

ARIEL MIRANDA DE SOUZA

**DOSAGE OF ECO-EFFICIENT SELF-COMPACTING MICROCONCRETES
CONTAINING ORNAMENTAL STONE WASTES**

Dissertation submitted to the Civil Engineering
Graduate Program of the Universidade Federal de
Viçosa in partial fulfillment of the requirements
for the degree of *Magister Scientiae*.

Advisor: José Maria Franco de Carvalho

Co-advisors: Carol Ferreira Rezende Santos
Ricardo André Fiorotti Peixoto

**VIÇOSA – MINAS GERAIS
2022**

**Ficha catalográfica elaborada pela Biblioteca Central da Universidade
Federal de Viçosa - Campus Viçosa**

T

S729d
2022 Souza, Ariel Miranda de, 1996-
Dosagem de microconcretos autoadensáveis ecoeficientes
contendo resíduo do beneficiamento de rochas ornamentais /
Ariel Miranda de Souza. – Viçosa, MG, 2022.
1 dissertação eletrônica (117 f.): il. (algumas color.).

Texto em inglês.

Inclui apêndices.

Orientador: José Maria Franco de Carvalho.

Dissertação (mestrado) - Universidade Federal de Viçosa,
Departamento de Engenharia Civil, 2022.

Inclui bibliografia.

DOI: <https://doi.org/10.47328/ufvbbt.2022.127>

Modo de acesso: World Wide Web.

1. Concreto autoadensável. 2. Sustentabilidade. 3. Concreto
leve. 4. Rochas ornamentais - Reaproveitamento. I. Carvalho,
José Maria Franco de, 1979-. II. Universidade Federal de Viçosa.
Departamento de Engenharia Civil. Programa de Pós-Graduação
em Engenharia Civil. III. Título.

CDD 22. ed. 624.1834

Bibliotecário(a) responsável: Alice Regina Pinto CRB 2523

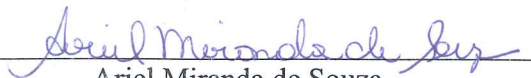
ARIEL MIRANDA DE SOUZA

**DOSAGE OF ECO-EFFICIENT SELF-COMPACTING MICROCONCRETES
CONTAINING ORNAMENTAL STONE WASTES**

Dissertation submitted to the Civil Engineering
Graduate Program of the Universidade Federal de
Viçosa in partial fulfillment of the requirements
for the degree of *Magister Scientiae*.

APPROVED: February 24, 2022.

Assent:



Ariel Miranda de Souza
Author



José Maria Franco de Carvalho
Adviser

ACKNOWLEDGMENTS

This work was an important part of my studies, providing me with a lot of knowledge and wisdom and developing new skills. It was carried out entirely in a period of a very serious pandemic, which required adaptations in the experimental processes, generated delays in the experiments, in addition to the constant concern for health. So many challenges encountered, pauses, and absences meant that this work was only completed with support from various groups.

I thank my family, friends, co-workers, teachers, advisors, lab technicians, teams and partner labs for all the support, assistance and inspiring words that made me get here and finish this work.

I especially thank Gamora, my little dog, for always being by my side on this journey, no matter the time or tiredness, for the understanding, support and affection that gave me the strength to stay stable and continue to love my work.

This work was carried out with the support of the Coordenação de Aperfeiçoamento de Pessoal do Nível Superior - Brazil (CAPES) - Funding Code 001.

ABSTRACT

SOUZA, Ariel Miranda de, M.Sc., Universidade Federal de Viçosa, February, 2022. **Dosage of eco-efficient self-compacting microconcretes containing ornamental stone wastes.** Advisor: José Maria Franco de Carvalho. Co-advisors: Carol Ferreira Rezende Santos and Ricardo André Fiorotti Peixoto.

The present work sought to evaluate the effects of incorporating a high concentration of waste from the processing of ornamental stone as a filler in self-compacting and lightweight self-compacting microconcrete containing expanded polystyrene waste through the evaluation of its physical-chemical, mechanical and eco-efficiency properties. The dosage of the concretes was done by the particle packing method to obtain the limits of the filler/cement, powder/total solids and lightweight aggregates/total aggregates ratios for the production of mixtures following a second-order composite experimental design. The samples produced were tested in fresh and hardened states. Eco-efficiency performance analyzes were carried out by Binder Intensity and assessment of the environmental impacts generated in the production of each material in the mixtures produced. The results, evaluated through response surfaces, showed that replacing cement with waste reduced the microconcretes mechanical strength but increased eco-efficiency compared to other self-compacting concretes of similar mechanical strength. In lightweight microconcrete, the residue increased workability and viscosity and reduced water consumption, helping to avoid segregation. However, despite the addition of lightweight aggregates reducing the density of microconcretes, it was not possible to stabilize the mixture for fixed spreading, with segregation occurring in mixtures with high levels of lightweight aggregates. Therefore, the residue can be promoted to a co-product for application in civil construction as a stabilizing agent in self-compacting microconcretes, capable of reducing the cement content and consequently the embodied CO₂ emissions, obtaining more eco-efficient matrices without significant losses in its technological properties.

Keywords: Self-compacting concrete. Eco-efficient concrete. Sustainability. Ornamental stone waste. Microconcrete. Lightweight self-compacting concrete.

RESUMO

SOUZA, Ariel Miranda de, M.Sc., Universidade Federal de Viçosa, fevereiro de 2022. **Dosagem de microconcretos autoadensáveis ecoeficientes contendo resíduo do beneficiamento de rochas ornamentais.** Orientador: José Maria Franco de Carvalho. Coorientadores: Carol Ferreira Rezende Santos e Ricardo André Fiorotti Peixoto.

O presente trabalho buscou avaliar os efeitos da incorporação de uma alta concentração do resíduo do beneficiamento de rochas ornamentais como fíler em microconcretos autoadensáveis e autoadensáveis leves, contendo resíduos de poliestireno expandido, por meio da avaliação de suas propriedades físico-químicas, mecânicas e de ecoeficiência. A dosagem dos concretos foi feita pelo método de empacotamento compressível para obtenção dos limites das relações fíler/cimento, finos/sólidos totais e agregados leves/agregados totais para a produção de traços obedecendo um planejamento experimental composto de segundo ordem. As amostras produzidas foram ensaiadas em estado fresco e estado endurecido. Foram realizadas análises de desempenho de ecoeficiência pela Intensidade do Ligante e avaliação dos impactos ambientais gerados na produção de cada material das misturas produzidas. Os resultados, avaliados por meio de superfícies de resposta, mostraram que a substituição do cimento pelo resíduo diminuiu a resistência mecânica dos microconcretos, porém, aumentou a ecoeficiência quando comparados a outros concretos autoadensáveis de resistências mecânicas similares. Nos microconcretos leves, o resíduo aumentou a trabalhabilidade e viscosidade, e diminuiu o consumo de água, ajudando no combate à segregação. Entretanto, apesar da adição de agregados leves diminuir a densidade dos microconcretos, não foi possível estabilizar a mistura para o espalhamento fixado, ocorrendo segregação nas misturas com elevados teores de agregados leves. Portanto, o resíduo possui potencial para ser elevado à condição de coproduto para aplicação na construção civil como agente estabilizador em microconcretos autoadensáveis, capaz de diminuir o teor de cimento e conseqüentemente as emissões de CO₂ associadas, obtendo-se matrizes mais ecoeficientes sem perdas significativas nas suas propriedades tecnológicas.

