperature before/after percolation are presented in Table 2.

Table 2: Experimental data

	Weight	Infiltration rate	pH before/after percolation				temperature before/after percolation (^0C)			
Sample	(g)	(mm/h)	DIS	ION	TAP	CAR	DIS	ION	TAP	CAR
1	3,354.30	1.14	7.4/ 7.1	9.6/ 8.7	8.5/ 5.1	5.4/ 3.2	22.7/ 21.9	23.5/ 21.9	27.0/ 24.2	24.3/ 21.8
2	3,236.90	1.27	8.2/ 7.1	9.8/ 8.7	8.6/ 5.1	5.1/ 3.2	22.9/ 22.1	23.2/ 21.5	25.9/ 22.8	24.3/ 21.3
3	3,308.20	1.31	7.6/ 7.1	9.6/ 8.7	7.8/ 5.1	4.6/ 3.2	22.5/ 21.3	22.9/ 21.2	27.1/ 23.4	23.5/ 21.1
4	3,304.80	1.23	7.6/ 7.1	9.6/ 8.7	8.5/ 5.1	4.7/ 3.2	22.5/ 21.6	22.4/ 20.9	27.0/ 22.9	23.1/ 21.1
5	3,285.80	1.27	7.5/ 7.1	9.5/ 8.7	8.3/ 5.1	4.6/ 3.2	22.3/ 21.1	22.3/ 21.1	25.3/ 22.3	22.7/ 20.7
6	3,148.50	1.22	8.0/ 7.1	9.6/ 8.7	8.8/ 5.1	4.6/ 3.2	22.2/ 21.8	22.6/ 21.5	25.3/ 22.3	22.7/ 20.6
7	3,257.00	1.55	7.7/ 7.1	9.4/ 8.7	8.3/ 5.1	4.5/ 3.2	21.8/ 20.6	22.6/ 22.3	26.1/ 23.4	22.5/ 21.4
8	3,405.90	1.26	7.4/ 7.1	9.3/ 8.7	8.2/ 5.1	4.0/ 3.2	21.3/ 20.6	22.7/ 22.7	25.8/ 23.6	22.6/ 22.0
9	3,164.30	1.31	8.2/ 7.1	9.2/ 8.7	9.0/ 5.1	4.3/ 3.2	21.5/ 21.2	21.1/ 20.0	25.3/ 23.9	22.4/ 22.0
10	3,269.90	1.26	8.8/ 7.1	9.4/ 8.7	8.5/ 5.1	4.3/ 3.2	21.6/ 21.5	21.1/ 19.9	25.0/ 24.3	22.8/ 21.7

Discussion

Infiltration Rate

As shown in Figure 3, the infiltration rate showed little variation between specimens for the same water type. The highest rates (smaller filtration time) were always under distilled water, suggesting that minerals may affect infiltration rates. Infiltration rate is within the expected parameters[15].

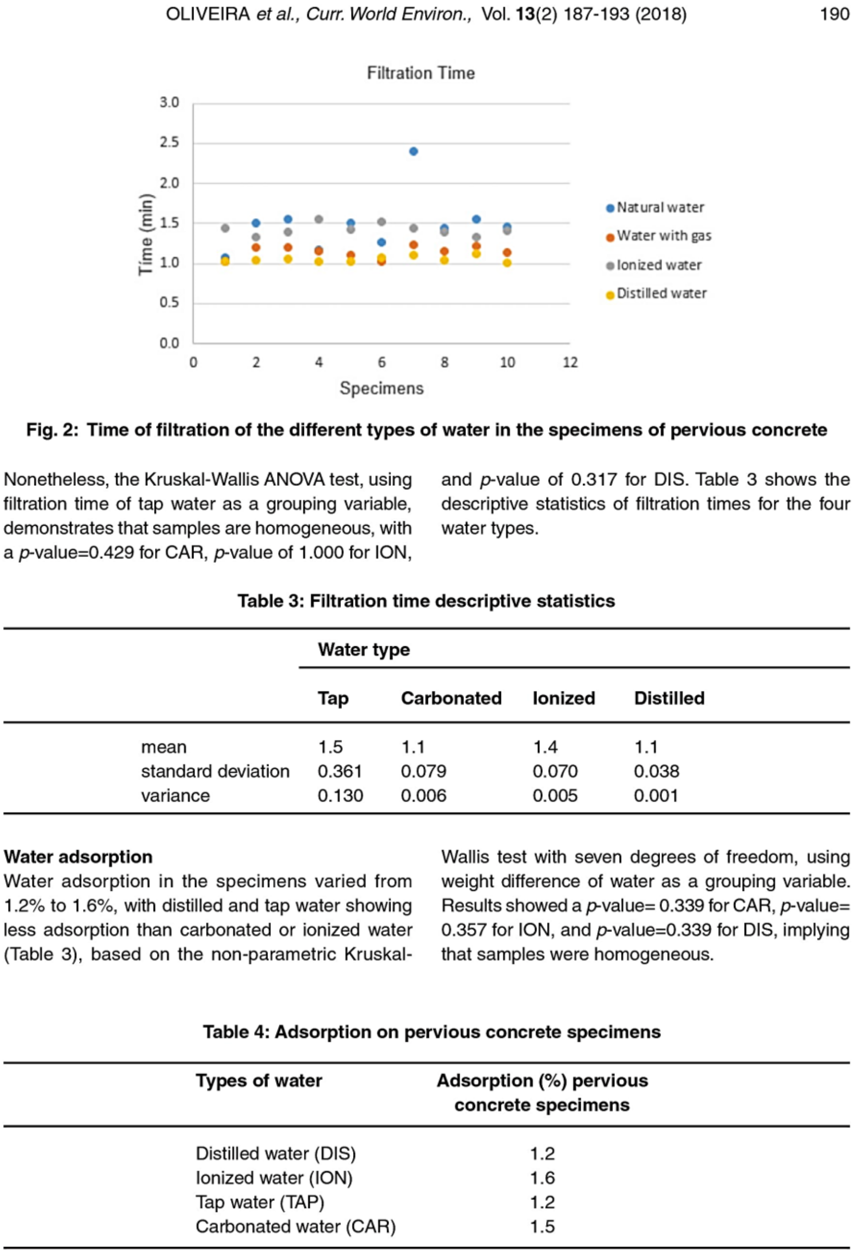


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Fig. 2: Time of filtration of the different types of water in the specimens of pervious concrete

Nonetheless, the Kruskal-Wallis ANOVA test, using filtration time of tap water as a grouping variable, demonstrates that samples are homogeneous, with a *p*-value=0.429 for CAR, *p*-value of 1.000 for ION, and *p*-value of 0.317 for DIS. Table 3 shows the descriptive statistics of filtration times for the four water types.

Table 3: Filtration time descriptive statistics

	Water type			
	Tap	**Carbonated**	**Ionized**	**Distilled**
mean	1.5	1.1	1.4	1.1
standard deviation	0.361	0.079	0.070	0.038
variance	0.130	0.006	0.005	0.001

Water adsorption

Water adsorption in the specimens varied from 1.2% to 1.6%, with distilled and tap water showing less adsorption than carbonated or ionized water (Table 3), based on the non-parametric Kruskal-Wallis test with seven degrees of freedom, using weight difference of water as a grouping variable. Results showed a *p*-value= 0.339 for CAR, *p*-value= 0.357 for ION, and *p*-value=0.339 for DIS, implying that samples were homogeneous.

Table 4: Adsorption on pervious concrete specimens

Types of water	**Adsorption (%) pervious concrete specimens**
Distilled water (DIS)	1.2
Ionized water (ION)	1.6
Tap water (TAP)	1.2
Carbonated water (CAR)	1.5

Figure 2 shows difference in weight before and after the infiltration process, suggesting that water adsorption is higher under ionized water, followed by carbonated water, distilled and tap water, suggesting that water with higher carbon concentration tends to adsorb more to concrete. Differences between samples are attributed to differences in porosity due to concrete molding.

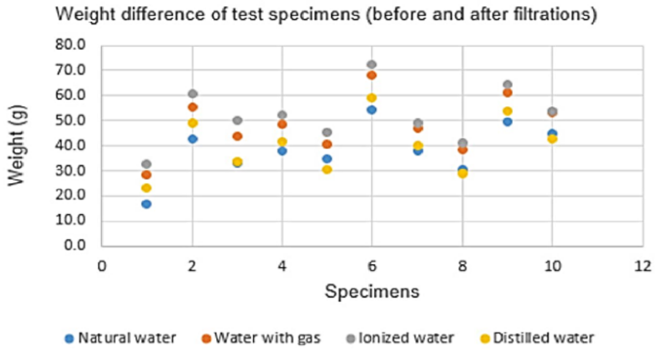


Fig. 3: Weight difference pervious concrete specimens, before and after water infiltration

As shown in Figure 4, all water samples filtered through the pervious concrete specimens changed their pH. Tap water and carbonated water showed higher pH differences, whereas ionized and distilled water showed smaller differences. These results suggest that pervious concrete adsorbs CO_2 from carbonated water, changing its pH.

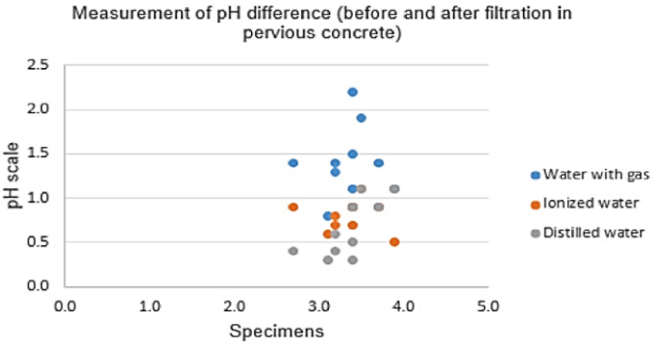
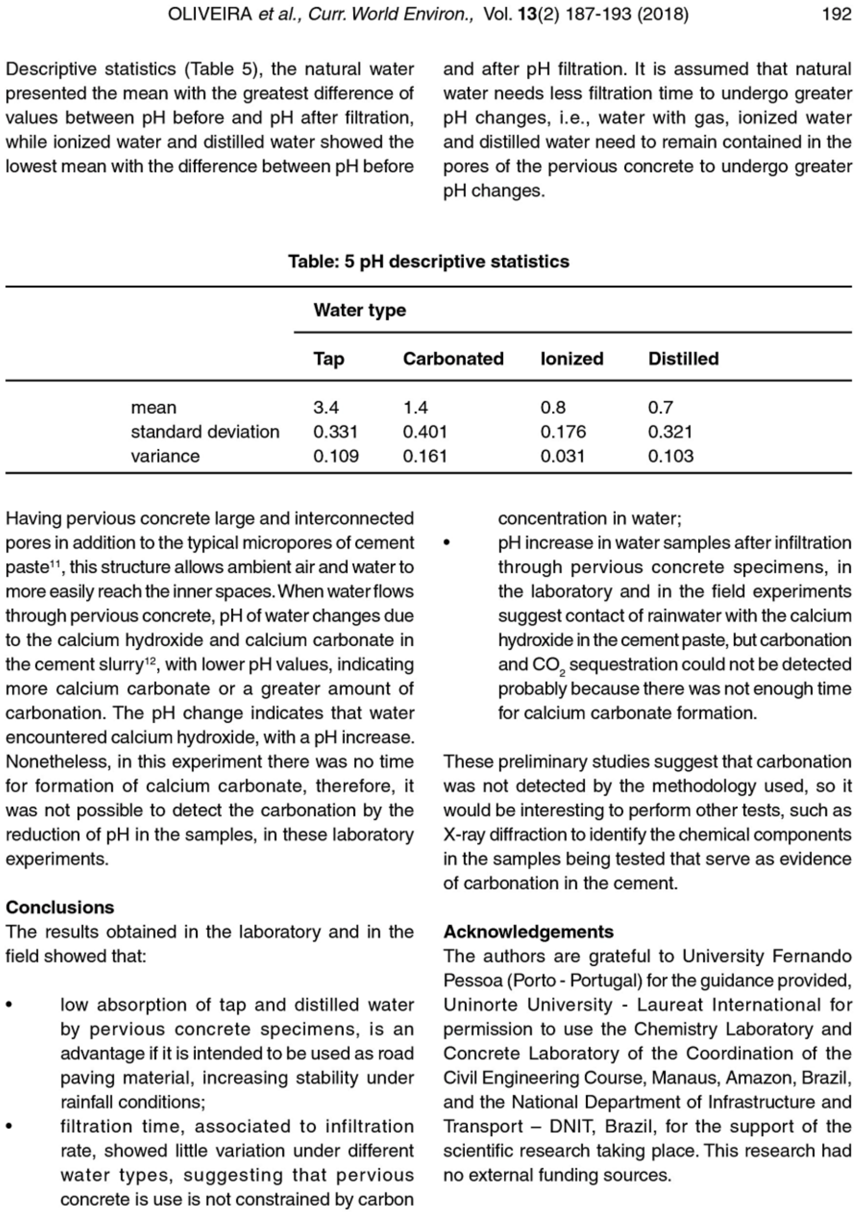


Fig. 4: pH difference of the pervious concrete specimens, before and after filtration of the different types of water

The Kruskal-Wallis test, using the difference data of pH of tap water as a grouping variable, resulted in a *p*-value of 0.860 for CAR, *p*-value of 0.471 for ION, and *p*-value of 0.481 for DIS, implying that samples are homogeneous ($p > 0.05$).



Descriptive statistics (Table 5), the natural water presented the mean with the greatest difference of values between pH before and pH after filtration, while ionized water and distilled water showed the lowest mean with the difference between pH before and after pH filtration. It is assumed that natural water needs less filtration time to undergo greater pH changes, i.e., water with gas, ionized water and distilled water need to remain contained in the pores of the pervious concrete to undergo greater pH changes.

Table: 5 pH descriptive statistics

	Water type			
	Tap	**Carbonated**	**Ionized**	**Distilled**
mean	3.4	1.4	0.8	0.7
standard deviation	0.331	0.401	0.176	0.321
variance	0.109	0.161	0.031	0.103

Having pervious concrete large and interconnected pores in addition to the typical micropores of cement paste[11], this structure allows ambient air and water to more easily reach the inner spaces. When water flows through pervious concrete, pH of water changes due to the calcium hydroxide and calcium carbonate in the cement slurry[12], with lower pH values, indicating more calcium carbonate or a greater amount of carbonation. The pH change indicates that water encountered calcium hydroxide, with a pH increase. Nonetheless, in this experiment there was no time for formation of calcium carbonate, therefore, it was not possible to detect the carbonation by the reduction of pH in the samples, in these laboratory experiments.

Conclusions

The results obtained in the laboratory and in the field showed that:

- low absorption of tap and distilled water by pervious concrete specimens, is an advantage if it is intended to be used as road paving material, increasing stability under rainfall conditions;
- filtration time, associated to infiltration rate, showed little variation under different water types, suggesting that pervious concrete is use is not constrained by carbon concentration in water;
- pH increase in water samples after infiltration through pervious concrete specimens, in the laboratory and in the field experiments suggest contact of rainwater with the calcium hydroxide in the cement paste, but carbonation and CO_2 sequestration could not be detected probably because there was not enough time for calcium carbonate formation.

These preliminary studies suggest that carbonation was not detected by the methodology used, so it would be interesting to perform other tests, such as X-ray diffraction to identify the chemical components in the samples being tested that serve as evidence of carbonation in the cement.

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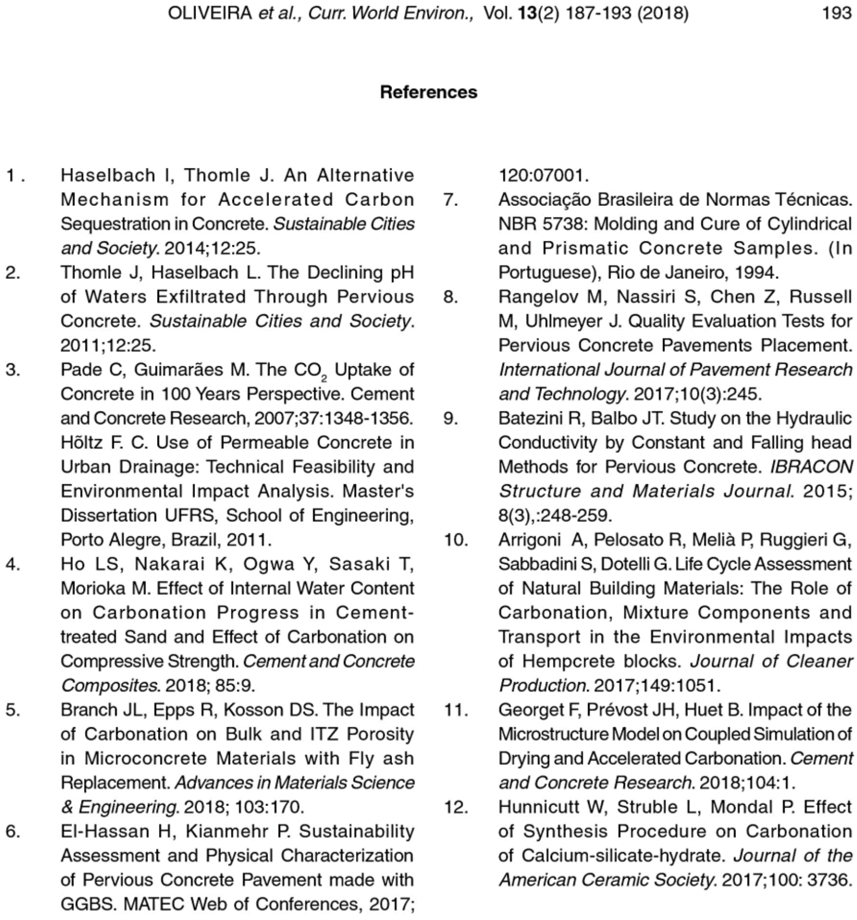

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CAPÍTULO III – Análise Estatística Comparativa entre o Novo Pavimento Urbano *versus* Pavimento Convencional de Betão Permeável

Este capítulo propõe uma comparação de inferência estatística entre o BPM com aditivo de $Ca(OH)_2$ e o BPC utilizado em pavimentos de vias urbanas e interurbanas, com base em estudos que mostraram serem estes aditivos que atuam no processo de sequestração de CO_2 durante a reação química da carbonatação (Haselbach e Thomle, 2014; Benitez-Guerrero *et al.*, 2018; Jamrunroj *et al.*, 2019; Gao *et al.*, 2020). A investigação envolveu a fabricação de um grupo controlo de 40 corpos de prova de BPC e um grupo de testes com 30 corpos de prova de BPM para realização de resistência à compressão (ASTM C-39, 2018), porosidade (Kóvac e Sikaková, 2018), densidade (ASTM C-127, 2015), permeabilidade (Batezini e Balbo, 2015), deformação e monitoramento de sequestração de CO_2, uma metodologia proposta neste artigo. Os resultados demonstram a necessidade da continuidade dos estudos para se encontrar uma proporção do novo BPM que acelere o sequestro de CO_2, sem prejudicar as propriedades físicas de permeabilidade e resistência à compressão.