Palavras-chave: Concreto autoadensável. Concreto ecoeficiente. Sustentabilidade. Resíduo de rocha ornamental. Microconcreto. Concreto autoadensável leve.

TABLE OF CONTENTS

CHAPTER 1 - General introduction	8
1.1 Introduction.....	9
1.2 Objectives	10
1.3 Dissertation structure	10
References.....	11
CHAPTER 2 - On the strategies to improve the eco-efficiency of self-compacting concrete using industrial waste: an analytical review	13
2.1 Introduction.....	14
2.2 Method	15
2.3 Eco-efficiency performance of self-compacting concretes (SCC)	15
2.4 Eco-efficiency analysis	17
2.5 Strategies to improve the SCC eco-efficiency performance.....	19
2.5.1 SCC mixture design methods.....	19
2.5.2 SCC containing industrial waste	29
2.6 Discussions	34
2.6.1 Self-compacting concrete constituents.....	34
2.6.2 Evaluation of the mixtures of the consulted literature	35
2.7 Conclusion	37
Acknowledgment	38
References.....	38
APPENDIX.....	50
CHAPTER 3 - Influence of filler/cement and powder/total ratio on the mixture design of self-compacting sand-concretes containing waste from the ornamental stone industry..	62
3.1 Introduction.....	63
3.2 Experimental program	64
3.2.1 Materials.....	64
3.2.2 Experimental design.....	66
3.2.3 Preparation of concrete and specimens casting.....	69
3.2.4 Rheological tests	69
3.2.5 Concrete characterization program	70
3.2.6 Eco-efficiency performance	70
3.2.7 Statistical analysis	73

3.3 Results and discussion	74
3.3.1 Rheological behavior.....	74
3.3.2 Microconcretes performance.....	75
3.3.3 Eco-efficiency performance	79
3.4 Conclusion	83
Acknowledgment	84
References.....	84
APPENDIX.....	89
CHAPTER 4 - Influence of filler/cement and lightweight aggregate /conventional aggregate ratios in the design of lightweight aggregate self-compacting concrete mixtures containing waste from the ornamental stone industry	92
4.1 Introduction.....	93
4.2 Experimental	94
4.2.1 Materials.....	94
4.2.2 Experimental design.....	96
4.2.3 Concrete production and specimens casting	100
4.2.4 Concrete characterization tests.....	100
4.2.5 Eco-efficiency performance	101
4.2.6 Statistical analysis	101
4.3 Results.....	101
4.3.1 Fresh state properties.....	101
4.3.2 Hardened state properties	104
4.3.3 Eco-efficiency performance	109
4.4 Conclusion	111
Acknowledgment	111
References.....	111
CHAPTER 5 - General conclusion	115
5.1 General conclusions	116
5.2 Proposals for future works	116

CHAPTER 1 - General introduction

Abstract

This chapter presents the entire work through a general introduction and the proposed objectives, in addition to explaining the organizational structure of the work, how it was divided, and showing some additional considerations for the reader's understanding.

1.1 Introduction

Brazil is one of the largest producers and exporters of ornamental stones, producing in 2019 more than 9 million tons [1]. The ornamental stone industry generates about 40% of raw material losses annually in the plates cutting and polishing processes, which generates a high demand for areas for disposal in landfills, which generates costs and environmental problems. Despite being classified as non-hazardous and inert, if incorrectly disposed of, such residue can cause silting of rivers, pollution of springs and diseases to the population due to the fine granulometry [2,3].

Regulations have been created targeting proper solid waste management, establishing adequate disposal, promoting reduction and recycling, and encouraging research into the insertion of waste in new raw materials through technical and financial cooperation between the public and private sectors [4,5].

Using these wastes in civil construction is a viable alternative since this sector consumes a large volume of natural resources and is prone to absorb solid waste [6]. Due to its granulometry with a high content of fines, the application of ornamental stone waste (OSW) as a filler in concrete adds commercial value to the waste and the product generated. In addition, it improves the physical and environmental characteristics of concrete by reducing the consumption of cement, since this material generates approximately 5% to 7% of global CO₂ emissions during clinker production, in addition to increasing the concrete hydration heat when used in large quantities [7–16].

Thus, OSW filler is recommended to increase fluidity and provide stability, moderate viscosity, cohesion, and resistance to segregation in mixtures with a high content of fines. Such aspects are critical in microconcretes, where the maximum dimension of the aggregates is limited, and the relative consumption of fines is considerably higher; in self-compacting concretes (SCC), that can flow and consolidate only by the action of gravity under its weight; and in lightweight self-compacting concrete (LWASCC), that demands high resistance to segregation [11,17–21].

Despite numerous works involving OSW in concrete, there is still no consensus on the ideal percentage of addition or even how much cement replacement by residue is still feasible.

In addition, no studies were found on self-compacting microconcrete with high waste incorporation and additions above 100% of cement consumption. Therefore, the present study aims to incorporate and evaluate the effects of high levels of OSW as a filler in self-compacting microconcrete. In addition, a study on the use of expanded polystyrene waste as lightweight fine aggregate in self-compacting microconcretes is provided. The analyses include properties in fresh and hardened states and eco-efficiency by quantifying environmental impacts using indicators proposed in the literature.

1.2 Objectives

This research aimed to evaluate the properties in fresh and hardened states and eco-efficiency of self-compacting microconcretes and lightweight self-compacting microconcretes containing ornamental stone waste as a filler and expanded polystyrene waste as lightweight fine aggregate. The following specific objectives are listed:

- Prepare mixtures of microconcretes and lightweight microconcretes using a method based on particle packing from the granulometric distribution of the materials;
- Produce and characterize, in the fresh and hardened states, different mixtures containing different filler/cement, powder/total solids, and light-weight aggregates/total aggregates ratios, according to composite second-order experimental designs;
- Evaluate the technological performance of the microconcretes produced from the quantification of the main physical properties in the fresh and hardened states through an analysis of variance;
- Measure the eco-efficiency performance of self-compacting concrete from the quantification of environmental impacts of the materials used and correlate with the mechanical strength.

1.3 Dissertation structure

This work was structured in chapters, containing a general introduction, three chapters in article format and a final chapter of conclusions. The second chapter is a systematic review article containing an abstract, introduction, literature review, conclusion and references. The third and fourth chapters are experimental articles composed of abstract, introduction, materials

and methods, results and discussions, conclusions, and bibliographic references. The final chapter presents final considerations and general conclusions.

Due to this format based on independent articles, the chapters contain their own renumbered bibliographic references. In addition, the chapters can share some bibliographic references, data on materials characterization, and methods.

References

- [1] ABIROCHAS, Balanço das Exportações e Importações Brasileiras de Rochas Ornamentais em 2019, ABIROCHAS. 55 (2020).
- [2] M.K. Degen, G.L. Vieira, L. Calmon, J.G. Uliana, R.S. Bastos, Concretos produzidos com resíduos provenientes do beneficiamento de rochas ornamentais como substituto parcial de cimento, An. Do 55º Congr. Bras. Concreto CBC2013. (2013) 1–12.
- [3] P. Danish, G. Mohan Ganesh, Study on influence of Metakaolin and waste marble powder on self-compacting concrete – A state of the art review, Mater. Today Proc. (2020). <https://doi.org/10.1016/j.matpr.2020.11.629>.
- [4] European Parliament and Council, Directive (EU) No 851/2018 - Waste, (2018).
- [5] Brasil, Plano Nacional de Resíduos Sólidos (Lei no 12.305/2010), Bras. Diário Of. Da União. (2011).
- [6] M.A. Rodrigues, J.A.M. Filho, Fabricação de concreto autoadensável com utilização de resíduos de marmorarias como adição mineral, Rev. Eletrônica Eng. Civ. 14 (2017) 50–71.
- [7] S. Çankaya, B. Pekey, A comparative life cycle assessment for sustainable cement production in Turkey, J. Environ. Manage. 249 (2019). <https://doi.org/10.1016/j.jenvman.2019.109362>.
- [8] N. Gupta, R. Siddique, R. Belarbi, Sustainable and Greener Self-Compacting Concrete incorporating Industrial By-Products: A Review, J. Clean. Prod. 284 (2020). <https://doi.org/10.1016/j.jclepro.2020.124803>.
- [9] P.C.C. GOMES, Optimization and Characterization of High-Strength Self- Compacting Concrete, Universitat Politècnica de Catalunya, 2002.
- [10] E. Bacarji, R.D. Toledo Filho, E.A.B. Koenders, E.P. Figueiredo, J.L.M.P. Lopes, Sustainability perspective of marble and granite residues as concrete fillers, Constr. Build. Mater. 45 (2013) 1–10. <https://doi.org/10.1016/j.conbuildmat.2013.03.032>.

- [11] P.K. Mehta, P.J.M. Monteiro, *Concreto: Propriedades e materiais*, IBRACON. (2014).
- [12] J. Lehne, F. Preston, *Making concrete change - Innovation in low-carbon cement and concrete*, 2018.
- [13] R.M. Andrew, Global CO₂ emissions from cement production, 1928-2018, *Earth Syst. Sci. Data*. 11 (2019) 1675–1710. <https://doi.org/10.5194/essd-11-1675-2019>.
- [14] E. Worrell, L. Price, N. Martin, C. Hendriks, L.O. Meida, Carbon dioxide emissions from the global cement industry, *Annu. Rev. Energy Environ.* 26 (2001) 303–329. <https://doi.org/10.1146/annurev.energy.26.1.303>.
- [15] D.C. Reis, P.C.R.A. Abrão, T. Sui, V.M. John, Influence of cement strength class on environmental impact of concrete, *Resour. Conserv. Recycl.* 163 (2020) 105075. <https://doi.org/10.1016/j.resconrec.2020.105075>.
- [16] Z.S. Ali, M. Hosseinpoor, A. Yahia, New aggregate grading models for low-binder self-consolidating and semi-self-consolidating concrete (Eco-SCC and Eco-semi-SCC), *Constr. Build. Mater.* 265 (2020). <https://doi.org/10.1016/j.conbuildmat.2020.120314>.
- [17] EFNARC, *The European Guidelines for Self-Compacting Concrete*, Eur. Guidel. Self Compact. Concr. (2005) 63. <http://www.efnarc.org/pdf/SCCGuidelinesMay2005.pdf>.
- [18] P.C.C. GOMES, A.R. Barros, *Métodos de dosagem de concreto autoadensável*, PINI, São Paulo, 2009.
- [19] A.M. Neville, *Propriedades do Concreto*, 5. ed, Bookman, Porto Alegre, 2016.
- [20] H. Okamura, M. Ouchi, Self-Compacting Concrete, *J. Adv. Concr. Technol.* 1 (2003) 5–15.
- [21] E.M. Lisbôa, *Obtenção do concreto auto-adensável utilizando resíduo do beneficiamento do mármore e granito e estudo de propriedades mecânicas*, Dissertação (Mestrado), Universidade Federal de Alagoas, 2004. http://www.repositorio.ufal.br/bitstream/riufal/377/1/EdvaldoMonteiroLisboa_Capa_Cap2.pdf.

CHAPTER 2 - On the strategies to improve the eco-efficiency of self-compacting concrete using industrial waste: an analytical review

Abstract

Self-compacting concrete (SCC) emerged as a proposal to obtain structures with higher performance. However, to obtain the necessary characteristics, high content of powder and chemical admixtures must be used, which leads to consequent high exploitation of natural resources and environmental impacts. In order to obtain more eco-efficient mixtures, several authors have proposed optimized SCC dosages and incorporated residues. Despite many studies that promise to improve the eco-efficiency of SCCs, few are those that prove the improvements using sustainability indicators. This review article sought to discuss and assess the main strategies to improve the eco-efficiency of SCCs. Based on a critical analysis of the articles consulted, it is demonstrated that the incorporation of waste in SCCs increases eco-efficiency when using efficient dosage methodologies.

Keywords: Self-compacting concrete. Eco-efficient concrete. Industrial waste. Dosage methods. Eco-efficiency analysis.

2.1 Introduction

Due to the need to build more durable, high-strength concrete structures, with reduced execution time and workforce, self-compacting concrete has become a significant research focus [1–4]. Possessing high workability, fluidity, cohesion, and ability to self-compact without using vibrators, self-compacting concrete is ideal for densely reinforced structures, such as large buildings, bridges, tunnels, anchor blocks, diaphragm walls, prefabricated elements, and structural reinforcement [4–13].

To stabilize self-compacting concrete, promoting the characteristics of fluidity, spreading, self-compacting, and resistance to segregation, high consumption of fine materials in the concrete mixture is necessary, which is associated with an increase in cement consumption [14,15]. This increase can improve the mechanical strength of concrete, and in structures with high reinforcement density, the increase in strength can promote a decrease in the reinforcement ratio, reducing the cost of the structure or the environmental impacts associated with steel production [16]. However, cement is responsible for about 5% to 7% of global CO₂ emissions, leading to low environmental efficiency self-compacting concrete [4,17].

To reduce the environmental impacts associated with cement production and exploitation of natural resources, more effective dosage techniques are used, based on the materials employed and desirable characteristics of the concrete and the incorporation of industrial waste in concrete as a replacement for conventional materials.

Materials such as steel slags, fly ash, rice husk ash, and sugarcane bagasse ash can increase the strength of concrete, promote pozzolanic properties, and partially replace the use of cement in concrete without loss of hardened characteristics [18–30]. Ashes can also act as viscosity modifiers for self-compacting concrete, increasing the resistance to segregation, although they tend to reduce its spreading [26,27].