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EIAETM, 23rd-27th September, 2019

COMPARATIVE STATISTICAL ANALYSIS NEW URBAN ROAD PAVEMENT VERSUS CONVENTIONAL PAVEMENT OF PERVIOUS CONCRETE[*]

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Abstract

This research proposes a variation to pervious concrete pavement, in which a mixture of cement, aggregates and water includes calcium hydroxide additive ($Ca(OH)_2$). This new approach focuses on two main environmental functions: increased permeability of urban soil favoring a decrease of total and peak runoff and resulting reduction of flood occurrence in the cities, and CO_2 absorption from the atmosphere, contributing to reduction of the negative impacts caused by the observed increased greenhouse effect in the cities. A series of 40 conventional pervious concrete pavement samples and 30 specimens of the proposed urban pavement were tested in the laboratory for permeability, density, porosity and compression resistance, and monitored for CO_2 absorption. Results show that there is an environmental benefit of CO_2 sequestration when adding $Ca(OH)_2$ to pervious concrete, but there is also a decrease in its compressive strength and permeability.

Keywords: CO_2 sequestration, road pavement, pervious concrete

1. Introduction

The special report of the Intergovernmental Panel on Climate Change (IPCC, 2018), endorsed by 192 countries, was the main decision-making tool for the Paris Agreement (UNFCCC, 2019). The same report (IPCC, 2018) indicates that a global warming scenario of 1.5°C above pre-industrial levels is safer than 2.0°C, which will promote devastating

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[*] Selection and peer-review under responsibility of the EIAETM
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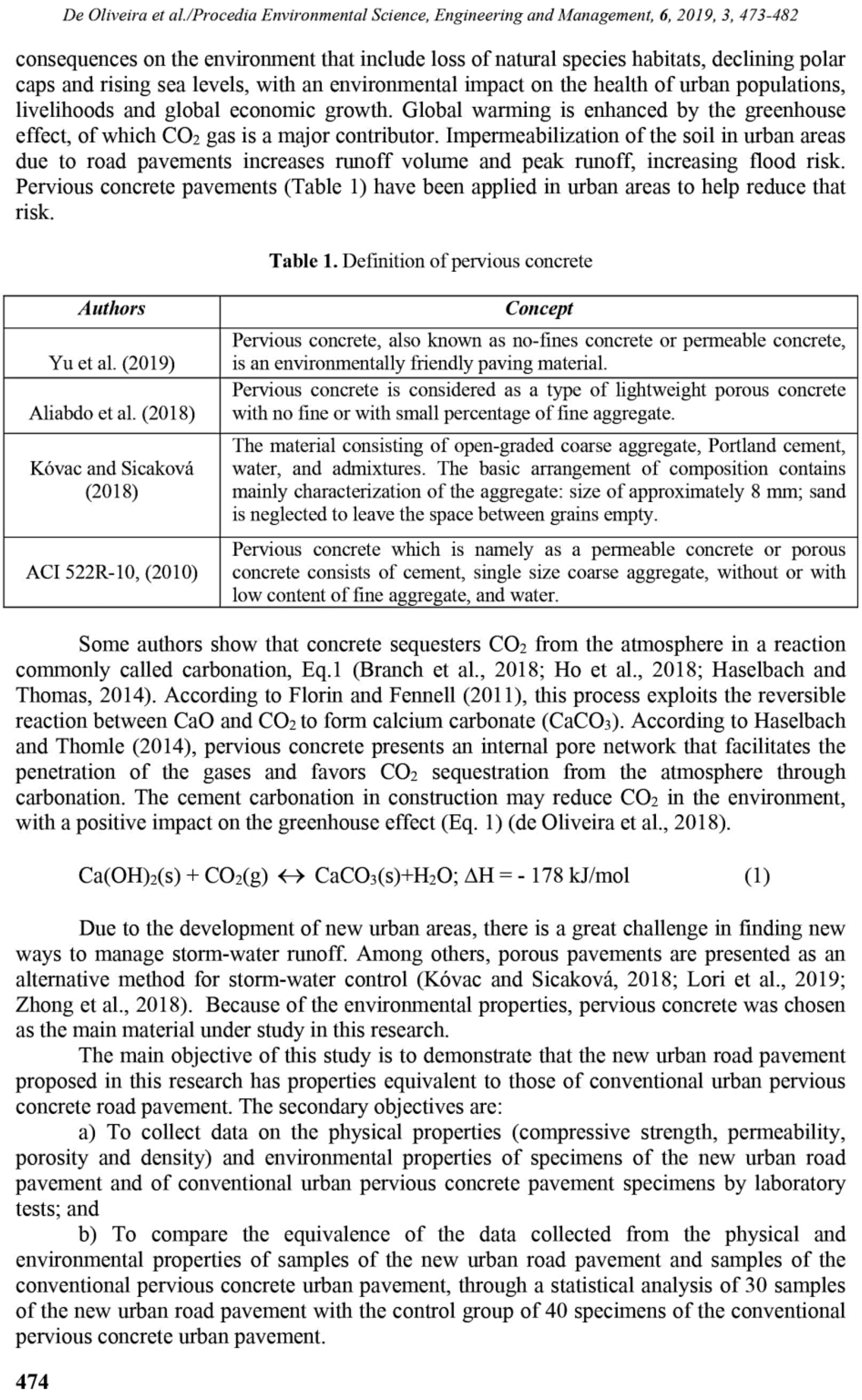


consequences on the environment that include loss of natural species habitats, declining polar caps and rising sea levels, with an environmental impact on the health of urban populations, livelihoods and global economic growth. Global warming is enhanced by the greenhouse effect, of which CO_2 gas is a major contributor. Impermeabilization of the soil in urban areas due to road pavements increases runoff volume and peak runoff, increasing flood risk. Pervious concrete pavements (Table 1) have been applied in urban areas to help reduce that risk.

Table 1. Definition of pervious concrete

Authors	***Concept***
Yu et al. (2019)	Pervious concrete, also known as no-fines concrete or permeable concrete, is an environmentally friendly paving material.
Aliabdo et al. (2018)	Pervious concrete is considered as a type of lightweight porous concrete with no fine or with small percentage of fine aggregate.
Kóvac and Sicaková (2018)	The material consisting of open-graded coarse aggregate, Portland cement, water, and admixtures. The basic arrangement of composition contains mainly characterization of the aggregate: size of approximately 8 mm; sand is neglected to leave the space between grains empty.
ACI 522R-10, (2010)	Pervious concrete which is namely as a permeable concrete or porous concrete consists of cement, single size coarse aggregate, without or with low content of fine aggregate, and water.

Some authors show that concrete sequesters CO_2 from the atmosphere in a reaction commonly called carbonation, Eq.1 (Branch et al., 2018; Ho et al., 2018; Haselbach and Thomas, 2014). According to Florin and Fennell (2011), this process exploits the reversible reaction between CaO and CO_2 to form calcium carbonate ($CaCO_3$). According to Haselbach and Thomle (2014), pervious concrete presents an internal pore network that facilitates the penetration of the gases and favors CO_2 sequestration from the atmosphere through carbonation. The cement carbonation in construction may reduce CO_2 in the environment, with a positive impact on the greenhouse effect (Eq. 1) (de Oliveira et al., 2018).

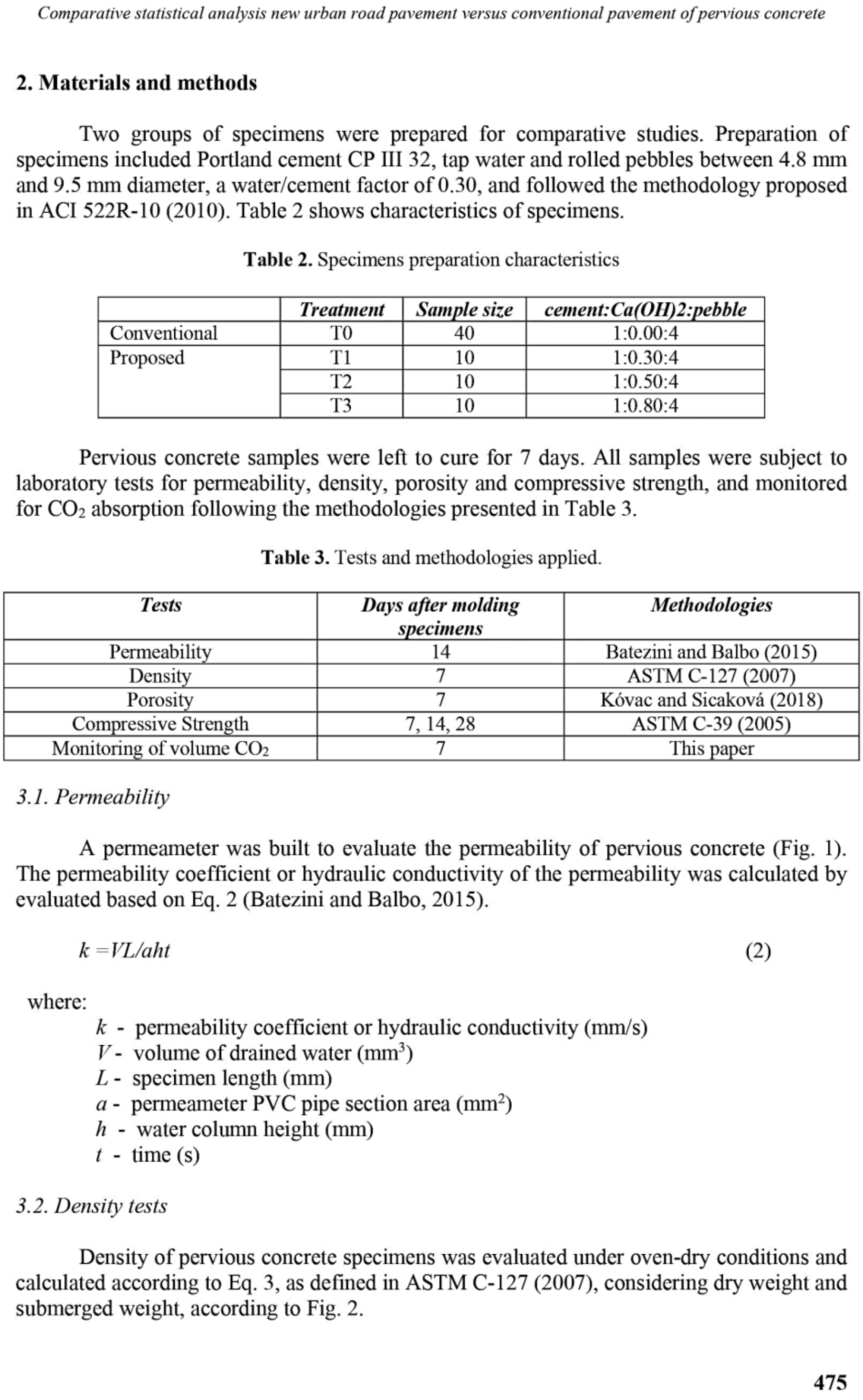
$$Ca(OH)_2(s) + CO_2(g) \leftrightarrow CaCO_3(s) + H_2O;\ \Delta H = -\ 178\ \text{kJ/mol} \qquad (1)$$

Due to the development of new urban areas, there is a great challenge in finding new ways to manage storm-water runoff. Among others, porous pavements are presented as an alternative method for storm-water control (Kóvac and Sicaková, 2018; Lori et al., 2019; Zhong et al., 2018). Because of the environmental properties, pervious concrete was chosen as the main material under study in this research.

The main objective of this study is to demonstrate that the new urban road pavement proposed in this research has properties equivalent to those of conventional urban pervious concrete road pavement. The secondary objectives are:

a) To collect data on the physical properties (compressive strength, permeability, porosity and density) and environmental properties of specimens of the new urban road pavement and of conventional urban pervious concrete pavement specimens by laboratory tests; and

b) To compare the equivalence of the data collected from the physical and environmental properties of samples of the new urban road pavement and samples of the conventional pervious concrete urban pavement, through a statistical analysis of 30 samples of the new urban road pavement with the control group of 40 specimens of the conventional pervious concrete urban pavement.



2. Materials and methods

Two groups of specimens were prepared for comparative studies. Preparation of specimens included Portland cement CP III 32, tap water and rolled pebbles between 4.8 mm and 9.5 mm diameter, a water/cement factor of 0.30, and followed the methodology proposed in ACI 522R-10 (2010). Table 2 shows characteristics of specimens.

Table 2. Specimens preparation characteristics

	Treatment	*Sample size*	*cement:Ca(OH)2:pebble*
Conventional	T0	40	1:0.00:4
Proposed	T1	10	1:0.30:4
	T2	10	1:0.50:4
	T3	10	1:0.80:4

Pervious concrete samples were left to cure for 7 days. All samples were subject to laboratory tests for permeability, density, porosity and compressive strength, and monitored for CO_2 absorption following the methodologies presented in Table 3.

Table 3. Tests and methodologies applied.

Tests	*Days after molding specimens*	*Methodologies*
Permeability	14	Batezini and Balbo (2015)
Density	7	ASTM C-127 (2007)
Porosity	7	Kóvac and Sicaková (2018)
Compressive Strength	7, 14, 28	ASTM C-39 (2005)
Monitoring of volume CO_2	7	This paper

3.1. Permeability

A permeameter was built to evaluate the permeability of pervious concrete (Fig. 1). The permeability coefficient or hydraulic conductivity of the permeability was calculated by evaluated based on Eq. 2 (Batezini and Balbo, 2015).

$$k = VL/aht \tag{2}$$

where:

k - permeability coefficient or hydraulic conductivity (mm/s)
V - volume of drained water (mm^3)
L - specimen length (mm)
a - permeameter PVC pipe section area (mm^2)
h - water column height (mm)
t - time (s)

3.2. Density tests

Density of pervious concrete specimens was evaluated under oven-dry conditions and calculated according to Eq. 3, as defined in ASTM C-127 (2007), considering dry weight and submerged weight, according to Fig. 2.

Fig. 1. Permeability test apparatus

$$D = 997.5A/(B-C) \quad (3)$$

where:

D = density (kg/m^3)
A = mass of oven-dry test sample in air, oven (kg)
B = mass of saturated-surface-dry test sample in air (kg)
C = apparent mass of saturated test sample in water (kg)

Fig. 2. Samples identified after weighing submerged in water

3.3. Porosity

Pervious concrete samples porosity was evaluated according to Kóvac and Sicaková (2018) as shown in Eq. (4):

$$Vr = (1-(w2-w1)/dV)\cdot 100 \quad (4)$$

where:

Vr - porosity (%)
$w2$ - oven dried mass of sample (kg)
$w1$ - mass of sample submerged in water (kg)
d - density of water (kg/m^3)
V – volume of specimen (m^3)

3.4. Compressive strength

The equipment used for the rupture tests was a calibrated and certified hydraulic press (Fig. 3), Pavitest100 (CONTENCO, 2019), with a breaking capacity up to 100 t, and a digital display. The specimens of pervious concrete were ruptured at 7, 14 and 28 days after molding, according ASTM C-39 (2005).

Fig. 3. Specimens identified for rupture tests

3.5. Monitoring of CO_2 volume

A CO_2/Temp/RH Data Logger with an 88.9 mm display was used for CO_2 volume monitoring. The Digital Carbon Dioxide Gas Meter is a measuring instrument for CO_2, temperature and humidity, with accuracy in the range of 0-9999 ppm CO_2, with accuracy of +/- 50 ppm CO_2. Specimens were placed under a 10,000 cm^3 sealed acrylic chamber. A digital carbon dioxide gas meter and a digital timer measure CO_2 changes in the atmosphere in contact with the pervious concrete samples (Fig. 4).

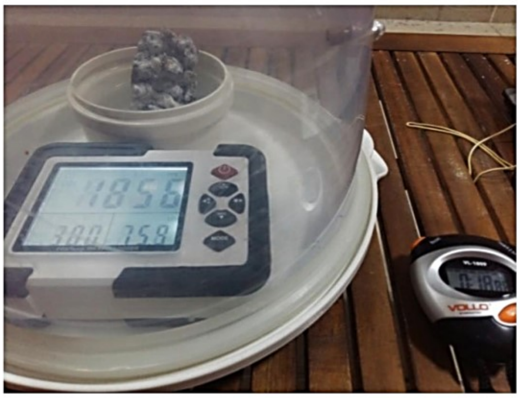


Fig. 4. Monitoring the volume of CO_2 (ppm) over time in an artificially isolated environment

3.6. Analysis

Treated (with $Ca(OH)_2$) and untreated (control group) pervious concrete samples were evaluated for normality by the Shapiro-Wilk test. The Mann-Whitney non-parametric test was applied on all variables to evaluate differences between the treated and control group. Data was analyzed with the statistical package SPSS version 25 2019.

3. Results and discussion

The results of the Permeability, Density, Porosity, Compression Strength tests will be presented in Figs. 5 to 8.