Inert materials, on the other hand, can be used as fillers, such as ornamental stone waste, limestone, and stone dust, ensuring the minimum proportion of fines needed in self-compacting concrete for its stabilization, reducing the hydration heat, without the need to maintain mechanical strength [31–35]. Inert materials can also be used as aggregates to replace

conventional aggregates, such as the use of recycled concrete aggregates and artificial sands, thus reducing the exploitation of natural resources [36–39]. However, the elongated, porous, and irregular particles of recycled aggregates can reduce the workability of concrete, requiring an adjustment in the dosage of superplasticizer admixture.

To evaluate the best techniques to increase the eco-efficiency performance of self-compacting concretes, this review article seeks to analyze existing dosage methodologies and compare different residues incorporated in self-compacting concretes by other authors through eco-efficiency assessments using indicators proposed in the literature.

2.2 Method

In this work, articles published in journals on the following platforms were searched: ScienceDirect, Google Scholar, CAPES Journal Portal, and specific editorial sites. The research focused on studies that address the different methodologies for dosing self-compacting concrete and the incorporation of industrial waste as a strategy to improve eco-efficiency, such as the incorporation of wastes including blast furnace slag, fly ash, rice husk ash, sugarcane bagasse ash, recycled concrete aggregates, and residue from ornamental stone processing.

For the research of studies with waste incorporation, articles by authors who studied only one addition per concrete mix were selected, in addition to the use of conventional materials, such as river sand and conventional coarse aggregate.

After researching and reading the articles, the main information on the proposed topic was extracted, comparing the data found by the authors to assess the eco-efficiency of different mixtures of self-compacting concrete.

2.3 Eco-efficiency performance of self-compacting concretes (SCC)

The concrete, one of the most used construction materials globally, consumes a large part of the total raw material extracted on the planet [40]. The construction industry produces around 11.5 billion tons of concrete a year, and it is expected to reach 16 to 18 billion tons a year by 2050 [4]. Increasingly, the choice of the materials used for its production should be guided by environmental criteria [4].

One of the materials used in concrete production is Portland cement, a material obtained by the calcination of clay and limestone at high temperatures, originating the cement clinker. However, cement is responsible for about 5% to 7% of global CO₂ emissions, generating low environmental efficiency self-compacting concrete [4,17,41–46].

Therefore, new dosage methodologies, reduced cement consumption, incorporation of waste, and increased concrete efficiency emerge as strategies to make concrete a more sustainable material. Comparing environmental performances through Life Cycle Assessment (LCA) data and using sustainability indicators are ways to assess the sustainability of a concrete concerning the environmental pillar. In this sense, simple or combined eco-efficiency indicators based on consumptions, emissions, and performances have been proposed in the literature [47–53].

One of the most used sustainability indicators in concrete is the binder intensity indicator (bi) proposed by Damineli et al. [52]. It is calculated by dividing the total consumption of binding material (*b*) by the performance (compressive strength at 28 days) (*p*), where lower bi represents more efficient concretes, with greater strength for lower cement consumption. Despite being a simplistic method, not taking into account the consumption of supplementary materials, aggregate characteristics, the influence of the proportion of materials on strength, or environmental impacts of other materials used, it is a generic way of evaluating a concrete mixture made with conventional materials through the strength achieved and the consumption of the material with the greatest environmental impact, cement.

According to Souza et al. [53], cement has the most significant impact on concrete, and its replacement brings great benefits to eco-efficiency. Nevertheless, the high consumption of conventional aggregates is also a factor to consider, taking into account their high aquatic and marine toxicity and their high exploitation of natural resources. Therefore, the partial or total replacement of conventional aggregates by recycled ones can further reduce the environmental impacts of concrete compared to concrete with low cement consumption.

In their attempt to analyze the eco-efficiency of concretes based on a material life cycle assessment database, Souza et al. [53] developed indicators that assess the environmental impacts of concrete using a statistical desirability tool through simple and intuitive parameters. Among the individual indicators proposed are the indicators of Total Primary Energy (TPE),

Primary Raw Material (PRM), Recycled Material (RM), Water Consumption (WC), Global Warming Potential (GWP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Marine Ecotoxicity Potential (MAETP), Ozone Depletion Potential (ODP), Eutrophication Potential (EP), and Acidification Potential (AP). For the combination of indicators, composite indicators were created, such as Energy Negative Impacts Reduction (EIR), Material Impacts Reduction (MIR), Greenhouse Gases Reduction (GGR), Ecotoxicity Potential Reduction (EPR), Acidification, Eutrophication, and Ozone Abatement (AEO), and the global composite indicator of Eco-Efficiency Potential (EEP).

2.4 Eco-efficiency analysis

The methodology based on binder consumption proposed by Damineli et al. [52] and the eco-efficiency analysis using the indicators proposed by Souza et al. [53] were applied to evaluate the eco-efficiency of self-compacting concretes by different mix design methodologies, and self-compacting concretes containing residues.

For this, several mixtures of self-compacting concrete were compared by different proportioning methodologies, with the addition of residues such as blast furnace slag [54–60], fly ash [55,58,61–64], rice husk ash [18,23,24,64,65], sugarcane bagasse ash [26,66,67], recycled aggregates [68,69], and ornamental stones processing residue [68,70–73].

The mixes were taken from articles on self-compacting concrete found in the literature and were limited to authors who presented the results of compressive strength at 28 days, spreading through the Slump Flow test, and consumption of materials used in each mix. Studies using only conventional fine and coarse aggregates were also limited, and only the additions considered in work by Souza et al. [53] were considered, as well as traits with variation in the consumption of only one residue.

The mixtures were renamed with abbreviations according to the type of waste used and the proportion of waste incorporation given by the author: blast furnace slag (0%GGBS to 80%GGBS), fly ash (0%FA to 80%FA), rice husk ash (0%RHA to 30%RHA), sugarcane bagasse (0%SCBA to 30%SCBA), recycled aggregates (0%RCA to 100% RCA), and waste from the processing of ornamental stones (0%OSW to 100%OSW).

Together with compressive strength results, spreading, and binder intensity, the mixtures are listed in Table A.2.1 in the appendix of this review. Cubic specimens were taken as default. Compressive strength results obtained from cylindrical specimens with a height/diameter ratio equal to 2 were converted to equivalent values by multiplying the results by the factor 1.25, as proposed by Neville [74].

The SCC environmental impacts were calculated using the eco-efficiency composite indicators equations (Table 2.1) and the environmental impacts of each material in the inventory (Table 2.2) proposed by Souza et al. [53]. The results of the impacts of each SCC are presented in Table A.2.2, which shows the relation between the environmental impacts of SSCs and the compressive strengths of the mixtures. The desirability values of the individual and combined indicators are shown in Table A.2.3.

Table 2.1 – Equations for calculating the eco-efficiency indicators by Souza et al. [53].

Indicator	Equation
Energy Negative Impacts Reduction (EIR)	$EIR = \left(\frac{TPE}{fc}\right)$
Material Impacts Reduction (MIR)	$MIR = \frac{1}{3} \cdot \left[\left(\frac{PRM}{fc}\right) + \left(\frac{RM}{fc}\right) + \left(\frac{WC}{fc}\right)\right]$
Greenhouse Gases Reduction (GGR)	$GGR = \left(\frac{GWP}{fc}\right)$
Ecotoxicity Potential Reduction (EPR)	$EPR = \frac{1}{3} \cdot \left[\left(\frac{FAETP}{fc}\right) + \left(\frac{TETP}{fc}\right) + \left(\frac{MAETP}{fc}\right)\right]$
Acidification, Eutrophication, and Ozone Abatement (AEO)	$AEO = \frac{1}{3} \cdot \left[\left(\frac{ODP}{fc}\right) + \left(\frac{EP}{fc}\right) + \left(\frac{AP}{fc}\right)\right]$
Eco-efficiency potential (EEP)	$EEP = \frac{1}{5} \cdot [EIR + GGR + EPR + AEO]$

Table 2.2 - Results of the life-cycle assessment obtained by Souza et al. [53] (TPE - total primary energy; WC - water consumption; GWP - global warming potential; FAETP - freshwater aquatic ecotoxicity potential; TETP - terrestrial ecotoxicity potential; MAETP - Marine ecotoxicity potential; ODP - Ozone Depletion Potential; EP - Eutrophication Potential; AP - Acidification Potential.

Component	TPE (MJ/kg)	WC (m ³ /kg)	GWP (kg CO ₂ eq./kg)	FAETP (kg 1,4- DB eq./kg)	TETP (kg 1,4-DB eq./kg)	MAETP (kg 1,4-DB eq./kg)	ODP (kg CFC- 11 eq./kg)	EP (kg PO ₄ ³⁻ eq./kg)	AP (kg SO ₂ eq./kgf)
Ordinary Portland Cement (OP)	4.359	3.84E-03	0.883	4.14E-03	1.17E-03	1.94E+01	2.04E-08	2.01E-04	1.54E-03
Fly ash (FA)	0.417	0.00E+00	0.008	1.47E-03	7.90E-05	1.61E+00	2.79E-09	6.84E-06	6.54E-05
Ground granulated blast furnace slag (GGBS)	1.580	2.23E-03	0.177	2.13E-03	1.58E-04	1.11E+01	2.47E-09	1.30E-04	1.76E-03

Sugar cane bagasse ash (SCBA)	0.900	0.00E+00	0.115	8.20E-04	2.02E-04	1.73E+01	5.32E-09	6.70E-05	4.01E-04
Rice husk ash (RHA)	0.540	0.00E+00	0.089	5.70E-04	1.26E-04	1.44E+01	4.65E-09	5.84E-06	6.26E-05
Ornamental rock waste (OSW)	0.003	1.06E-04	0.001	5.17E-06	3.25E-07	5.38E-06	1.26E-10	9.41E-08	3.39E-06
Recycled concrete aggregate (RCA)	0.041	0.00E+00	0.008	1.57E-03	2.00E-05	3.53E+00	1.04E-09	9.99E-06	3.00E-05
Conventional fine aggregate	0.085	2.20E-06	0.007	5.87E-04	6.31E-06	1.72E+00	1.60E-09	5.84E-06	6.26E-05
Conventional coarse aggregate	0.068	3.44E-05	0.015	2.38E-03	2.09E-05	7.75E+00	1.00E-09	1.41E-05	4.54E-05
Superplasticizer (SP)	24.700	6.04E-03	1.445	2.08E-01	5.13E-03	3.35E+02	9.42E-08	1.46E-03	6.40E-03
Water	0.002	1.00E-03	0.000	5.16E-05	2.03E-06	7.62E-02	1.04E-11	7.48E-08	1.18E-06

2.5 Strategies to improve the SCC eco-efficiency performance

Reducing cement consumption in concrete becomes a challenge for civil construction to follow more sustainable [75]. The development of dosage methodologies that improve the characteristics of concrete only with readjustment in the proportion of materials can increase mechanical strength and reduce cement consumption [45,76–78].

An efficient dosage can promote high durability of reinforced concrete structures and high mechanical strength, allowing the reduction of reinforcement rates, which, in addition to reducing the cost of large structures, allows for a reduction in the environmental impact and an increase in the eco-efficiency of the reinforced concrete due to the decrease in steel production [16].

The adaptation of concrete to incorporate waste into its matrix replacing conventional materials proves to be the most effective way of mitigating environmental impacts, high energy consumption, generation of greenhouse gases, and exploitation of natural resources through the extraction of new building materials, and also can dispose of the waste for sustainable reuse. Due to the high consumption of concrete worldwide, even low replacements of conventional materials by waste can effectively reduce the environmental impact [31,77,79].

2.5.1 SCC mixture design methods

Several methodologies for dosing self-compacting concrete have been developed over the years to increase the matrices' fluidity, strength, and durability. Due to the wide variety of dosage studies and the difficulty of comparing these studies, Shi et al. [80] proposed the

classification of methodologies in empirical dosage, compressive strength, particle packing, factorial statistical model, and paste rheology.

In general, the dosages presented are based on proportions of the materials, and the tests for adequacy and confirmation of workability, fluidity, passing ability, and resistance to segregation are carried out using spreading (Slump flow), V-funnel, J-ring, and L-box, among other tests recommended by The European Guidelines for Self-Compacting Concrete and standardized [15].

The dosing methodologies most cited in the literature for self-compacting concrete can be found in Table 2.3.

Table 2.3 – Dosage methodologies.

Reference	Classification	Method	Essays	¹ Considerations
Okamura, Ozawa, Maekawa, and Ouchi (1995) [3]	Experimental, empirical	Coarse aggregates fixed at 50% of the solids volume. Fine aggregates fixed at 40% of the mortar volume. Assigning values for the water/fines ratio from 0.9 to 1.0 in volume. Testing the superplasticizer content through the parameters G_m for fluidity and R_m for viscosity, that relate different slump cone dimensions with the results obtained.	Slump-test flow V-funnel	Simplified methodology. Several laboratory tests are needed. High consumption of superplasticizer and possibility of blocking. Do not consider the use of supplementary materials.
EFNARC (2005) [15]	Experimental, empirical	Definition of the water/fines ratio (by volume) from 0.80 to 1.10. Cement quantity between 350 kg/m ³ to 450 kg/m ³ . More than 500 kg/m ³ can increase shrinkage. Less than 350 kg/m ³ only with the inclusion of another cementitious material. Total amount of fines from 160 liters to 240 liters (400 kg/m ³ - 600 kg/m ³). Quantity of coarse aggregate typically between 28% to 35% of the mix volume. Quantity of water does not exceed 200 liters/m ³ . Optimal volume of sand in the mortar varies between 40% and 50%.	Slump-Test flow L-box U-box V-funnel J-ring	Defines specific requirements for the SCC constituents, their composition, and application based on research. Simplified methodology. Several laboratory tests are needed.
Petersson, Billberg, and Van (1996) [81]	Particle packing	Determination of a granular skeleton through blocking risk equations. Delimitation of a volume of paste that guarantees self-compaction without the risk of segregation.	Slump-test flow L-box	Obtaining concrete with dense packing and fluidity without the risk of segregation. Difficult application.