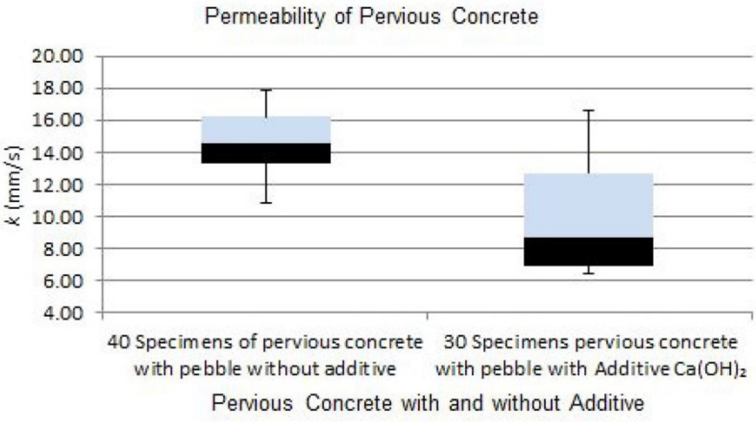


Fig. 5. Permeability coefficient of 40 permeable concrete samples (control group) and 30 samples of the new urban road pavement

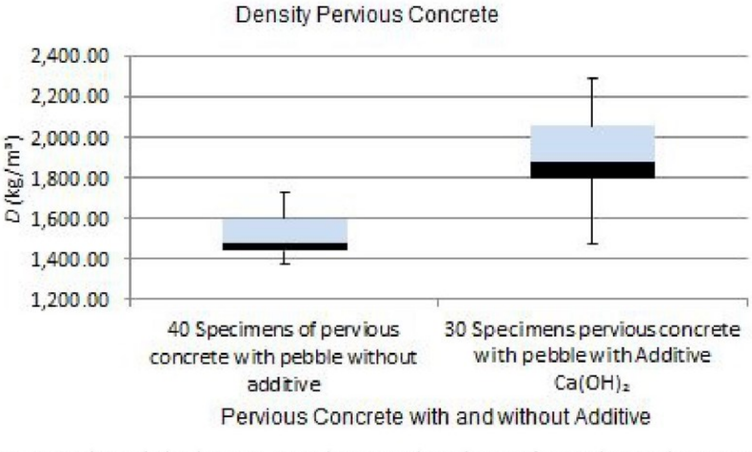


Fig. 6. Density variation between control group and specimens of new urban road pavement

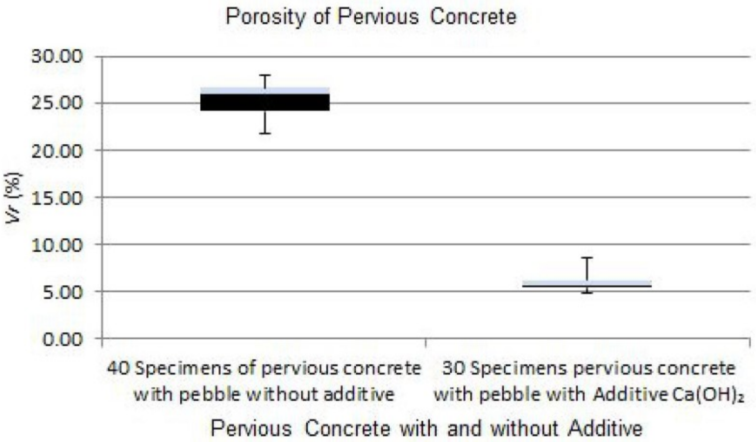


Fig. 7. The porosity of the new urban road pavement is smaller than that of the control group

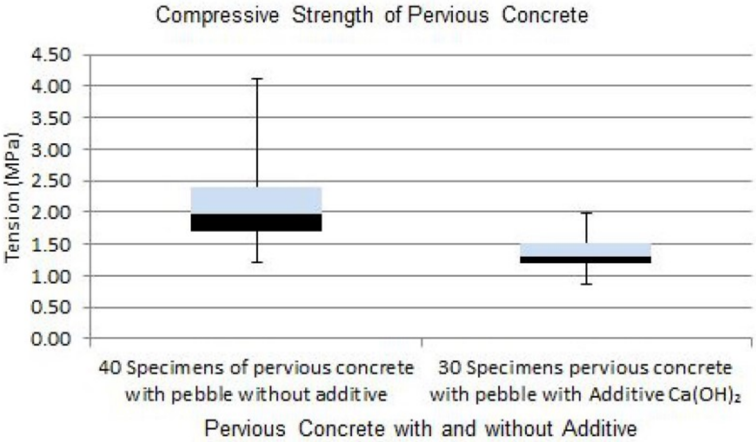
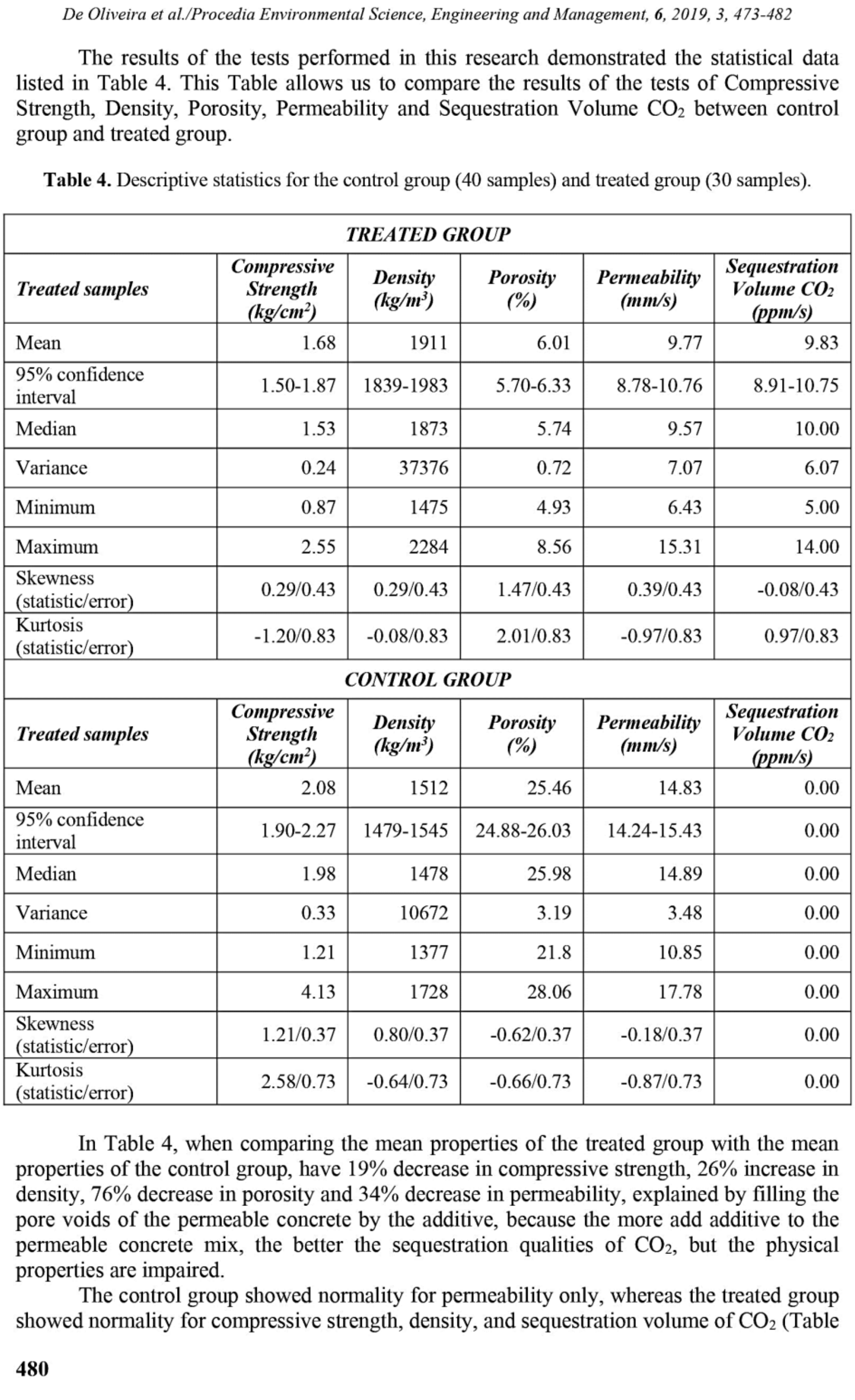


Fig. 8. Test of the compression rupture at 28 days after of specimens molding

The permeability and porosity graphs show a tendency for results below the control group, naturally due to the pore filling by the additive added to the pervious concrete mix. The density graph shows that the new pavement is more compact than the conventional pervious concrete pavement, a characteristic also demonstrated in the permeability and porosity graphs. The compressive strength graph shows a reduction in the maximum compressive strength limit in the new urban pavement samples, which occurs as the amount of additive in the pervious concrete mix increases. Increasing the additive tends to improve CO_2 absorption capacity, but also reduces the compressive strength and permeability of the new pervious concrete pavement. A study of the ideal amount of additive in the mixture was performed by testing the 3 different proportions of additive in the 0.3, 0.5 and 0.8 fractions of $Ca(OH)_2$ additive in the pervious concrete mixture. To verify the normality of the sample results, a statistical study was performed next.



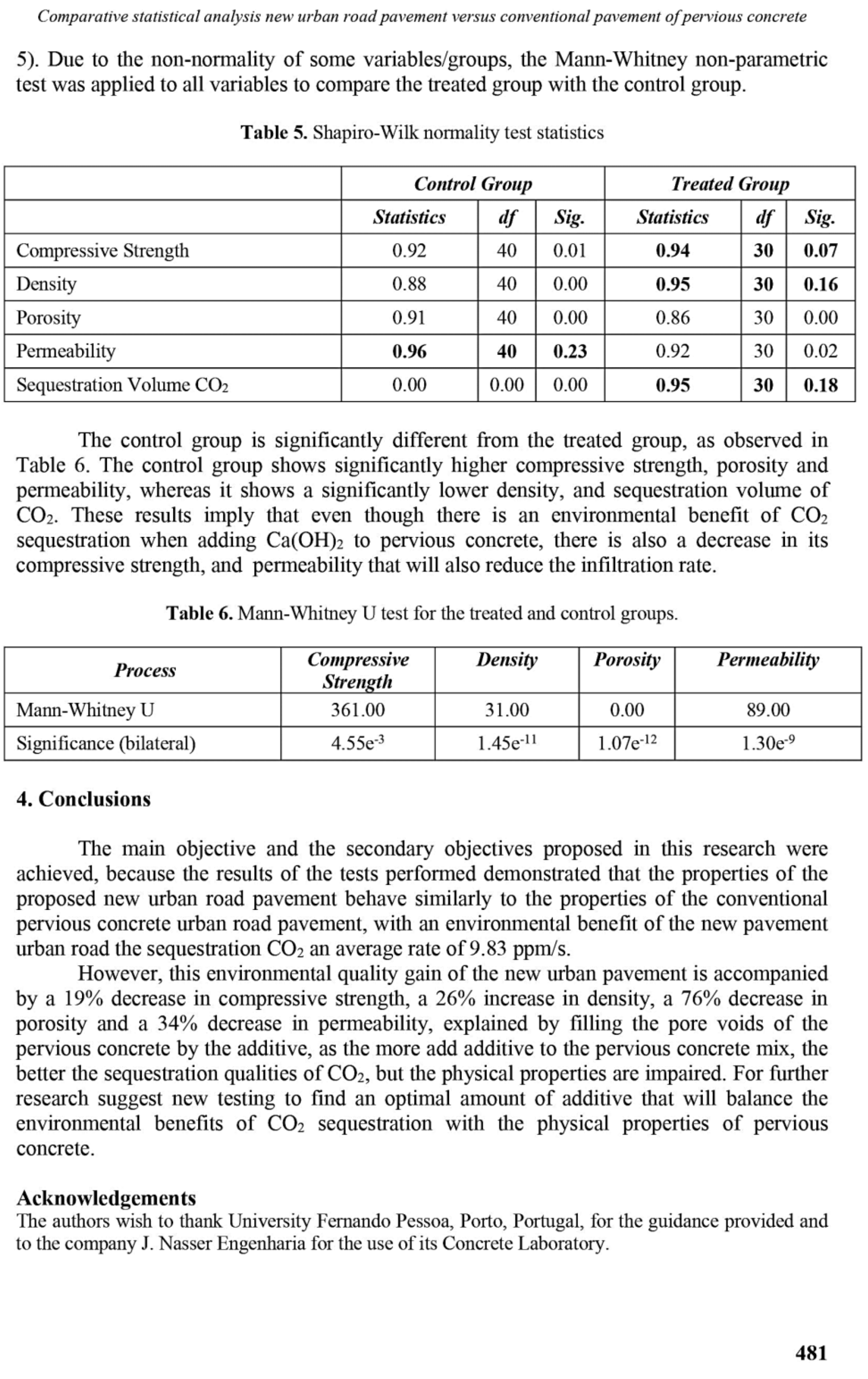
The results of the tests performed in this research demonstrated the statistical data listed in Table 4. This Table allows us to compare the results of the tests of Compressive Strength, Density, Porosity, Permeability and Sequestration Volume CO_2 between control group and treated group.

Table 4. Descriptive statistics for the control group (40 samples) and treated group (30 samples).

TREATED GROUP					
Treated samples	***Compressive Strength (kg/cm^2)***	***Density (kg/m^3)***	***Porosity (%)***	***Permeability (mm/s)***	***Sequestration Volume CO_2 (ppm/s)***
Mean	1.68	1911	6.01	9.77	9.83
95% confidence interval	1.50-1.87	1839-1983	5.70-6.33	8.78-10.76	8.91-10.75
Median	1.53	1873	5.74	9.57	10.00
Variance	0.24	37376	0.72	7.07	6.07
Minimum	0.87	1475	4.93	6.43	5.00
Maximum	2.55	2284	8.56	15.31	14.00
Skewness (statistic/error)	0.29/0.43	0.29/0.43	1.47/0.43	0.39/0.43	-0.08/0.43
Kurtosis (statistic/error)	-1.20/0.83	-0.08/0.83	2.01/0.83	-0.97/0.83	0.97/0.83
CONTROL GROUP					
Treated samples	***Compressive Strength (kg/cm^2)***	***Density (kg/m^3)***	***Porosity (%)***	***Permeability (mm/s)***	***Sequestration Volume CO_2 (ppm/s)***
Mean	2.08	1512	25.46	14.83	0.00
95% confidence interval	1.90-2.27	1479-1545	24.88-26.03	14.24-15.43	0.00
Median	1.98	1478	25.98	14.89	0.00
Variance	0.33	10672	3.19	3.48	0.00
Minimum	1.21	1377	21.8	10.85	0.00
Maximum	4.13	1728	28.06	17.78	0.00
Skewness (statistic/error)	1.21/0.37	0.80/0.37	-0.62/0.37	-0.18/0.37	0.00
Kurtosis (statistic/error)	2.58/0.73	-0.64/0.73	-0.66/0.73	-0.87/0.73	0.00

In Table 4, when comparing the mean properties of the treated group with the mean properties of the control group, have 19% decrease in compressive strength, 26% increase in density, 76% decrease in porosity and 34% decrease in permeability, explained by filling the pore voids of the permeable concrete by the additive, because the more add additive to the permeable concrete mix, the better the sequestration qualities of CO_2, but the physical properties are impaired.

The control group showed normality for permeability only, whereas the treated group showed normality for compressive strength, density, and sequestration volume of CO_2 (Table



5). Due to the non-normality of some variables/groups, the Mann-Whitney non-parametric test was applied to all variables to compare the treated group with the control group.

Table 5. Shapiro-Wilk normality test statistics

	Control Group			*Treated Group*		
	Statistics	***df***	***Sig.***	***Statistics***	***df***	***Sig.***
Compressive Strength	0.92	40	0.01	**0.94**	**30**	**0.07**
Density	0.88	40	0.00	**0.95**	**30**	**0.16**
Porosity	0.91	40	0.00	0.86	30	0.00
Permeability	**0.96**	**40**	**0.23**	0.92	30	0.02
Sequestration Volume CO_2	0.00	0.00	0.00	**0.95**	**30**	**0.18**

The control group is significantly different from the treated group, as observed in Table 6. The control group shows significantly higher compressive strength, porosity and permeability, whereas it shows a significantly lower density, and sequestration volume of CO_2. These results imply that even though there is an environmental benefit of CO_2 sequestration when adding $Ca(OH)_2$ to pervious concrete, there is also a decrease in its compressive strength, and permeability that will also reduce the infiltration rate.

Table 6. Mann-Whitney U test for the treated and control groups.

Process	***Compressive Strength***	***Density***	***Porosity***	***Permeability***
Mann-Whitney U	361.00	31.00	0.00	89.00
Significance (bilateral)	$4.55e^{-3}$	$1.45e^{-11}$	$1.07e^{-12}$	$1.30e^{-9}$

4. Conclusions

The main objective and the secondary objectives proposed in this research were achieved, because the results of the tests performed demonstrated that the properties of the proposed new urban road pavement behave similarly to the properties of the conventional pervious concrete urban road pavement, with an environmental benefit of the new pavement urban road the sequestration CO_2 an average rate of 9.83 ppm/s.

However, this environmental quality gain of the new urban pavement is accompanied by a 19% decrease in compressive strength, a 26% increase in density, a 76% decrease in porosity and a 34% decrease in permeability, explained by filling the pore voids of the pervious concrete by the additive, as the more add additive to the pervious concrete mix, the better the sequestration qualities of CO_2, but the physical properties are impaired. For further research suggest new testing to find an optimal amount of additive that will balance the environmental benefits of CO_2 sequestration with the physical properties of pervious concrete.