Reference	Classification	Method	Essays	¹ Considerations
Larrard and Sedran (1999) [82]	Particle packing	<p>Characterization of materials.</p> <p>Adjustment of the granular skeleton of the aggregates through equations.</p> <p>Adjust the paste using equations in the fresh state (flow stress and viscosity) and hardened (strength and modulus of elasticity).</p>	Slump-test flow Rheometry	<p>Obtention of concrete with good packing density.</p> <p>Difficult to apply without the use of software due to the existence of many equations.</p>
Su, Hsu and Chai [83]	Particle packing	<p>Determination of the aggregates proportioning through a packing factor.</p> <p>Cement consumption due to the required strength.</p> <p>Water consumption by w/c ratio.</p> <p>Calculation of the amount of supplementary material (filler, pozzolan, and slag) required for 1 m³ of concrete.</p> <p>Adjust the dosage of water and superplasticizer.</p>	Slump-test flow L-box U-box V-funnel	<p>Simple and with low cement consumption.</p> <p>Concrete dosed based on strength, fluidity, and packing.</p> <p>Packing factor is assumed empirically.</p> <p>Only allows additions of fly ash and blast furnace slag.</p>
Tutikian (2004) [84]	Particle packing	<p>Determination of the granular skeleton through packing.</p> <p>Determination of the w/c and admixture ratio.</p> <p>Blend dosages.</p> <p>Correction of segregation through the use of fines and viscosity modifier admixtures.</p>	Slump-test flow	Possibility of making lower-cost concretes.
Gomes, Gettu, and Agulló (2002, 2003) [85]	Particle packing and rheology	<p>Fixing the w/c ratio <0.40.</p> <p>Optimization of the superplasticizer to cement and fines to cement ratios.</p> <p>Determination of the granular skeleton through the largest unit mass (smallest number of voids) and aggregate size limit in 20 mm.</p> <p>Evaluation of the paste according to workability.</p>	Slump-test flow L-box U-box V-funnel	<p>Superplasticizer at saturation point.</p> <p>High strength.</p> <p>Carrying out different mixtures to adjust the water/binder ratio.</p>
Kanadasan and Razak (2014) [86]	Particle packing	<p>Use of particle packing using palm oil aggregate.</p> <p>Selection of a lubrication factor.</p> <p>Determination of cement and paste contents.</p> <p>Determination of the consumption of additional water and powder. Concrete evaluation.</p>	Slump-test flow L-box T ₅₀₀ V-funnel	<p>Possibility of using other aggregates.</p> <p>Sustainable and save natural resources.</p>
Hwang, and Tsai (2005) [87]	Particle packing and Lightweight aggregates	Method based on the Densified Mixture Design Algorithm (DMDA).		Applicable to lightweight concrete.
Saak et al. (1999 and 2001) [88]	Rheology	<p>Concept of the self-fluid rheological zone (ZAF).</p> <p>Segregation control is calculated through the cement paste's yield stress, viscosity, and density.</p>	U-box	<p>Control through optimal rheology for resistance to segregation or self-flow.</p> <p>Difficult to apply.</p>

Reference	Classification	Method	Essays	¹ Considerations
Repetto-Melo (2005) [89]	Strength	Determination of w/c ratio based on poor (w/c: 0.56), rich (w/c: 0.39) or intermediate (w/c: 0.48) dosages. Definition of fine aggregate content between 35% and 55% of the mortar volume. Choice of the superplasticizer admixture content through the parameters G_m for fluidity and R_m for viscosity. Adjustment in coarse aggregate content between 27% and 33% of the total volume of concrete.	Slump-Test flow L-box V-funnel	Based on normal strengths. Use conventional materials.
Shi and Yang (2005) [90]	Lightweight aggregates	Use of a combination of paste and ACI dosing methodology for conventional structural lightweight concretes. Add fly ash and glass filler for increased fluidity and resistance to segregation.	-	Good fluidity and resistance to segregation. Applicable to lightweight concrete.

¹Considerations made by the authors of this review.

2.5.1.1 Empirical design method

The first methodologies were based on experimental results, which can be called empirical dosages, where limit values were found for the proportion of each material. However, despite being easy to apply, being able to choose the desired trait based only on limit values, methodologies based on empirical dosages are simplified and require laboratory tests to adapt the materials to the mixture, in addition to not considering the characteristics of the materials used, suitability and use of alternative materials, or optimization of concrete properties [3,15,80,91].

This type of dosage does not always achieve an optimal result, with the best proportion of materials for the necessary characteristics of self-compacting concrete, which can raise the cost of concrete by incorporating large amounts of chemical admixtures to stabilize the properties in the fresh state without compromising the hardened state properties [80].

Applying this methodology in isolation requires extensive sampling for characterization tests or repeated treatments. However, the empirical dosage can be used as a basis for applying other existing dosage methodologies, delimiting the consumption of each material and using particle size curves or regression equations to optimize the desired properties of concrete, or experimental planning to reduce the number of samples to be tested.

2.5.1.2 Particle packing method

With the advancement of technologies and dissemination of the use of self-compacting concrete, new researches and methodologies emerged, such as dosages based on particle packing, in which the granular skeleton of materials is studied for a better proportion, to fill the voids with smaller particles and decrease the porosity of the mixture, and consequently increase the strength and durability of concrete [80,92].

The first particle packing models used equations based on particle size to create an ideal particle size curve, which would guarantee the lowest number of voids, to be adjusted to the particle size curve of the mixture of materials so that the closer these curves, the denser the packing of the mixture and the smaller the number of voids [93–95]. Despite these models presenting good packing results, they cannot predict the results of the concrete produced because they do not consider the mechanical and chemical characteristics of the materials used; therefore, they need laboratory analysis to verify the properties of the concrete produced.

The models proposed by Furnas [94], Andreassen and Andersen [95], Funk and Dinger [93] are not exclusive to self-compacting concrete but can be adjusted using the "q" distribution coefficient of the equations, in which to obtain a good flowability and density, the coefficient should be between 0.20 and 0.30, where values between 0.20 and 0.23 are more workable by increasing the fines content, keeping the proportion of fines above 40% of the volume of the mixture, reducing the interference of larger grains, causing only the strength of the matrix to appear in the system [15,92,96–98]. The modified Andreassen curves for different coefficients can be found in Figure 2.1, where it is demonstrated that there is an increase in the fines content of the mixture for smaller coefficients.

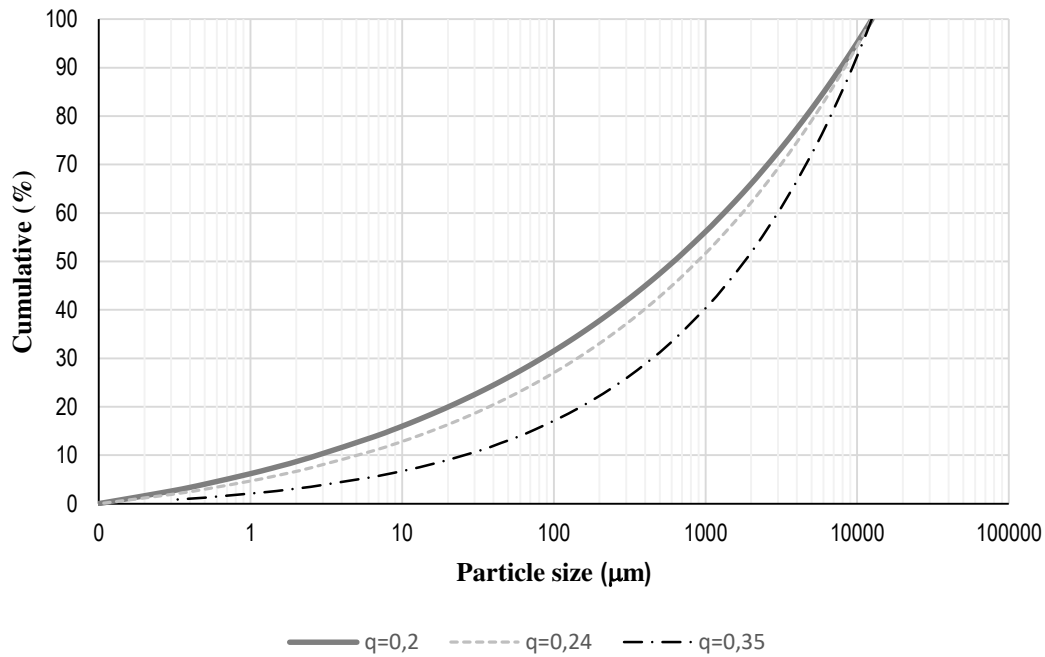


Figure 2.1 - Modified Andreassen curves for different q coefficients

Other specific dosage models for self-compacting concrete were proposed considering the high concentration of fine material and superplasticizer content, and because they are based on particle size, the equations can be used for different materials with good packing results. However, they do not consider the morphology of the particles, and there may be changes when using a large amount of materials with physical characteristics very different from conventional materials [1,81–84,86,87,99–101].

2.5.1.3 Rheology of paste model

The methodology by studying the rheology of the paste aims to control the rheological zone, maintaining fluidity and resistance to segregation by assessing the paste, considering the properties of the previously chosen aggregates [1,102–105]. It is the paste that controls much of the segregation resistance and workability, and to assess the rheology, it should initially be tested while maintaining a minimum viscosity (dynamic particle condition, such as during concreting) and the yield stress (static particle condition) [88,102].

High yield stress and viscosity decrease the mix's workability, decreasing the fluidity and self-compacting ability of the concrete [88]. However, the yield stress and viscosity control the segregation of the aggregates, and, therefore, a minimum must be established for the self-

compacting concrete to guarantee its fluidity characteristics without compromising the stability of the matrix [88].

Saak et al. [88] studied pastes by testing the matrix's yield stress and viscosity. The gravitational force of the particle, which is determined by its density, is opposite to the buoyancy force given by the density of the paste. When particle density and slurry density are similar, the mixture remains stable, and flow tension or viscosity can be disregarded in segregation resistance but still influences the mixture's fluidity. When there is a significant difference in material densities, the force exerted on the particle makes it move, which is controlled by an adequate flow tension or viscosity [88].

Therefore, a balance of densities, yield stress, and viscosity must be established, which can be controlled through the study of the physical properties of the paste and the characteristics of the aggregates, reaching optimal rheology, where there is a minimum resistance to segregation while maintaining the workability of concrete [88,103–106]. The diagram shown in Figure 2.2 demonstrates the achievement of the optimal rheology region.

In general, in self-compacting concretes, the paste density must be increased, and the concrete's yield stress decrease by increasing the fines content in the concrete and reducing the water consumption in the paste, controlling the fluidity of the mixture with the use of superplasticizers. A decrease in fines content or increased water consumption leads to a low paste density and low yield stress, leading to segregation risks.

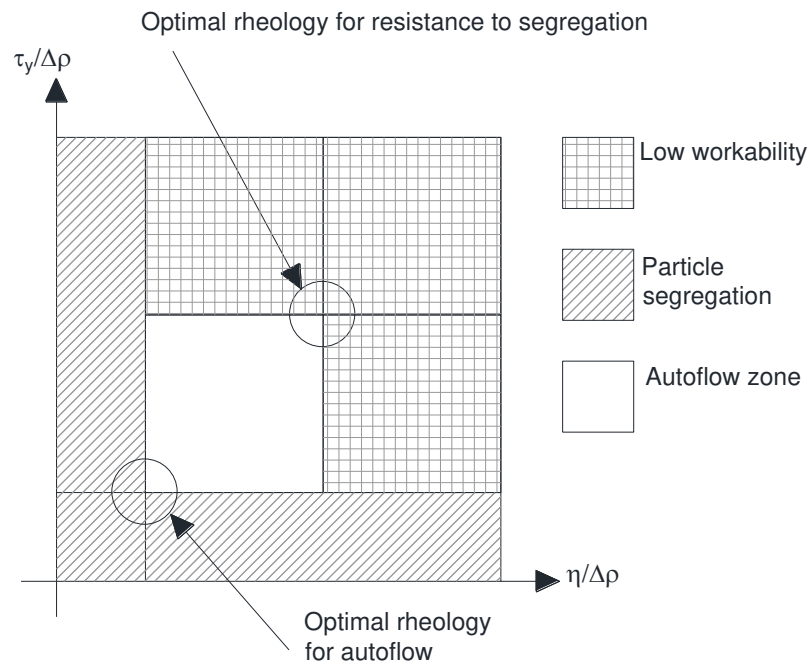


Figure 2.2 – Flow stress ($\tau_y/\Delta\rho$) versus viscosity ($\eta/\Delta\rho$) diagram, adapted from Saak et al. [88].

2.5.1.4 Compressive strength method

Concrete dosing methods by fixing strengths according to cement consumption were adapted for self-compacting concretes. They used compressive strength results of several mixtures, with different proportions of conventional materials previously studied, and may use other methodologies to adapt these mixtures for making calculation equations for materials based on a fixed compressive strength. These methodologies are similar to conventional concrete dosages, such as the ABCP [107] or ACI 211.1 methods [60,89,100,108,109].

The equations require some material characteristics, such as fineness modulus and maximum size of the aggregates, requiring laboratory characterization studies. For industries where materials are constantly characterized, this does not become an obstacle, making this a usual method for standard self-compacting concrete dosages [80].

Despite being practical equations for using self-compacting concretes with usual strengths, they do not allow for the diversification of materials or proportions, incorporations, or replacements that are not previously adapted to the methodology, with the risk of obtaining unforeseen results. Therefore, special self-compacting concretes, such as reactive powders,

lightweight concretes with fiber additions or with residue incorporations, must be studied in the laboratory for mix adequacy, or other dosage methodologies can be applied.