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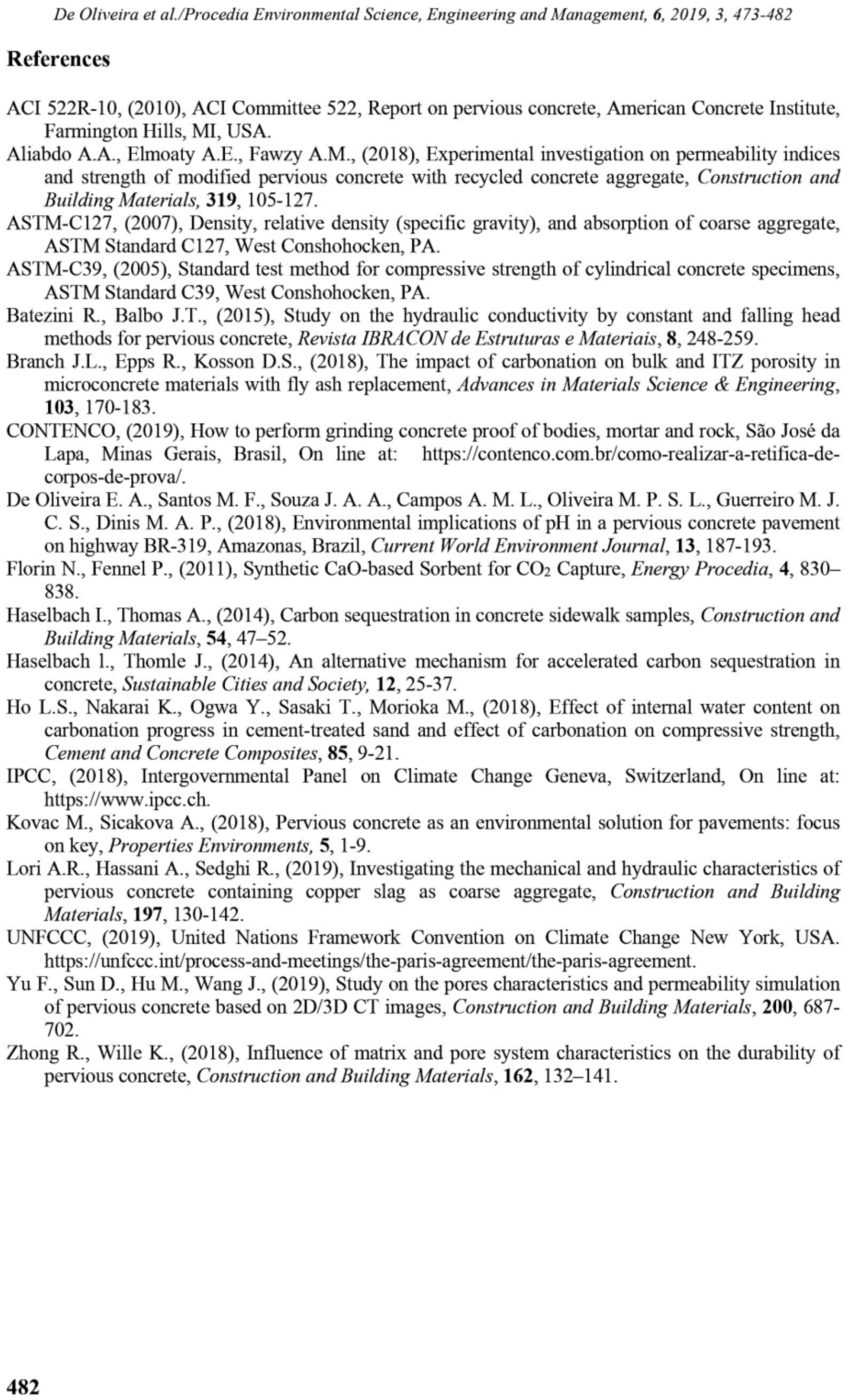

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CAPÍTULO IV – Implicações Ambientais da Sequestração de CO_2 pelo Pavimento de Betão Permeável em Vias Urbanas

Este capítulo apresenta os estudos do BPM com aditivos de $Ca(OH)_2$ e resíduos de borracha de pneus usados de veículos automotores. Este BPM pode ser utilizado como revestimento de pavimentação de vias urbanas com propriedades de reciclagem e reuso dos resíduos de borracha automotiva. O novo BPM possui agregados de seixo e brita nativa originados do próprio estado do Amazonas, o que contribui com a mitigação das emissões de CO_2. A pesquisa utilizou dois grupos de corpos de prova, sendo um grupo controlo de BPC e outro grupo de testes, composto do novo BPM com aditivos, para realização de ensaios de porosidade, densidade, condutividade hidraulica, resistência à compressão e monitoramento de absorção de CO_2. Os resultados foram utilizados em análises estatísticas, paramétricas e não paramétricas, para verificação da normalidade das amostras, o qual demonstraram que o novo BPM possui propriedades físicas compatíveis com o BPC.

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ENVIRONMENTAL IMPLICATIONS of CO_2 ABSORPTION BY PERVIOUS CONCRETE PAVEMENT IN URBAN ROADS

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Abstract

This research deals with a new material, made from conventional pervious concrete, but with the addition of two components in its mixture, calcium hydroxide ($Ca(OH)_2$), to improve its carbon dioxide (CO_2) absorption properties from the atmosphere, and Scrap Tyre Tubes (STT), a rubber waste from used tyres of vehicle (motorcycles and cars), which makes the new material lighter and contributes to urban sustainability by reusing industrial waste automotive. Conventional pervious concrete has a main property that benefits the environment, which is natural from its porous structure, which is the permeability of the urban pavement, which allows the drainage of rainwater from the urban pavement to the underground, contributing to the reduction of flooding in cities through the infiltration of water into the groundwater. This research sought to improve conventional pervious concrete through additives in its mix to create a new porous material, more efficient at sequestering CO_2 from the atmosphere, lighter and reusing rubber waste from used tyres. The porosity of conventional pervious concrete makes this material ideal for carbon dioxide (CO_2) sequestration due to the ease of CO_2 penetration into its internal structure pore network, which interacts with cement and other additives, which by means of a chemical reaction called carbonation, absorbs CO_2 from the atmosphere to form calcium carbonate ($CaCO_3$) in its internal structure, which is an excellent environmental benefit for the materials used in the manufacture of urban pavements, as it makes the urban pavement contribute directly for air quality and for the control of pollution emanating from motor vehicles traveling on urban roads. In this investigation were performed laboratory tests of compressive strength and permeability, because these are the most important properties of conventional permeable concrete that make this building material a porous pavement that can be used on urban roadways, these properties are essential for the new pervious concrete material, were also CO_2 volume monitoring in contact with specimens of conventional pervious concrete and specimens of new material, because this environmental benefit of CO_2 absorption from the atmosphere is very important for the control of air quality in large metropolis, which have high levels of pollution that affect the life of urban citizens, causing respiratory diseases in old and children. In this research, 40 conventional pervious concrete were manufactured with limestone aggregate, to serve as a control group in the statistical analysis and 10 specimens of the new material of pervious concrete also were manufactured with proportions of 1:0.5:4 (cement:$Ca(OH)_2$:pebble), factor water/cement (*w/c*) of 0.30, with 5% STT in mix, because the proportion of SST in the mix defines how much waste tyre waste can be reused in the manufacture of this new material. The STT is a non-biodegradable material that occupies a lot of urban space, so it harms the environment and the quality of life of the urban citizen, an alternative to reuse STT in the mix of new pervious concrete material is a very important sustainable solution to modern cities around the world due to the progressive annual increase of this waste tire rubber from automotive industries. In this research the results of the tests served to compare compression and permeability, as well as monitoring the absorption of CO_2 from the atmosphere of the different groups. The results of the compressive strength and permeability tests and CO_2 volume monitoring were analyzed statistically for normality and the *t*-Student test. This analysis showed that the improvement of environmental properties harms the physical properties of the new material with compressive strength of 1.25 MPa, permeability of 7.00 mm/s and 5% of STT in the mix of new material of the pervious concrete, however, this new permeable concrete material can be used in non-structural works, such as

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garden pavement, pedestrian sidewalks, finishes to beautify buildings and condominium facades, etc., due to the environmental benefits it produces and cannot be neglected.

Key words: sustainable pavement; air quality; urban pollution control

1. Introduction

New, cheaper and more efficient carbon dioxide (CO_2) capture techniques to control urban pollution and reduce the greenhouse effect are in high demand (Bhawna et al., 2019), so this research is important for reducing CO_2 emitted by factories, industries, vehicles and other combustion engines that promote pollution in the urban atmosphere, and this research also contributes to the recycling of waste tyres that increase each year in cities, the reuse of waste tyres from automotive factories is urgently needed because waste tyres are not biodegradable and take up a lot of urban space (Arulrajah et al., 2019), and the European Commission determines that by 2020 in Europe 50% of waste is recycled or reused (Directive 2008/98/EC, 2008). This research deals with the study of a new material, created from conventional pervious concrete, material formed by cement, aggregates and water with porous properties (Lori et al., 2019). The new material has the addition of calcium hydroxide ($Ca(OH)_2$) in its mixture, which uses the porous internal structure of pervious concrete to produce the following chemical reactions: calcination, hydration and carbonation. Calcination (eq.1) is an endothermic reaction that produces calcium oxide (CaO); Hydration (eq.2) is an exothermic chemical reaction that produces $Ca(OH)_2$, a cheap and abundant material in nature; and carbonation (eq.3), which is an exothermic chemical reaction that captures CO_2 from the atmosphere to produce calcium carbonate ($CaCO_3$), (Jamrunroj et al., 2019).

$$CaCO_{3(s)} \longleftrightarrow CaO_{(s)} + CO_{2(g)} \qquad \Delta H = +178 \text{ kJ/mol} \qquad (1)$$

$$CaO_{(s)} + H_2O_{(aq)} \longleftrightarrow Ca(OH)_{2(s)} \qquad \Delta H = -178 \text{ kJ / mol} \qquad (2)$$

$$Ca(OH)_{2(s)} + CO_{2(g)} \longleftrightarrow CaCO_{3(s)} + H_2O \qquad \Delta H = -178 \text{ kJ / mol} \qquad (3)$$

More complex CO_2 capture studies have been performed in China (Li et al., 2019), including the use of artificial atmospheric pressure to accelerate carbonation, but it is a very expensive and energy-intensive method in urban environments. In the search for cheaper solutions, it was decided in this research to study the addition of $Ca(OH)_2$ to the pervious concrete during the preparation, because the high porosity of this material facilitates the penetration of external gases of the atmosphere, which catalyze the carbonation in the process for the CO_2 sequestration, as the pH within the internal structure (De Oliveira, 2018). Studies for adsorption of CO_2 by porous solid materials used techniques for CO_2 capture technologies with CaO-based sorbent, applied for high-temperature (Jamrunroj et al., 2019), but it is also a process that uses a lot of energy and is very expensive.

The new material keeps the characteristics of pervious concrete conventional of infiltrating rainwater and allowing it to infiltrate the soil, it preserves groundwater and reduces the flow of rainwater on urban roads, preventing flooding and car accidents caused by aquaplaning (Sun et al., 2019). The type of aggregate, pebble or limestone in the permeable concrete mix influences its physical and environmental properties (Kovác and Sicaková, 2018), therefore in this research we used the 2 types of aggregates, pebble and limestone, in each control group of specimens. A holistic view of the environment in which pervious concrete will be applied is required during the engineering design phase by studying the benefits and sustainability and durability of pervious concrete (Xie et al., 2019).

In addition to the environmental benefits of CO_2 absorption from the atmosphere, the new material can also be used to reuse tyre waste from vehicles, motorcycles and cars from the automotive industry, which could contribute to the movement of the circular waste economy already implemented in Europe. Tyre waste recovery is already becoming a trend in more developed countries, according to the European Tyre and Rubber Manufacturers Association over 3.6 million tons per year of tyre waste was reused in Europe (ETRA, 2015), despite initial resistance due to contamination of tyre waste by steel particles and rubber dust making reuse and recycling difficult (Onuaguluchi and Banthia, 2019). The European Union volume of waste generated each year, about 15 million tons per year (Eurostat, 2016) is of concern, as it tends to grow as the world fleet of vehicles also grows, knowing that the used tyre is It is a non-biodegradable material and occupies a lot of urban space, although it can be stacked (Arulrajah et al., 2019). More and more studies on tyre waste utilization are being carried out, such as the reuse in foundations of construction works, respecting the load and overload limits of infrastructure and soil (Gill and Mittal, 2019), reuse of fibers rubber in concrete strengths, called concrete reinforcement fibers (FRC), tested in the laboratory to obtain better strength of concrete, within the limits of the technical standards governing the fabrication of structural reinforced concrete (Chen et al., 2019) and the reuse of rubber waste at the base and subbase of flexible asphalt pavement as well as asphalt aggregate itself (Saberian et al., 2019). Studies are also being conducted for the use of recycled tyre polymer fibers (RTPF) as micro reinforcement in concrete mixtures (Baricevic et al., 2018). In Brazil the problem of tyre waste is more serious than in Europe, because waste management by the circular economy has not yet been implemented, and the volume per year of Construction and Demolition Waste (RCD) and other waste only tends to increase each year (Lamego Oliveira et al., 2019). In Australia, studies have shown a growing increase in landfills and solid waste generation, which has increased CO_2 emissions in that region, mainly due to burning of rubber waste (Saberian and Li, 2018). This is why the importance of recycling and reuse of construction waste materials (CCR), such as the recycling of rubber waste pavement (Li et al., 2018). Recycling and reuse of materials can reduce CO_2 emissions and according to UN environmental policy the temperature of the planet is rising every year because of the greenhouse effect and urgent measures must be taken to reduce greenhouse gas emissions (IPCC, 2018). All of these studies prove the increasingly urgent need for reuse and recycling of used tyre waste to keep pace with the increasing volume/year of this waste, a volume that grows with the growing fleet of vehicles in the world, and so harms the environment. The new material under study in this research also allows the reuse of tyre waste through scrap tyre tubes (STT) in the mixture during its manufacture. The study conducted in this research is very important for improving air quality and for recycling and reusing tyre waste in the cities.

The main objective of this research is to verify the behavior of the physical properties of the new pervious concrete material when subject to the improvement of environmental properties by adding $Ca(OH)_2$ and STT to the mixture during its manufacture. Secondary objectives are the collection of data on physical and environmental properties of the new pervious concrete material through tests of compressive strength and permeability, as well as monitoring of CO_2 volume, in isolated environment, in the presence of specimens of the new pervious concrete with $Ca(OH)_2$ and STT additives.

2. Materials and Methods

In this research the methodology applied for the preparation of pervious concrete specimens was from ASTM C192, with the moulds made of PVC pipe, in the dimensions of 200.0 mm (height) by 100.0 mm (diameter), and the characterization of the aggregates was done by granulometry test, ASTM C136, of pebble and limestone aggregates, approximately 4.5 mm to 9.0 mm in size, through sieving. The methodology applied to the rubber tyre reuse STT specimens was the one performed by Boon et al. (2017). The pebble aggregate, Figure 1, originated from the Juruá River (Amazon), the limestone, Figure 2, originated from the crushing processing of rocks found in the neighboring cities of Manaus (Amazonia) and the STT, Figure 3, used in this research originated from discarded used tyres in the city of Manaus (Amazonia).

Figure 1. **Pebble aggregate *scale* algures**

Figure 2. **Aggregate limestone *scale* algures**

Source: authors.

Recycling of used tires follows the methodology proposed by Boon et al. (2017), carried out by processing the STT which is washed to remove impurities and cut into small rectangular shaped rubber particles, with an average size of 10.0 mm by 6.00 mm, for mixing during the manufacture of permeable concrete. The proportion of tube-rubber particles is 5% of the cement mass, about 19.0 kg/m³ of STT. The value of 5% was proposed by Boon et al. (2017) after conducting tests with the proportions of 3%, 5% and 7% to verify the physical properties with the mixture of STT in pervious concrete, which concluded that when STT is added to the mass of pervious concrete the physical properties of compressive strengths are impaired. In this research we have adopted the average value of 5% STT in relation to the pervious concrete mix so as not to overly affect the compressive strength property of our new pervious concrete material with STT. Figure 4 shows the tube-rubber particles after preparation and ready for mixing into the pervious concrete mass during their manufacture.

Figure 3. **Scrap Tyte Tube (STT)**

Figure 4. **Tube-rubber particles *scale* algures**

Source: authors.

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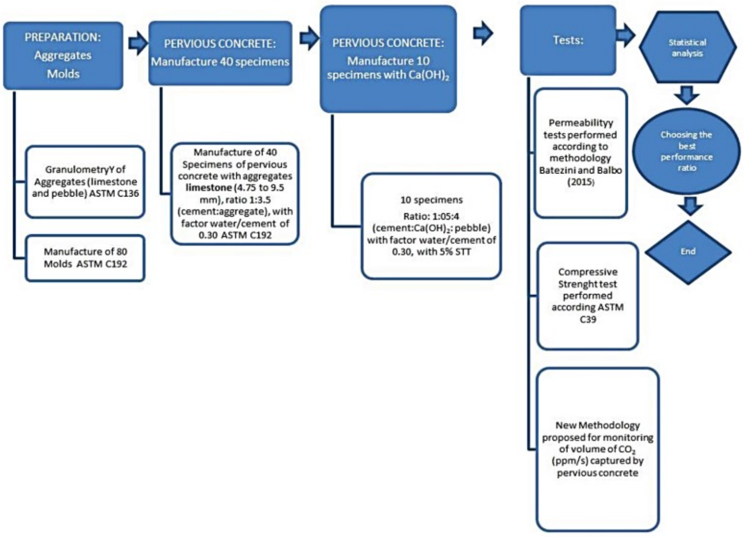
The tests were carried out at the Laureat Universit International Concrete Laboratory, in Manaus, Amazonas, Brazil. The methodology used followed the activity flowchart of Figure 5.

Figure 5. **Activity Flowchart**



Source: authors.

The pervious concrete specimen with STT is shown in the Figures 6 and 7.

Figure 6. **Pervious concrete with STT**

Figure 7. **Pervious concrete weighing with STT**

Source: authors.

The granulometry tests were carried out, the following proportions of aggregates were determined in the pervious concrete mixtures, according to percentage of sieves #4.75 (30%), #6.3 (40%) e #9.5 (30%). The molds were manufactured for the preparation of pervious concrete species in the laboratory. The molds were made of PVC, with the dimensions of 100 x 200 mm, according to ASTM C192. The methodology applied to calculate the trace of pervious concrete was the one proposed by Batezini and Balbo (2015) for the mixture ratio of Pervious Concrete. The materials used were the ordinary Portland cement CP IV 32, aggregates and water. The sand was not used in the mixture, only pebble and calcareous gravel. A 180,000 cm3 three-phase concrete mixer was the equipment used to mix the aggregates and cement at a ratio of 1: 4.4, with a water/cement factor (w/c) of 0.30. The mixing ratio of pervious concrete is composed of 380.0 kg/m³ cement, 1,700 kg/m³ coarse aggregate, factor 0.30 (w/c), and 1:4.4 (cement:aggregate) with 19.0 kg/m³ of STT. The 10 specimens of pervious concrete with 19.0 kg/m³ of STT were manufactured in this research. The 40 specimens of pervious concrete conventional were produced with limestone aggregate, according to the molding in Figure 3, and demoulding occurred in 24 h, to serve as a control group in the statistical analysis. Studies were carried out with 10 specimens new material of the pervious concrete with an increase of $Ca(OH)_2$ during its mixture, with the proportions of 1:0.5:4 (cement:Ca(OH)2: pebble), factor 0.30 (*w/c*), in order to verify the ratio with better performance in the tests. In this research were carried out tests of permeability and compressive strength of specimens of pervious concrete. The permeability coefficient or hydraulic conductivity of the permeability was calculated by evaluated based on eq.4 (Batezini and Balbo, 2015). The methodology used in laboratory tests followed ASTM standards according to modern laboratory techniques and proposed technological precepts (Aliabdo et al., 2018).

$$k = \frac{VL}{aht} \tag{4}$$

Where:

- k - permeability coefficient or hydraulic conductivity (mm/s)
- V - volume of drained water (mm^3)
- L - specimen length (mm)
- a - permeameter PVC pipe section area (mm^2)
- h - water column height (mm)
- t - time (s)

A permeameter was built with PVC tubes ϕ50.00 mm to evaluate the permeability coefficient of pervious concrete (Afonso et al., 2019). The Figure 8 show the equipment used in test of the permeability.

Figure 8. **Permeameter equipment**

Source: authors.

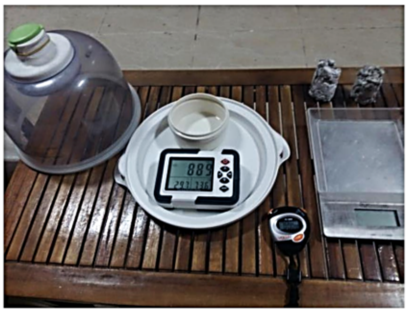
The pervious concrete specimens were ruptured at compressive strength at 7, 14 and 28 days after casting, as per ASTM C-39 (2018). The equipment used for the rupture tests was a calibrated and certified Pavitest100 hydraulic press with a rupture capacity of up to 100 t and equipped with a digital display.

Figure 9. **Test of Compreension Strength**

Source: authors.

The monitoring of CO_2 volume was performed through the equipment digital carbon dioxide (CO_2) gas meter, temperature and humidity, measuring in the range 0-9999 ppm CO_2 and +/- 50 ppm CO_2 accuracy. A carbon dioxide digital carbon meter and a digital timer measure the changes in CO_2 in the atmosphere in contact with the pervious concrete specimens were placed under a 10,000 cm^3 sealed acrylic chamber as shown in Figure 10. The CO2 monitoring tests were performed with the control group of 40 samples of conventional permeable concrete and 10 samples of the new permeable concrete material with STT.

Figure 10. **The monitoring of CO_2 volume**



Source: authors.

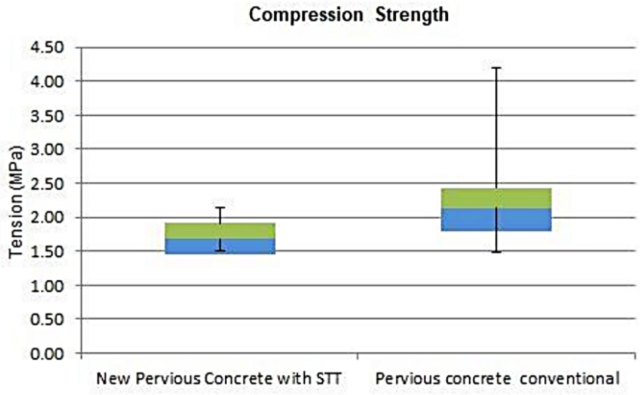
The statistical analysis was performed with the statistical package SPSS version 25 2019. The control groups formed by 40 specimens of the pervious concrete conventional with limestone aggregate and treated group formed by 10 specimens new material of pervious concrete. The study performed the statistical analysis to verify the normality of the data. The specimens group

of the new material with $Ca(OH)_2$ additive in proportion 1:0.5:4 (cement:$Ca(OH)_2$):pebble), factor water/cement (*w/c*) of 0.30, and the 5% STT group in their mixture were treated for comparison with the control groups.

3. Results and Discussion

Figure 11 shows the results of the specimens of pervious concrete conventional control group and the results of the treated group of the new material pervious concrete with additives for analysis and comparison.

Figure 11. **Results of Tests Compressive Strength**



Source: authors.

Analyzing the data shown in Figure 12 it can be stated that when comparing the pervious concrete conventional control groups with limestone aggregate and new material with STT in the compressive strength results, about 15% to 20% reduction in compressive strength, probably due to the addition of additive in the mix of new pervious concrete material with natural aggregate of river gravel type, pebbles of limestone, quartz and various metamorphits (Kovác and Sicaková, 2018). Comparing the results of the groups formed by the new pervious concrete with addition of $Ca(OH)_2$ and STT, it is found that the best result was the group control of pervious concrete conventional without addition of $Ca(OH)_2$ in the ratio of 1:0.50:4 (cement:$Ca(OH)_2$:pebble) and without STT. The new pervious concrete group with $Ca(OH)_2$ addition at a ratio of 1: 0.50: 4 (cement:$Ca(OH)_2$:pebble) shows results about 15% to 20% loss than the pervious concrete control group, probably due to the internal pore structure of the pervious concrete that has been filled by the additives to make the material more compact and durable. The worst result was the new pervious concrete group with 5% STT added, because the addition of STT impairs the mechanical strength of the material (Boon et al., 2017), which shows that the addition of $Ca(OH)_2$ and STT additives impair the compressive strength of the pervious concrete material. Excess additive in the pervious concrete mix impairs the pervious concrete mix making the material more fragile and poorly resistant. The results demonstrate that the amount of additives to be added to the pervious concrete mix, such that the material has acceptable loss in compressive strength without weakening it, and maintain the benefits to the

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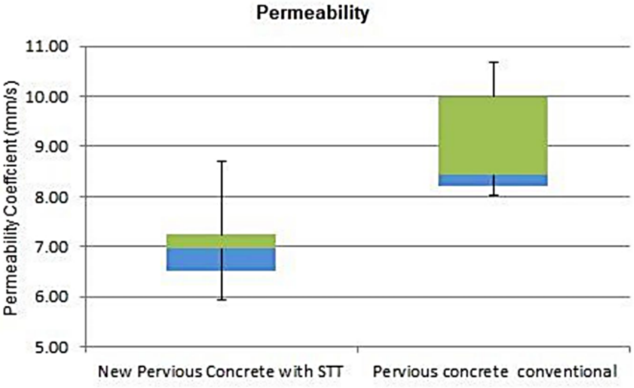
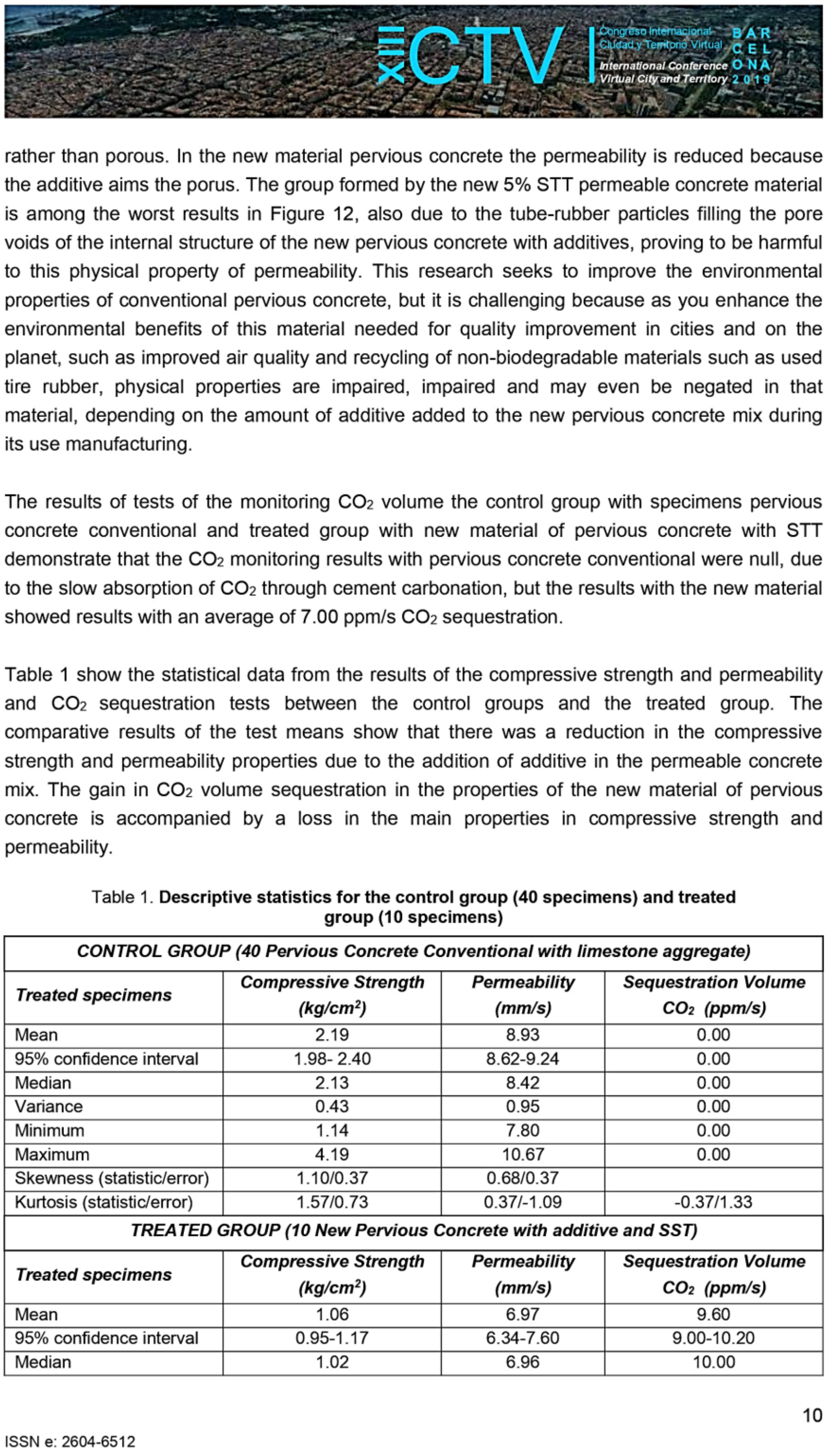
urban sequestration environment CO_2 and recycling of used vehicle tires is the ratio of 1: 0.50: 4 (cement:$Ca(OH)_2$:pebble) with an additive of 5% STT. Further future studies should be performed to prove this hypothesis, including field experimentation of the new pervious concrete material with additives that improve CO_2 absorption and allow the reuse of used tires, environmental benefits that offset the loss of compressive strength. This is because this new material can be used in works that do not require structural strength, such as pedestrian sidewalks, garden pavements, etc. The results of the permeability tests of the specimens of pervious concrete conventional control groups and the treated group of the new pervious concrete with additives and STT are shown in Figure 12.

Figure 12. **Results of Tests Permeability**



Source: authors.

The permeability coefficient or hydraulic conductivity is one of the most important property of permeability medium (Afonso et al., 2019). Analyzing Figure 12, it can be seen that the pervious concrete conventional control group presented the best result, about 20% to 30% higher than the other groups, probably due to the smooth faces structure of the river aggregate that facilitates the passage of water through the internal pore network in the pervious concrete structure. The conventional pervious concrete control group with limestone aggregate had a lower result than the pebble aggregate group, probably due to the shape and roughness of this aggregate that make it difficult for water to pass through the internal pore network of the pervious concrete. The compressive strength result and this permeability result indicate the pebble as an efficient aggregate for the new pervious concrete material with $Ca(OH)_2$ and STT additives. Comparing the results of the new pervious concrete material groups with additives in the ratios of 1:0.50:4 (cement:$Ca(OH)_2$:pebble) it is observed that as we add additive to the pervious concrete mixture the permeability coefficient decreases in the same proportion. The explanation for this result is that the additive fills the internal voids of the internal pore structure of the pervious concrete, so the more void filling, the lower the permeabilization capacity of the new pervious concrete with $Ca(OH)_2$ additive. Excessive addition of additive to the new pervious concrete material can nullify the permeability of this material, making the material compact



rather than porous. In the new material pervious concrete the permeability is reduced because the additive aims the porus. The group formed by the new 5% STT permeable concrete material is among the worst results in Figure 12, also due to the tube-rubber particles filling the pore voids of the internal structure of the new pervious concrete with additives, proving to be harmful to this physical property of permeability. This research seeks to improve the environmental properties of conventional pervious concrete, but it is challenging because as you enhance the environmental benefits of this material needed for quality improvement in cities and on the planet, such as improved air quality and recycling of non-biodegradable materials such as used tire rubber, physical properties are impaired, impaired and may even be negated in that material, depending on the amount of additive added to the new pervious concrete mix during its use manufacturing.

The results of tests of the monitoring CO_2 volume the control group with specimens pervious concrete conventional and treated group with new material of pervious concrete with STT demonstrate that the CO_2 monitoring results with pervious concrete conventional were null, due to the slow absorption of CO_2 through cement carbonation, but the results with the new material showed results with an average of 7.00 ppm/s CO_2 sequestration.

Table 1 show the statistical data from the results of the compressive strength and permeability and CO_2 sequestration tests between the control groups and the treated group. The comparative results of the test means show that there was a reduction in the compressive strength and permeability properties due to the addition of additive in the permeable concrete mix. The gain in CO_2 volume sequestration in the properties of the new material of pervious concrete is accompanied by a loss in the main properties in compressive strength and permeability.

Table 1. **Descriptive statistics for the control group (40 specimens) and treated group (10 specimens)**

CONTROL GROUP (40 Pervious Concrete Conventional with limestone aggregate)			
Treated specimens	***Compressive Strength (kg/cm^2)***	***Permeability (mm/s)***	***Sequestration Volume CO_2 (ppm/s)***
Mean	2.19	8.93	0.00
95% confidence interval	1.98- 2.40	8.62-9.24	0.00
Median	2.13	8.42	0.00
Variance	0.43	0.95	0.00
Minimum	1.14	7.80	0.00
Maximum	4.19	10.67	0.00
Skewness (statistic/error)	1.10/0.37	0.68/0.37	
Kurtosis (statistic/error)	1.57/0.73	0.37/-1.09	-0.37/1.33
TREATED GROUP (10 New Pervious Concrete with additive and SST)			
Treated specimens	***Compressive Strength (kg/cm^2)***	***Permeability (mm/s)***	***Sequestration Volume CO_2 (ppm/s)***
Mean	1.06	6.97	9.60
95% confidence interval	0.95-1.17	6.34-7.60	9.00-10.20
Median	1.02	6.96	10.00

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Variance	0.02	0.78	0.71
Minimum	0.87	5.51	8.00
Maximum	1.33	8.71	11.00
Skewness (statistic/error)	0.81/0.69	0.38/0.69	-0.39/0.69
Kurtosis (statistic/error)	-0.37/1.33	0.94/1.33	0.37/1.34

Source: authors.

Comparing the statistical data found that control group 1 has better results than control group 2, demonstrating that in pervious concrete the pebble aggregate is more efficient than limestone aggregate. Comparing the control group 1 with the other treated groups, found a decrease in the physical properties results, showing that the additives incorporated in the new permeable concrete mixture impair their physical qualities, as the amount of additive increases.

The control group is significantly different from the treated group, as observed in Table 2. According to Figure 12 the new permeable concrete material with additives showed better results than the conventional permeable concrete control group, about 20 to 30%, but the result was due to the 1: 0.50 ratio being optimized, since the addition of Additive in the mixture causes the material to break down and its strength to resist. Figure 13 shows a negative result for the new STT additive permeable concrete group, as it shows a 5 to 15% reduction in permeability compared to the control group. The additive fills the voids in the internal pore network, which impairs the permeability coefficient or the hydraulic conductivity of the new material. Whereas in Figure 12 there is an apparent increase in resistance, probably due to the new material becoming more compact with the addition of additive in its mix, but Figure 13 demonstrates that this material compactness reduces permeability. A balance between compressive strength and permeabilide is very important and can only be found through testing.

Due to the non-normality of all the variables of the treated group, the nonparametric Mann-Whitney test was applied to all variables to compare the treated group with the control group as presented in Table 2. The results of the volume CO2 sequestration were not presented because the control group presented null results.

Table 2. **Mann-Whitney U test for the treated and control groups**

Process	***Compressive Strength***	***Permeability***
Mann-Whitney U	5.500	23.000
Significance (bilateral)	0.000	0.000

Source: authors.

Table 3 shows the normality test statistics of the Shapiro-Wilk with tests of the compressive strength, permeability and sequestration volume CO_2.

Table 3. **Shapiro-Wilk normality test statistics**

	Control Group 1			***Treated Group***		
	Statistics	***df***	***Sig.***	***Statistics***	***df***	***Sig.***
Compressive Strength	0.923	40	0.010	**0.894**	**10**	**0.189**
Permeability	0.847	40	0.000	**0.975**	**10**	**0.935**
Sequestration Volume CO_2				**0.890**	**10**	**0.172**

Source: authors.

4. Conclusions

In this research, the main objective was achieved when it was found that the addition of $Ca(OH)_2$ and STT in the mixture of the new pervious concrete material, during its manufacture, presents a behavior detrimental to the physical properties of compressive strength and permeability, despite improve their environmental benefits from CO_2 sequestration and reuse of rubber the old tires. The data obtained in this research it was found that the proportion of the new pervious concrete material that presented better results was 1:0.5:4 (cement:$Ca(OH)_2$:pebble), with water factor cement (*w*/*c*) of 0.3, and a 5% of STT. The new pervious concrete material with $Ca(OH)_2$ and STT additives can be used in non-structural works such as pedestrian walkways, garden pavements, architectural beautification of building facades and interiors of homes. For further research suggest more tests to find an optimal balance between the improvement of environmental properties through additives in the mixing of the new pervious concrete material with loss of the physical properties of this material.

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Conflicts of Interest: The authors declare no conflict of interest.

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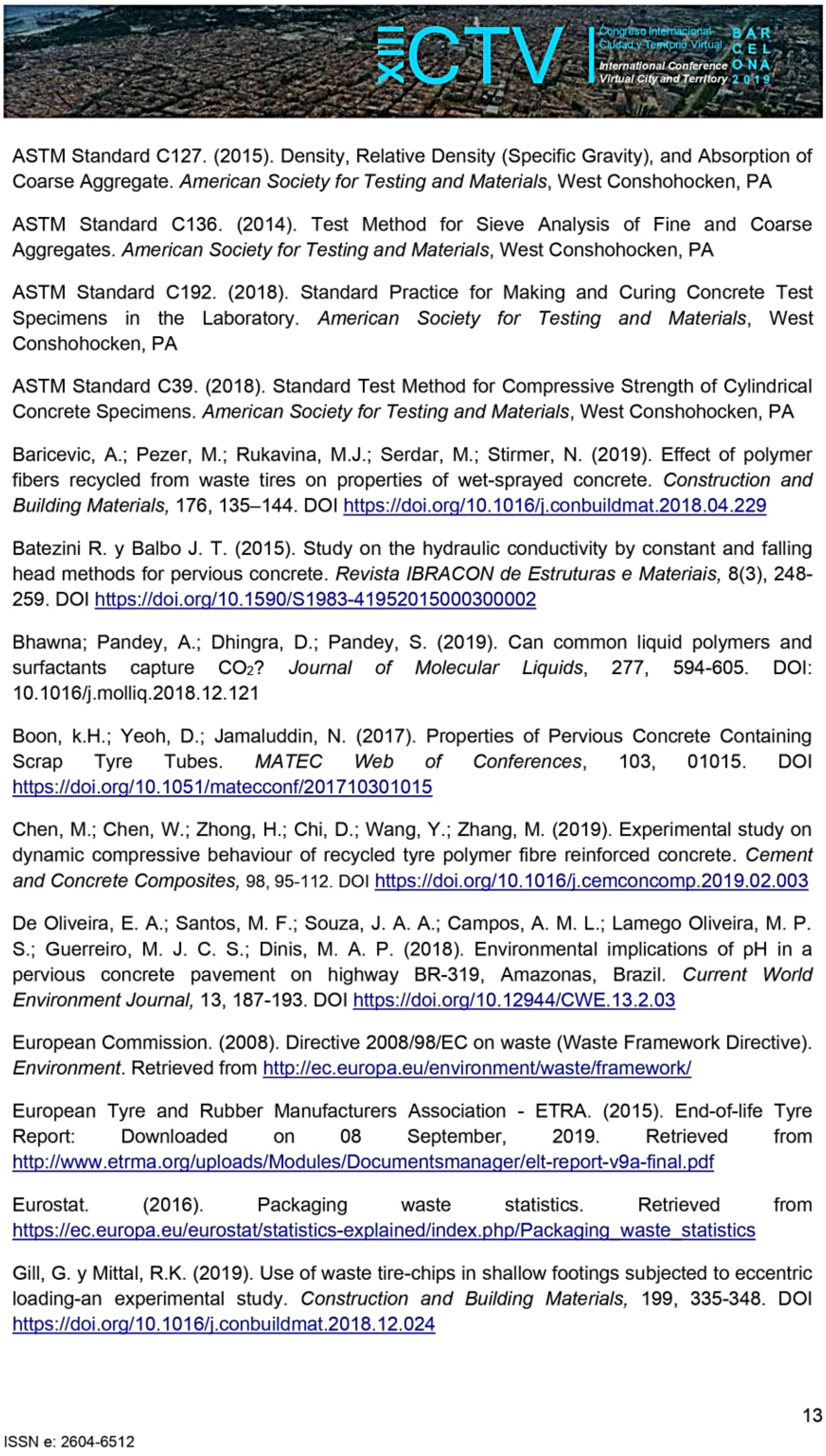

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CAPÍTULO V – Um Novo Pavimento de Betão Permeável Microbicida para Estacionamento de Hospitais: Avaliação do Módulo de Elasticidade

Neste capítulo final, a pesquisa aborda os estudos que abrangem as propriedades antimicrobianas dos aditivos CaO e $Ca(OH)_2$ utilizados no BPM, os quais possibilitam a utilização do BPM como pavimento antimicrobiano no estacionamento de hospitais, uma contribuição para a manutenção do rigor dos protocolos de segurança da Organização Mundial da Saúde. Os resultados demonstraram um equilíbrio entre o aditivo e as características físicas do BPM, com a preservação das propriedades de porosidade, permeabilidade e resistência à compressão, além dos benefícios antimicrobianos dos aditivos acrescentados à mistura do novo BPM, o que é promissor quanto à possibilidade de utilização do novo BPM no controlo da reprodução de macroinvertebrados transmissores de endemias, como a malária.

Nesta publicação, o primeiro autor participou no desenvolvimento da metodologia, investigação e recolha de dados e na escrita do manuscrito. A citação completa da publicação encontra-se apresentada a seguir:

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A NEW MICROBICIDAL PERVIOUS CONCRETE PAVEMENT FOR HOSPITAL PARKING–LOTS: ASSESSMENT OF THE MODULUS OF ELASTICITY[*]

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Abstract

In the coronavirus pandemic (COVID-19), it is important to articulate a safeguard against urban contamination originating from hospitals, mainly the tires of vehicles that travel in the hospital parking-lots and contaminating the various parts of the city through traffic on urban roads. With the purpose of disinfecting the pavement of hospital parking-lots to prevent diseases, this research proposes the use of a new pavement composed of pervious concrete with calcium hydroxide ($Ca(OH)_2$) additive, i.e., lime powder. The well-known powder lime becomes a disinfectant with a microbicidal effect which increases the pH of the pavement, being a low cost and an abundant material. Studies have shown that this additive affects the mechanical strength of pervious concrete when added to its mixture. Accordingly, the objective of the study is to find a balance between mechanical strength and the ideal proportion of lime powder additive in the pervious concrete mixture through finite element prototypes subjected to vertical loads of 10,000 N with variation in the modulus of elasticity. The results of the structural simulations indicate the prototype with the best performance ratio is 1:0.8:4 (cement:$Ca(OH)_2$:limestone), compressive strain of 15.70 kg/cm^2, density of 1,971.42 kg/m^3 and modulus of elasticity of 1,480.22 MPa, with demonstrates a satisfactory mechanical performance for the use of this new pavement in hospital parking-lots.

Keywords: calcium hydroxide, elasticity, lime powder, microbicidal pavement, pervious concrete

1. Introduction

The Coronavirus Pandemic (COVID-19) forced the entire planet to revise hygiene and cleaning habits, through the guidelines and protocols of the World Health Organization

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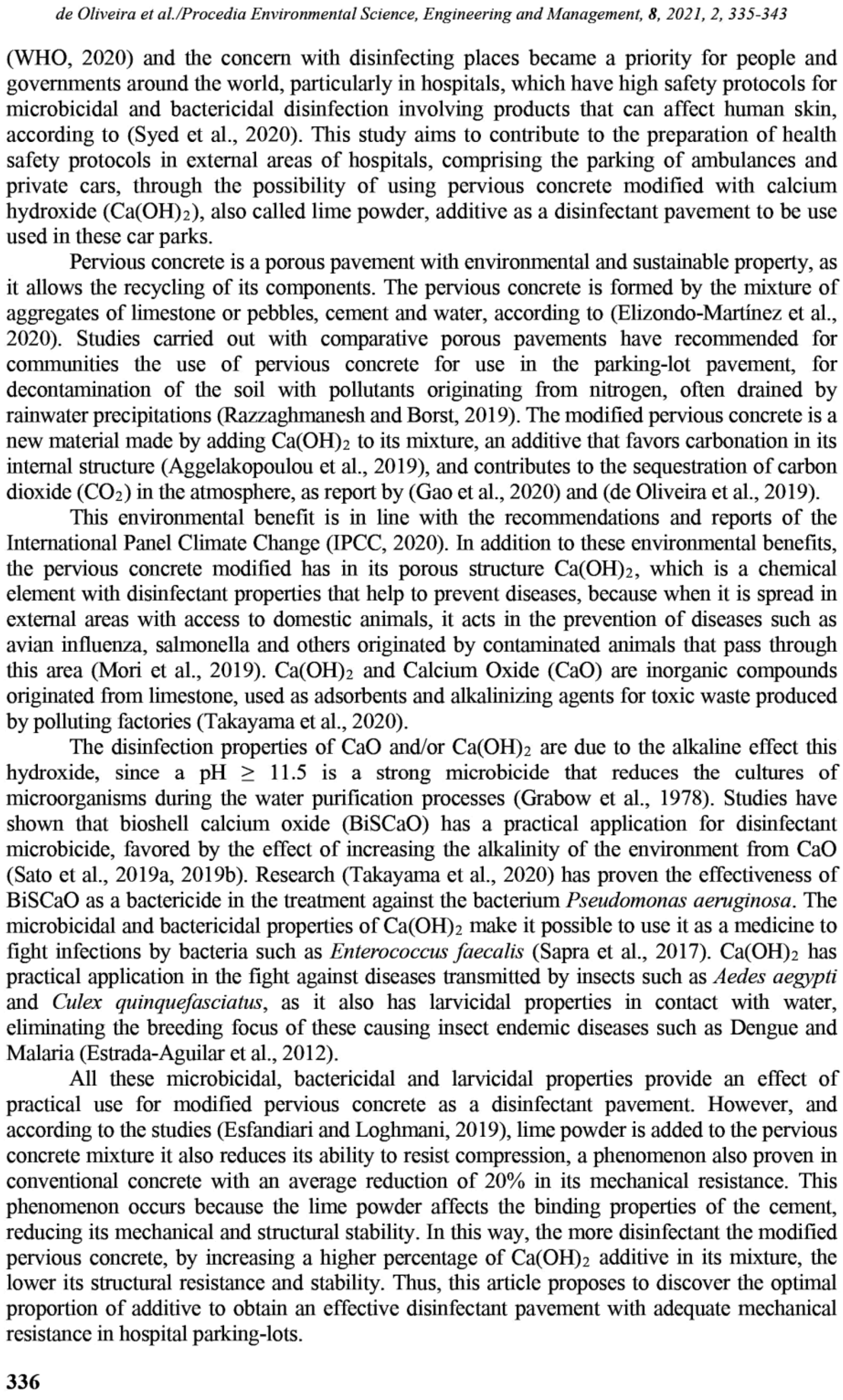


(WHO, 2020) and the concern with disinfecting places became a priority for people and governments around the world, particularly in hospitals, which have high safety protocols for microbicidal and bactericidal disinfection involving products that can affect human skin, according to (Syed et al., 2020). This study aims to contribute to the preparation of health safety protocols in external areas of hospitals, comprising the parking of ambulances and private cars, through the possibility of using pervious concrete modified with calcium hydroxide ($Ca(OH)_2$), also called lime powder, additive as a disinfectant pavement to be use used in these car parks.

Pervious concrete is a porous pavement with environmental and sustainable property, as it allows the recycling of its components. The pervious concrete is formed by the mixture of aggregates of limestone or pebbles, cement and water, according to (Elizondo-Martínez et al., 2020). Studies carried out with comparative porous pavements have recommended for communities the use of pervious concrete for use in the parking-lot pavement, for decontamination of the soil with pollutants originating from nitrogen, often drained by rainwater precipitations (Razzaghmanesh and Borst, 2019). The modified pervious concrete is a new material made by adding $Ca(OH)_2$ to its mixture, an additive that favors carbonation in its internal structure (Aggelakopoulou et al., 2019), and contributes to the sequestration of carbon dioxide (CO_2) in the atmosphere, as report by (Gao et al., 2020) and (de Oliveira et al., 2019).

This environmental benefit is in line with the recommendations and reports of the International Panel Climate Change (IPCC, 2020). In addition to these environmental benefits, the pervious concrete modified has in its porous structure $Ca(OH)_2$, which is a chemical element with disinfectant properties that help to prevent diseases, because when it is spread in external areas with access to domestic animals, it acts in the prevention of diseases such as avian influenza, salmonella and others originated by contaminated animals that pass through this area (Mori et al., 2019). $Ca(OH)_2$ and Calcium Oxide (CaO) are inorganic compounds originated from limestone, used as adsorbents and alkalinizing agents for toxic waste produced by polluting factories (Takayama et al., 2020).

The disinfection properties of CaO and/or $Ca(OH)_2$ are due to the alkaline effect this hydroxide, since a pH $\geq$ 11.5 is a strong microbicide that reduces the cultures of microorganisms during the water purification processes (Grabow et al., 1978). Studies have shown that bioshell calcium oxide (BiSCaO) has a practical application for disinfectant microbicide, favored by the effect of increasing the alkalinity of the environment from CaO (Sato et al., 2019a, 2019b). Research (Takayama et al., 2020) has proven the effectiveness of BiSCaO as a bactericide in the treatment against the bacterium *Pseudomonas aeruginosa*. The microbicidal and bactericidal properties of $Ca(OH)_2$ make it possible to use it as a medicine to fight infections by bacteria such as *Enterococcus faecalis* (Sapra et al., 2017). $Ca(OH)_2$ has practical application in the fight against diseases transmitted by insects such as *Aedes aegypti* and *Culex quinquefasciatus*, as it also has larvicidal properties in contact with water, eliminating the breeding focus of these causing insect endemic diseases such as Dengue and Malaria (Estrada-Aguilar et al., 2012).

All these microbicidal, bactericidal and larvicidal properties provide an effect of practical use for modified pervious concrete as a disinfectant pavement. However, and according to the studies (Esfandiari and Loghmani, 2019), lime powder is added to the pervious concrete mixture it also reduces its ability to resist compression, a phenomenon also proven in conventional concrete with an average reduction of 20% in its mechanical resistance. This phenomenon occurs because the lime powder affects the binding properties of the cement, reducing its mechanical and structural stability. In this way, the more disinfectant the modified pervious concrete, by increasing a higher percentage of $Ca(OH)_2$ additive in its mixture, the lower its structural resistance and stability. Thus, this article proposes to discover the optimal proportion of additive to obtain an effective disinfectant pavement with adequate mechanical resistance in hospital parking-lots.

2. Material and methods

The ANSYS 2019 R1 software was used to develop simulations in 30 pervious concrete prototypes modified with $Ca(OH)_2$ additive. Each digital prototype has the dimensions of 1 m wide, 1 m long and 0.40 m thick. The load used in the simulations was 10,000 N with dynamic variation applied in the center of the prototype, in the vertical direction. The simulations were divided into 2 groups, a G1 group with 15 prototypes that had a progressive increase in the $Ca(OH)_2$ additive, from 0.1 until 1.5%, in the proportion of pervious concrete modified mixture, and another G2 group with 15 prototypes that had progressive increase of cement, from 0.1 until 1.5%, in the proportion of pervious concrete modified mixture. Table 1 indicates the materials and constant and variable proportions used in the 30 prototypes and in the two G1 and G2 groups to perform the deformation calculations using the finite element method.

Table 1. Characteristics of the virtual prototypes of the G1 and G2 groups of modified pervious concrete

Groups	*Prototype number*	*Materials*	*Proportion*[1]	*Type*	*Additive Materials*	*Proportion*[1]
G1	15	Cement Aggregate water/cement	1.0 4.0 0.3	II[2] Limestone[3] Distilled	$Ca(OH)_2$	0.1 to 1.5 %
G2	15	Additive Aggregate water/cement	0.8 4.0 0.3	$Ca(OH)_2$ Limestone[3] Distilled	Cement	0.1 to 1.5 %

[1] Proportion in relation to cement mass. [2]ASTM C150. [3]Granite stone 4.8 to 9.5 mm

Fig. 1 demonstrates photo of the compression and density measurement methodology.

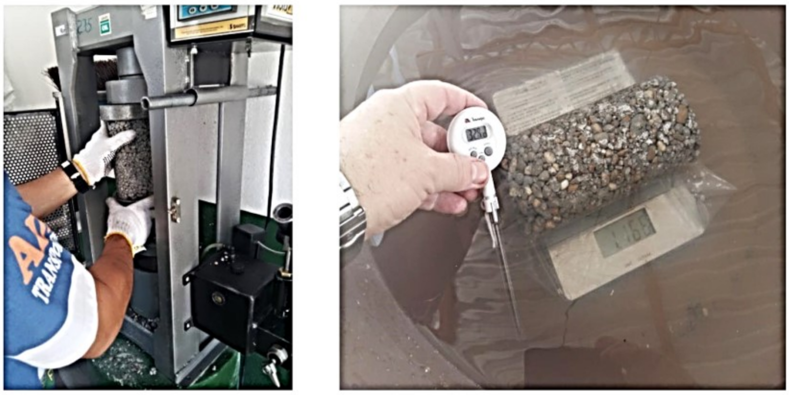
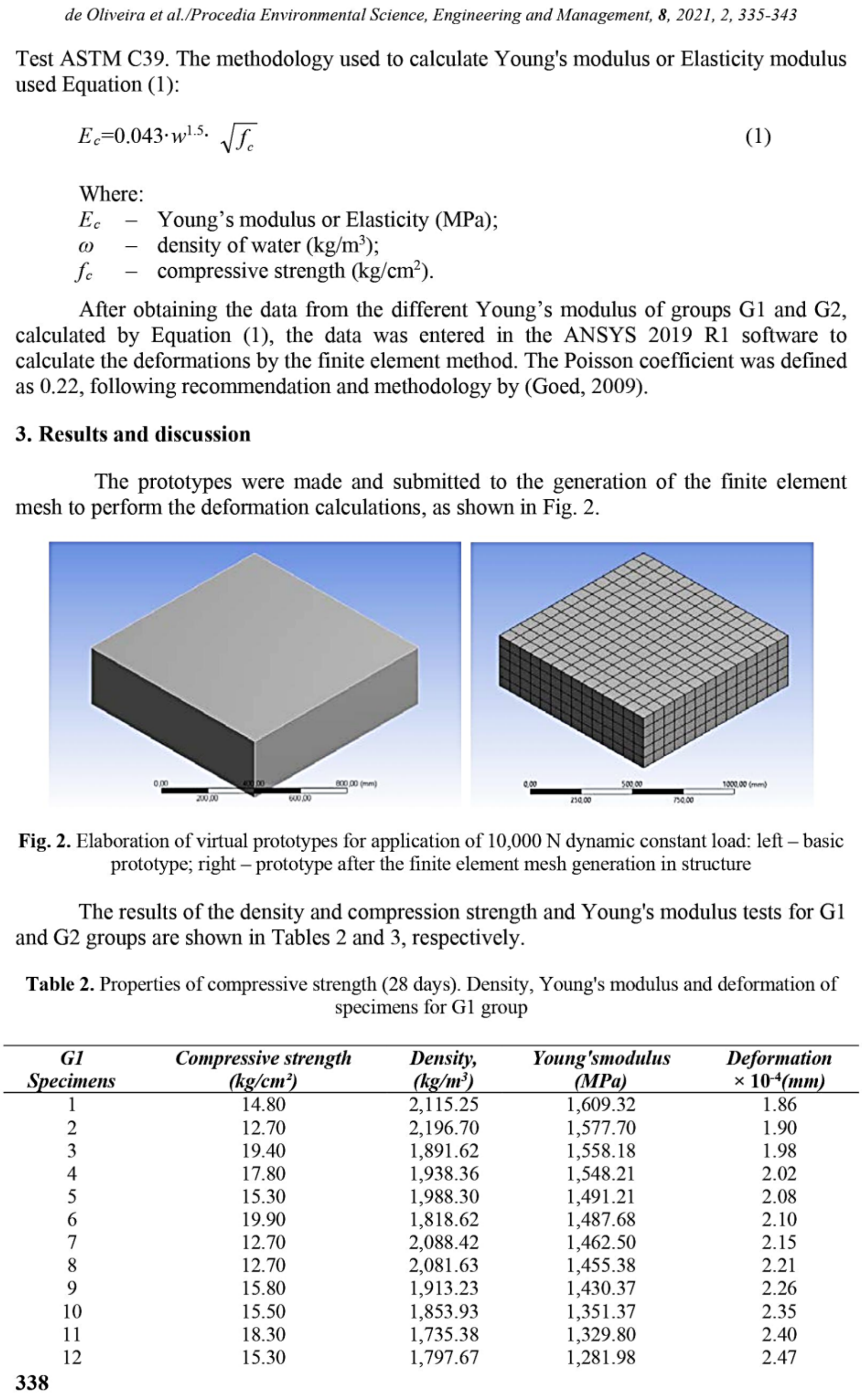


Fig. 1. Compression and density tests: left – rupture of cylindrical specimens; right – weighing of cylindrical specimen submerged in water

Following the indications in Table 1, 30 specimens were prepared, 15 specimens for each G1 and G2 group, to carry out Density Test ASTM C127, and Compressive Strength



Test ASTM C39. The methodology used to calculate Young's modulus or Elasticity modulus used Equation (1):

$$E_c=0.043\cdot w^{1.5}\cdot \sqrt{f_c} \tag{1}$$

Where:
E_c – Young's modulus or Elasticity (MPa);
ω – density of water (kg/m^3);
f_c – compressive strength (kg/cm^2).

After obtaining the data from the different Young's modulus of groups G1 and G2, calculated by Equation (1), the data was entered in the ANSYS 2019 R1 software to calculate the deformations by the finite element method. The Poisson coefficient was defined as 0.22, following recommendation and methodology by (Goed, 2009).

3. Results and discussion

The prototypes were made and submitted to the generation of the finite element mesh to perform the deformation calculations, as shown in Fig. 2.

Fig. 2. Elaboration of virtual prototypes for application of 10,000 N dynamic constant load: left – basic prototype; right – prototype after the finite element mesh generation in structure

The results of the density and compression strength and Young's modulus tests for G1 and G2 groups are shown in Tables 2 and 3, respectively.

Table 2. Properties of compressive strength (28 days). Density, Young's modulus and deformation of specimens for G1 group

G1 Specimens	*Compressive strength (kg/cm²)*	*Density, (kg/m³)*	*Young'smodulus (MPa)*	*Deformation × 10⁻⁴(mm)*
1	14.80	2,115.25	1,609.32	1.86
2	12.70	2,196.70	1,577.70	1.90
3	19.40	1,891.62	1,558.18	1.98
4	17.80	1,938.36	1,548.21	2.02
5	15.30	1,988.30	1,491.21	2.08
6	19.90	1,818.62	1,487.68	2.10
7	12.70	2,088.42	1,462.50	2.15
8	12.70	2,081.63	1,455.38	2.21
9	15.80	1,913.23	1,430.37	2.26
10	15.50	1,853.93	1,351.37	2.35
11	18.30	1,735.38	1,329.80	2.40
12	15.30	1,797.67	1,281.98	2.47

13	15.00	1,806.44	1,278.64	2.50
14	11.70	1,911.25	1,228.96	2.53
15	12.90	1,843.77	1,222.71	3.06

Table 3. Properties of compressive strength (28 days). Density, Young's modulus and Deformation of specimens for G2 group

G2 Specimens	*Compressive Strength (kg/cm²)*	*Density (kg/m³)*	*Young's modulus (MPa)*	*Deformation ×10⁻⁴ (mm)*
1	15.30	1,797.67	1,281.98	2.61
2	18.30	1,735.38	1,329.80	2.58
3	15.50	1,853.93	1,351.37	2.51
4	15.80	1,913.23	1,430.37	2.47
5	12.70	2,081.63	1,455.38	2.35
6	12.70	2,088.42	1,462.50	2.28
7	19.90	1,818.62	1,487.68	2.20
8	15.30	1,988.30	1,491.21	2.20
9	17.80	1,938.36	1,548.21	2.08
10	19.40	1,891.62	1,558.18	2.05
11	12.70	2,196.70	1,577.70	1.98
12	14.80	2,115.25	1,609.32	1.80
13	14.30	2,166.43	1,639.65	1.72
14	13.20	2,270.06	1,689.70	1.65
15	14.80	2,227.54	1,739.15	1.51

Fig. 3 shows the deformations of samples G1and G2 groups.

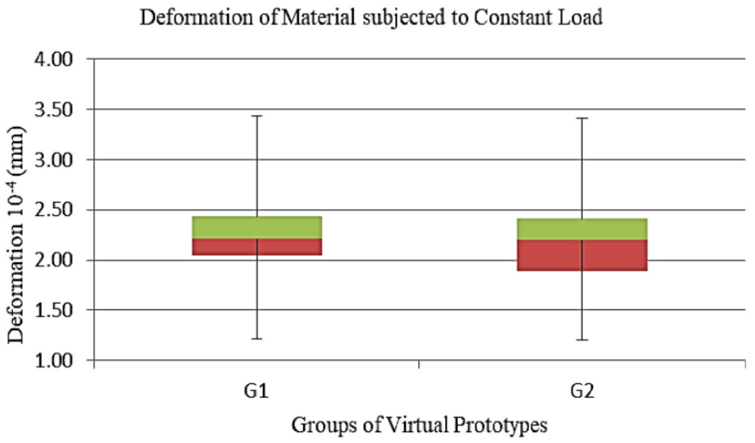


Fig. 3. Deformation of the material with changes in the additive (G1 group) and changes in cement (G2 group)

Fig. 4 shows the deformation of prototype 11 (G1) of pervious concrete modified after loading the dynamic constant force 10,000 N.

In G1 group, as the additive ($Ca(OH)_2$) is added to the pervious concrete mixture, there is an increase in the Young's modulus and a gradual increase in deformation, because the additive impairs the binding property cement, which causes a progressive disruption of the material, until it becomes unstable. In the group G2 the opposite effect occurs because as the cement is added, the material becomes more stable, with a gradual reduction of the elasticity module and a gradual reduction of the deformation, because the cement strengthens the bond between the aggregates, producing a more resistant material.

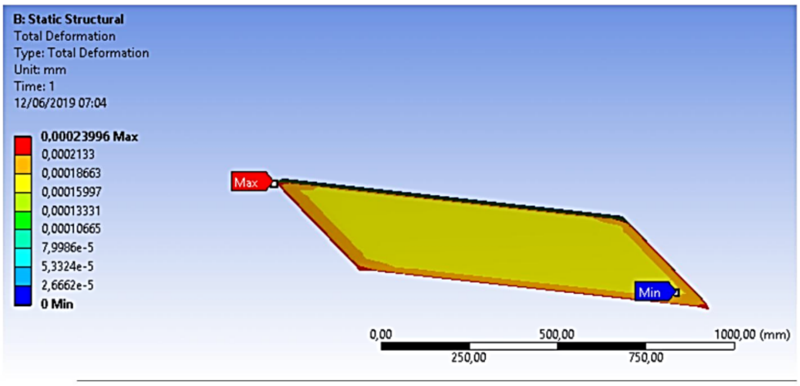


Fig. 4. Deformation of the modified pervious concrete material with loading applied in the center of the prototype

According to (Yu et al., 2019) the pore size of the modified pervious concrete makes the material dependent on cement for binding aggregate particles. For this reason, the interference of the additive when mixing with the cement generates strong destabilization in the internal structure of the modified pervious concrete. The addition of additive interferes with the adhesion of the cement that acts as a binder between the aggregates preventing the cement from acting integrally in the connection between the particles. Porosity is a property that defines pervious concrete itself (Zhang et al., 2019), however the $Ca(OH)_2$ additive fills the voids, the additive impairing this important property, which even affects the possibility of recycling the material (Aliabdo et al., 2018).

For this reason, despite the important advantages of the $Ca(OH)_2$ additive as a larvicide and microbicidal bactericide, which makes it an efficient disinfectant material, it cannot be added in significant percentage in the mixture of the modified pervious concrete, because it may cause complete destabilization of the internal structure material, rendering it useless for structural use, such as pavement for parking vehicles. The solution to the problem is the use of additives within an equilibrium range that encompasses the balance of the properties of G1 and G2 groups, an equilibrium between the $Ca(OH)_2$ additive and the cement used in the mixture of modified pervious concrete. The balance range is the meeting point of two curves with opposite trends.

The G1 curve is ascending, because the more additive is added to the modified pervious concrete mixture, the greater the deformations of the material, tending to a weak and unstable material, the G2 curve is descending, because the more cement is added to the modified pervious concrete mixture, the less the deformation of the material, tending to a resistant material, but with a high financial cost due to the gradual increase in cement.

The meeting point of these two curves, ascending G1 and descending G2, represents the balance range, an optimum point that corresponds to the prototypes with characteristics of compressive strength and percentage of additive coinciding in the two curves, with structural and economic stability properties for the use of modified pervious concrete as a disinfectant pavement in a hospital parking-lot. The balance range contained in the intersection of the curves of the G1 and G2 groups, is shown in Fig. 5, as a solution to the problem of stability of the proposed disinfectant pavement of modified pervious concrete.

Fig. 5 shows the equilibrium range of the modified pervious concrete mixture at the intersection of the ascending curve of the G1 group and the descending curve of the G2 group, considering the deformation in relation to the results found by the finite element method in G1 and G2 groups. The equilibrium range encompasses the properties of the virtual pervious concrete prototype specimens in the range of specimens from 7 to 9, with proportions of 0.7 to 0.9% of $Ca(OH)_2$ additive in the G1 curve and 0.7 to 0.9% cement in the G2 curve. The equilibrium range comprises the values of the compressive strength, density and Young's modulus properties, expressed in Table 4.

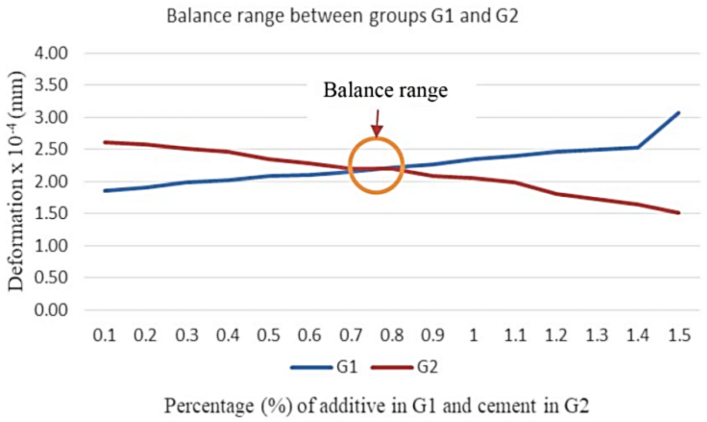


Fig. 5. Balance range between G1 and G2 groups, defined through the intersection point between the deformations of the material in both groups

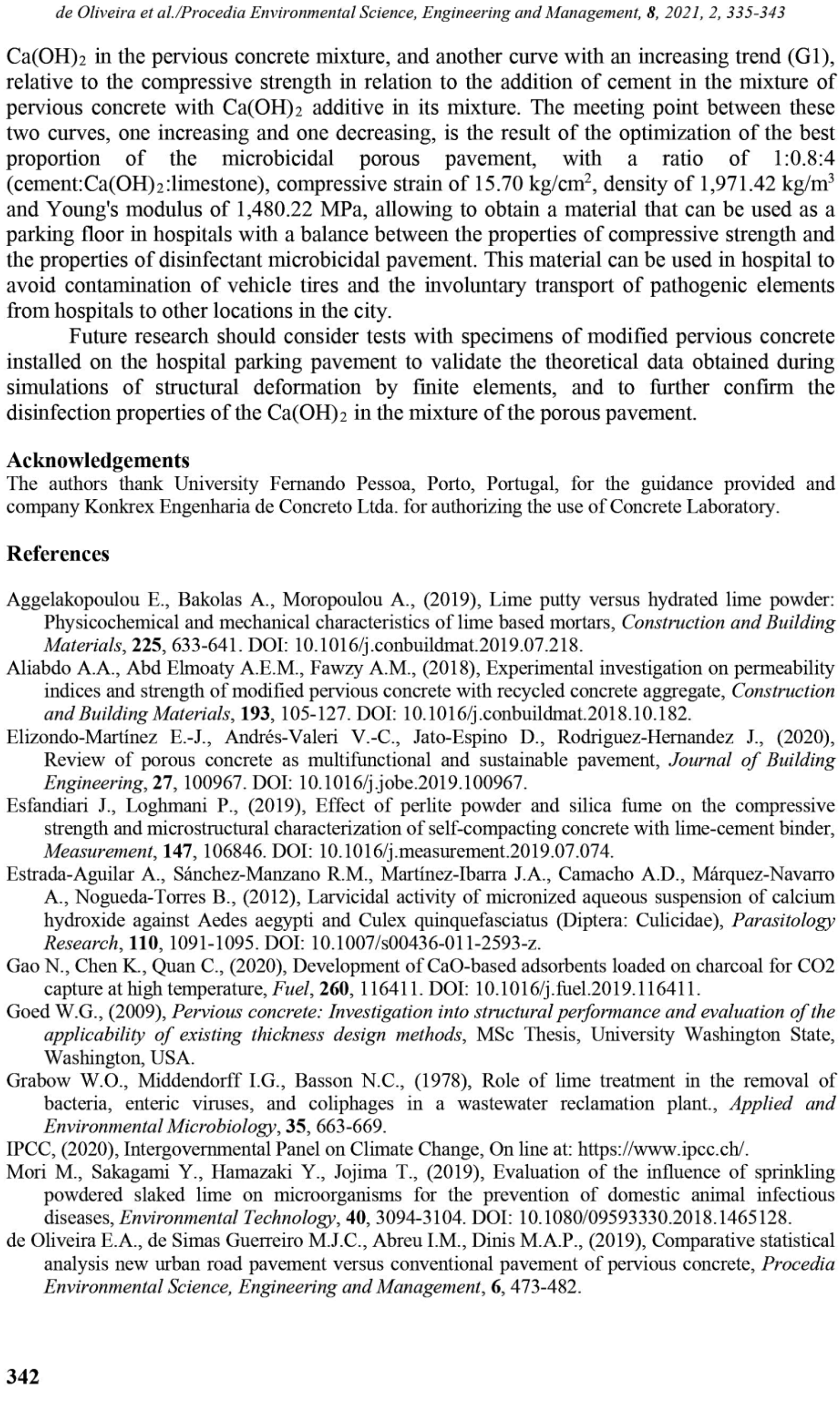
Table 4. Properties of compressive strength, density, Young's modulus of specimens from balance range

Groups	*Compressive Strength (kg/cm²)*	*Density (kg/m³)*	*Young's modulus (MPa)*
G1	12.70	2,088.42	1,462.50
	12.70	2,081.63	1,455.38
	15.80	1,913.23	1,430.37
G2	19.90	1,818.62	1,487.68
	15.30	1,988.30	1,491.21
	17.80	1,938.36	1,548.21

The average values included in Table 4 were calculated. They reflect the following ratios 1:0.8:4 (cement:$Ca(OH)_2$:limestone), compressive strain of 15.70 kg/cm^2, density of 1,971.42 kg/m^3 and Young's modulus of 1,480.22 MPa, with cement and additive proportions of 0.8%, for obtaining a new modified pervious concrete with disinfectant properties and compatible strength to support vehicle loads up to 10,000 N in hospital parking-lots.

4. Conclusions

The structural simulations in the prototypes of concrete with $Ca(OH)_2$ additive, with finite element modeling, showed results that enabled the drawing of two curves, a curve with a downward trend (G2), relative to the compressive strength in relation to the addition of



$Ca(OH)_2$ in the pervious concrete mixture, and another curve with an increasing trend (G1), relative to the compressive strength in relation to the addition of cement in the mixture of pervious concrete with $Ca(OH)_2$ additive in its mixture. The meeting point between these two curves, one increasing and one decreasing, is the result of the optimization of the best proportion of the microbicidal porous pavement, with a ratio of 1:0.8:4 (cement:$Ca(OH)_2$:limestone), compressive strain of 15.70 kg/cm^2, density of 1,971.42 kg/m^3 and Young's modulus of 1,480.22 MPa, allowing to obtain a material that can be used as a parking floor in hospitals with a balance between the properties of compressive strength and the properties of disinfectant microbicidal pavement. This material can be used in hospital to avoid contamination of vehicle tires and the involuntary transport of pathogenic elements from hospitals to other locations in the city.

Future research should consider tests with specimens of modified pervious concrete installed on the hospital parking pavement to validate the theoretical data obtained during simulations of structural deformation by finite elements, and to further confirm the disinfection properties of the $Ca(OH)_2$ in the mixture of the porous pavement.

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REFLEXÕES E CONCLUSÕES

Face aos ODS apresentados na Agenda 2030 da ONU, fica evidente a importância da escolha de materiais a utilizar nas infraestruturas de engenharia civil, que incluem os pavimentos das vias de comunicação urbana e interurbana. Procura-se desenvolver materiais que tenham uma vida útil com capacidade de beneficiar o meio ambiente de forma sustentável.

Este trabalho pretende contribuir para a sustentabilidade urbana através do betão permeável modificado (BPM), uma proposta de material alternativo aos pavimentos convencionais de betão e asfalto, com benefícios ambientais em harmonia com os ODS 9 e 13 da Agenda 2030 (Agenda 2030, 2015), como sequestração de CO_2, reciclagem para preservação dos recursos naturais, reutilização de borracha de pneus descartáveis e permeabilidade da superfície do pavimento para drenagem de águas pluviais e fluviais para o subsolo.

O Brasil continua a utilizar os tradicionais pavimentos de massa asfáltica de betume na sua estrutura de pavimentação. A sua fabricação utiliza métodos que divergem de uma economia circular sustentável, como a extração de recursos naturais sem preocupação com as gerações futuras (Lin, 2020) e a produção de pavimentação de asfalto com emissão de gases poluentes, tais como sejam o NO_2 e SO_2 (EPA, 2021a, EPA, 2021b), Figura 7.

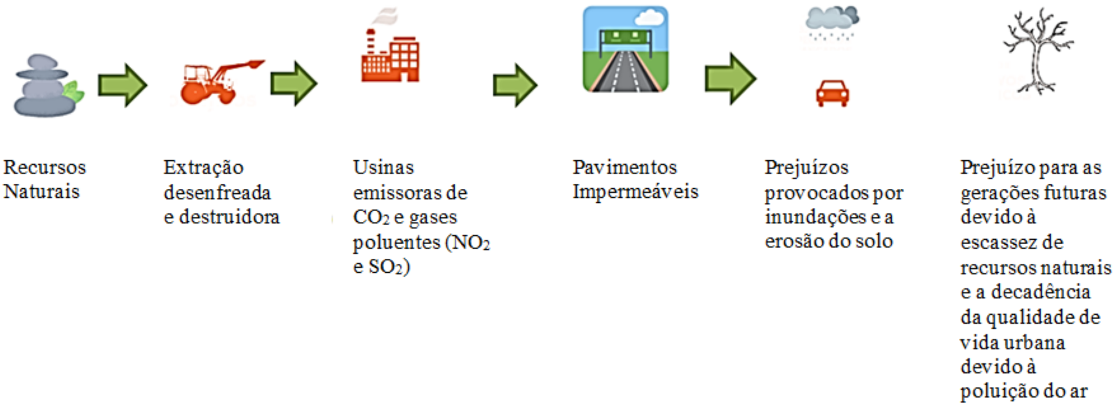

Figura 7. Processo utilizado na fabricação de pavimentação de asfalto com impactes ambientais negativos para o meio ambiente urbano (Lin, 2020, EPA, 2021a, EPA, 2021b).

Os estudos realizados no âmbito desta tese visam assim contribuir para implementação da economia circular no Brasil no setor de infraestrutura de pavimentação, nos moldes da economia circular já praticada no contexto Europeu (**de Oliveira** *et al.*, 2019b). O material proposto adequa-se à utilização em um ciclo utilização-reciclagem-utilização no Brasil, Figura 8.

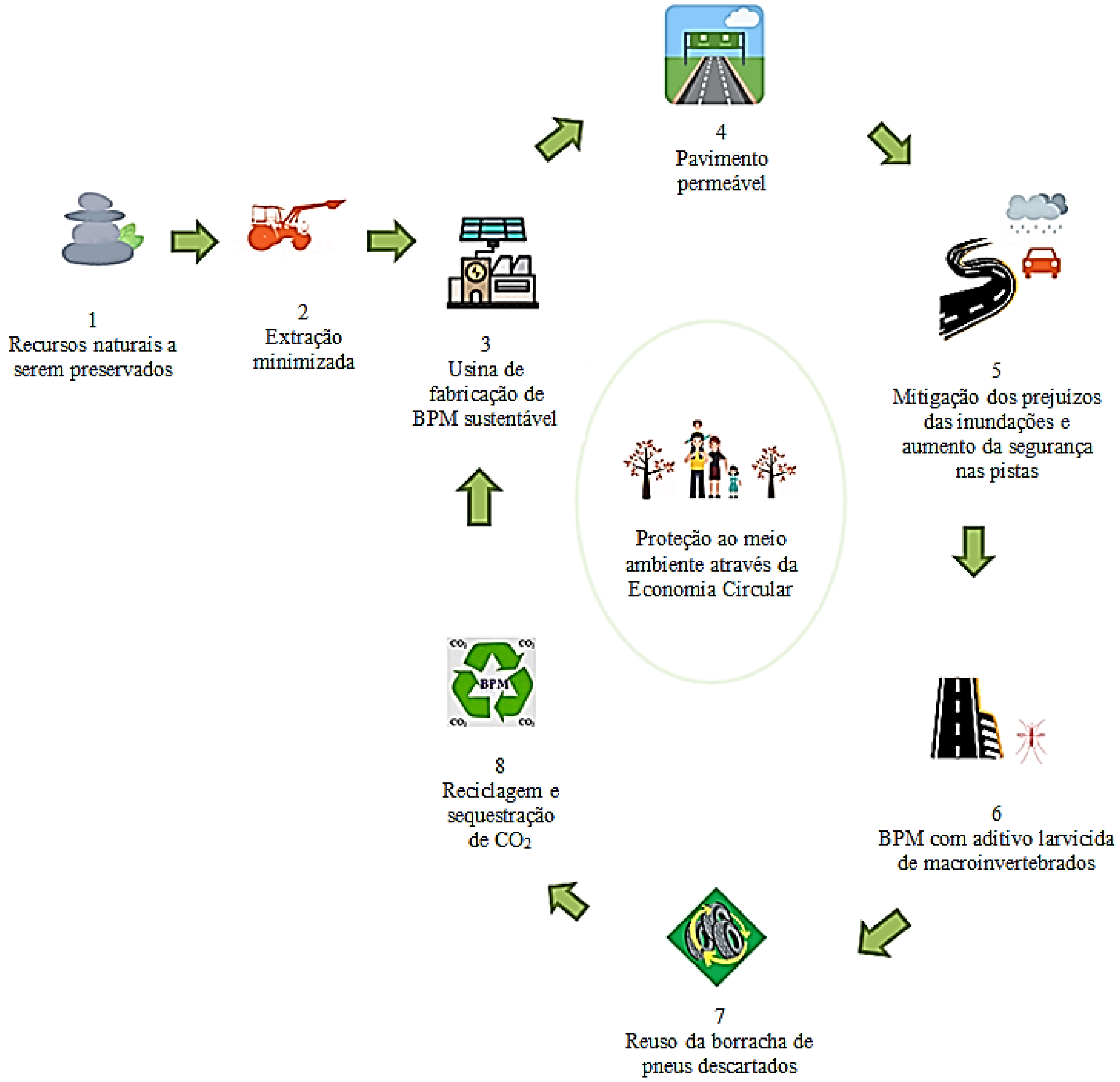

Figura 8. Ciclo de economia circular a adotar no contexto da pavimentação de vias urbanas com o BPM.

As inovações tecnológicas nas infraestruturas de pavimentação do Brasil são essenciais porque os futuros projetos nessa área devem necessariamente contemplar o modelo de economia circular patente na Figura 8. De outra forma, o Brasil não estará em sintonia com os ODS 9 e 13 (Agenda 2030, 2015) da ONU (Figura 9), em relação ao principal meio de transporte no país, o transporte terrestre, que representa 71 % da circulação de mercadorias no país (CNT, 2021). Neste sentido, o BPM minimiza a extração de recursos naturais, uma vez que não utiliza areia em sua composição (**de Oliveira** *et al.*, 2020), contribuindo para a preservação deste importante recurso extraído de forma ilegal e descontrolada das margens dos rios das bacias hidrográficas no Brasil, com impactes negativos ao meio ambiente (Oliveira, 2020, Ramadon, 2016, Silva, 2005).

Figura 9. Objetivos de Desenvolvimento Sustentável 9 e 13 para a Agenda 2030 abrangidos nesta pesquisa (Plataforma Agenda 2030 Brasil, 2021).

A minimização da extração de recursos naturais na produção do BPM é possível porque os agregados utilizados na mistura do BPM podem ser reutilizados no fabrico do material estudado (**de Oliveira** *et al.*, 2019b). O BPM proposto é um material projetado para minimizar extrações de agregados como o seixo e a brita, materiais nativos e passíveis de rastreabilidade e correspondente fiscalização socioambiental da extração de recursos naturais no meio ambiente, no Amazonas, Brasil. A porosidade do BPM contribui para a redução da extração dos recursos naturais porque os vazios ocupam os espaços que seriam de outro modo ocupados por agregados numa mistura de betão convencional, que inclui areia na sua composição. De forma análoga à porosidade, a utilização de resíduos de borracha de pneus descartados na mistura do BPM também contribui para a minimização da extração de agregados da natureza, porque substitui em até 5 % o volume de agregados na mistura (**de Oliveira** *et al.*, 2019b). Assim, quando se utiliza os resíduos de borracha, o volume ocupado por estes resíduos na composição do BPM substitui o volume de agregados antes ocupado por seixo ou brita, um contributo para minimização da extração de brita e seixo nativos da natureza. O BPM é um pavimento poroso sustentável (EPA, 2021c), que reutiliza resíduos de borracha de pneus descartados, pode ser reciclado, contribui para sequestração de CO_2 e é permeável, de acordo com os resultados de análise estatística contidos nos estudos realizados no âmbito deste trabalho (**de Oliveira** *et al.*, 2019a; **de Oliveira** *et al.*, 2019b). Estes experimentos corroboram os resultados dos estudos apresentados por Boon *et al.* (2017) e Xie *et al.* (2019).

Embora haja um benefício ambiental de sequestração de CO_2 no meio ambiente pela utilização dos aditivos de $Ca(OH)_2$, também constatado por Rahmani e Gheib (2019), houve uma perda das propriedades de resistência à compressão e permeabilidade do BPM. Para solução deste problema de perda das propriedades de resistência à compressão e permeabilidade, esta tese inovou através dos estudos para se otimizar os valores do cimento e do aditivo $Ca(OH)_2$, encontrados através da intercessão de duas curvas de deformação do material, obtidas pela aplicação de esforços de compressão no material proposto. Uma ascendente, que se refere à deformação *versus* a adição de $Ca(OH)_2$ à mistura do BPM e outra, descendente, relativa à deformação *versus* o acréscimo de cimento à mistura do BPM. O aumento na proporção de cimento na mistura do BPM evita a degradação, i.e., a possibilidade de fragmentação do material ao ser submetido a esforços externos de compressão do BPM com aditivo $Ca(OH)_2$ acrescentado à mistura do material proposto (**de Oliveira** *et al.*, 2021). O aditivo $Ca(OH)_2$ tem ainda efeito larvicida e biocida comprovado por Mori *et al.* (2019), Sapra *et al.* (2017), Estrada-Aguilar *et al.* (2012), Mohammadi e Dummer (2011), Sirén *et al.* (2004) e Grabow *et al.* (1978), podendo ser utilizados em estacionamentos dos hospitais como uma proposta para a redução de macroinvertebrados como o *Aedes aegypti* e *Culex quinquefasciatusi,* portadores de doenças como dengue, febre amarela e malária (**de Oliveira** *et al.*, 2021).

Embora existam benefícios para a sustentabilidade, devido à reutilização dos resíduos de borracha de pneus descartados, não se compromete a integridade do material quanto à fragmentação ao ser submetido a esforços externos de compressão do BPM (**de Oliveira** *et al.*, 2019b, Boon *et al.*, 2017 e Xie *et al.*, 2019).

Com base no trabalho desenvolvido, constatou-se que foram alcançados todos os objetivos específicos estabelecidos no âmbito do objetivo geral, i.e., a criação de uma alternativa para a pavimentação convencional, uma proposta de contribuição para o alcance dos ODS 9 e 13 da Agenda 2030, de acordo com o contexto da presente tese de doutoramento. Estes objetivos foram fruto da minuciosa experimentação técnico-científica, somada à detida análise dos dados adquiridos durante todo o trabalho realizado, assente numa forma componente metodológica e de prévia e extensa pesquisa científica.

O material proposto, BPM com a inclusão de aditivos e/ou outros materiais reciclados, apresenta-se como um pavimento alternativo com potencial contribuição para um meio ambiente mais sustentável. O BPM demonstrou assim poder ser incluído como um material de pavimentação em obras não estruturais, como calçadas, jardins e fachadas de edifícios e residências, e obras estruturais de vias urbanas com trânsito leve. O BPM pode ser ainda usado em estacionamentos, pelos seus benefícios ambientais de maior permeabilidade e respectiva recarga dos aquíferos e minimização de inundações sazonais, redução na utilização de recursos não renováveis (e.g. areias e britas) e reutilização da borracha dos pneus descartados da indústria automobilística. A sequestração de CO_2 para a mitigação das alterações climáticas é outra consequência da sua utilização. Pode ainda servir de proposta para um material que auxilie na redução da proliferação das larvas dos macroinvertebrados transmissores de doenças endêmicas. Desta forma, o BPM proposto é assim um material sustentável para uso em pavimentação de vias urbanas no Amazonas, Brasil, fabricado com recurso à inclusão de materiais nativos que podem ser rastreados e fiscalizados quanto à responsabilidade socioambiental da extração de recursos naturais.

No âmbito das aplicações práticas do BPM, destaca-se a validação do Departamento Nacional de Infraestrutura de Transportes (DNIT), órgão do Governo Federal responsável pelas obras de infraestrutura no Brasil, quanto à utilização do BPM nos projetos de infraestrutura de pavimentação da via rodoviária federal BR-319, nos trechos do km 250,0 até o km 655,7 no estado do Amazonas, Brasil. A Superintendência Regional do DNIT no Amazonas reconheceu, assim, a importância da aplicabilidade do estudo realizado no âmbito desta tese, conforme o exposto no Ofício nº 145346/2020/NAA - AM/SRE - AM, datado de 02/12/2020, da Superintendência Regional do DNIT no estado do Amazonas, Brasil.

Ressalta-se que este material apresenta uma capacidade de carga à compressão inferior ao pavimento tradicional e, por isso, deve ter a sua utilização limitada a zonas de menor tráfego e de menor carga. O comportamento do BPM em relação aos aditivos CaO, $Ca(OH)_2$ e resíduos de borracha demonstraram, como já se mencionou atrás, uma perda nas propriedades mecânicas de resistência à compressão e permeabilidade, o que reforça a limitação do pavimento para zonas de trânsito leve de veículos e cargas. Além disso, apesar do aditivo $Ca(OH)_2$ ser comprovadamente larvicida e biocida, não foram realizados estudos de campo para definição do grau de esterilização do pavimento a ser utilizado nos estacionamentos dos hospitais. Não foram realizadas pesquisas de campo extensivas ao efeito antimicrobiano do BPM nos estacionamentos dos hospitais em virtude do agravamento da pandemia do COVID-19 no Brasil. Estes aspetos constituem limitações dos estudos realizados.

As pesquisas futuras devem continuar com os experimentos de campo com o BPM, visando à confirmação dos resultados teóricos alcançados referentes às propriedades físicas de resistência à compressão, permeabilidade, porosidade, densidade e módulo de Young, bem como as propriedades biocidas, que podem ser melhor estudadas. Os estudos centrados nos benefícios ambientais de melhoria da qualidade do ar também devem ser investigados noutros contextos urbanos, com diferentes níveis de concentração de CO_2, e com experimentação de outros tipos de aditivos, como a biomassa, por exemplo. Considera-se ainda relevante a continuação dos estudos para confirmação do efeito antimicrobiano da superfície do BPM, devido à adição do aditivo $Ca(OH)_2$ na mistura de fabricação deste pavimento, o qual contribuirá para a inibição da proliferação de larvas de macroinvertebrados transmissores de malária, febre amarela e dengue, em locais húmidos de vias urbanas e estacionamentos, particularmente em países com o clima tropical, sujeitos a constantes precipitações.

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