However, some authors were able to adapt methodologies based on compressive strength to use specific materials, such as Shi and Yang [90], who used the methodology of ACI 211.1 [109] for self-compacting concrete with the incorporation of lightweight aggregate.

2.5.1.5 Statistical factorial model

Although several studies and adaptations of methodologies are already established, there is still no universal dosage for self-compacting concrete that is easy to apply and allows the integration of different types of materials [80]. For the use of unconventional materials previously studied in the literature in self-compacting concrete incorporations, analyses of the incorporations must be carried out in the laboratory in different proportions and combinations. One way to optimize the experimental planning of new mixtures, investigate several factors simultaneously, minimize work and experimental cost, and promote assertive studies is to use a statistical experimental design [110].

The factorial statistical planning method emerges as a new dosage methodology. It can be done through factorial models that use independent variables, a central composite factor model with repetitions only at the central point, and a central rotational composite where the points in the sample space are equidistant from the central point (Figure 2.3). One can also use a mixture design through proportions of materials dependent on each other [80,111].

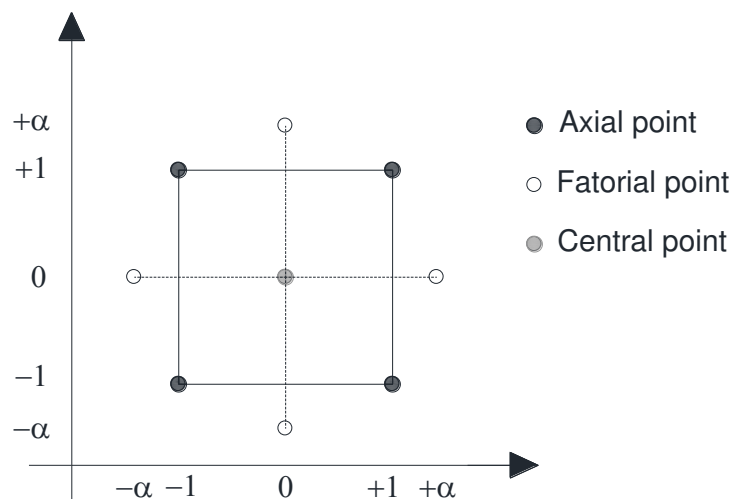


Figure 2.3 - Rotational central composite diagram.

The composite experimental design developed by Box and Wilson [112] uses polynomial functions where the experimental error is smaller, allowing the repetition of only the central treatments. For application, the ratios to be studied must be chosen, and these must be independent of each other, such as the water/cement ratio or the powder/aggregate ratio, where changing the value of one of the ratios does not change the others. These relationships have their values delimited, which can be done through studies involving the other dosage methodologies already mentioned. The proportions of each relationship are combined through a factorial model to make the mixture proportions of the samples to be tested.

With the results of the samples, it is possible to correlate the values obtained from each test to the stipulated relations using regression equations, and the response surface methodology can be used [113]. One way to analyze the results is through the statistical tool desirability, which makes a simultaneous optimization of multiple responses generating a maximized value [114].

The great advantage of the statistical method is the optimization of the number of samples to be tested and the explanatory power of the results, which consequently reduces the laboratory cost concerning the range of results obtained, being able to analyze the influence of each material on the composition statistically. However, this method requires testing in laboratories, and, compared to proportioning techniques that only require a single proportion to be tested, this can be considered a high-cost method, making its use interesting only for studies of new incorporations or optimizations in self-compacting concrete [30,80,115].

For practical applications, equations predefined by other authors can be used. An example of application of the statistical model is the work of Kostrzanowska-Siedlarz and Gołaszewski [116], who studied the rheological properties of ultra-strength self-compacting concrete and found equations relating the paste, water-cement ratio, superplasticizer content, percentage of silica, and sand percentage with the values of diameter and spreading time using the Slump Flow test. Matos et al. [117] used statistical models and numerical optimization techniques to find the best proportion of materials that would reduce the risk of cracking and increase the waterproofing of high-strength self-compacting concrete in maritime regions. Moretti, Nunes, and Sales [118] studied the incorporation of sugarcane bagasse ash in self-

compacting concrete using a factorial statistical approach to evaluate the fresh state, hardened state, and durability properties.

Bouziani [119] used simplex-lattice mix planning to analyze different types of sand (river, crushed, and dune) in fresh and hardened properties in self-compacting concrete, enabling the optimization of properties that meet specific recommendations. Ozbay et al. [120] used the Taguchi experimental dosage methodology [121] analysis of variance to study the parameters water/cementitious materials (W/C), water content (W), percentage of fine aggregates to total aggregates (w/a), fly ash content (FA), air entrainment (AE) and superplasticizer (SP) in the properties of mechanical strength, ultrasonic pulse velocity, permeability, porosity and water absorption in high strength self-compacting concretes.

Sonebi [122] investigated the pulverized fuel ash in a medium strength self-compacting concrete using a factorial model to optimize the experiments and regression analysis to evaluate the ash concentration and superplasticizer content in the fresh state and compressive strength properties. Almeida Filho et al. [123] studied the compressive strength, tensile strength, and modulus of elasticity of self-compacting concrete, evaluating the maximum aggregate size, paste concentration, and coarse aggregate based on histograms. Abouhussien and Hassan [124] used statistical proportioning to optimize mixtures and produce equations for high-strength self-compacting concretes' fresh and hardened state properties using metakaolin.

2.5.2 SCC containing industrial waste

To increase the sustainability of self-compacting concrete, reduce costs with new materials, exploitation of natural resources, reduce cement consumption and improve the characteristics of self-compacting concrete and promote the correct disposal of waste, several researches are being carried out. As a result, new dosages using recycled materials such as blast furnace slag, fly ash, rice husk ash, recycled concrete aggregates, sugarcane bagasse ash, and ornamental stone waste has been proposed and investigated. Some studies containing residues in self-compacting concrete are shown in Table A.2.1 in the Appendix of this review.

2.5.2.1 Ground-granulated blast-furnace slag (GGBFS)

Blast furnace slag (BFS) is formed by mixing impurities from iron ore with limestone, dolomite, and coal ash during the manufacture of pig iron [22,125]. It is then separated from the cast iron and cooled [22,125]. It can be cooled quickly, which generates the formation of non-crystalline, amorphous silicate compounds with high pozzolanicity, or it can be cooled slowly, generating glassy compounds and crystalline silicates with low pozzolanicity [22,125].

Quickly cooled slag can serve as a substitute for cement, increasing the durability of concrete to thermal cracking, increasing resistance to sulfate and chloride attack, reducing hydration heat, water demand, and permeability, and increasing long-term mechanical strength [22]. On the other hand, the slag cooled slowly can serve as a substitute for conventional aggregates.

In self-compacting concrete, some authors observed that the replacement of cement by GGBFS tends to reduce spreading and to lose workability and fluidity, requiring an increase in the superplasticizer content [22,56,59,60]. However, other authors have found an increase in the spread of the mixture [54,55,57,126,127].

GGBFS proves to be a good partial substitute for cement, which, despite reduced mechanical strength in the early ages in high replacements, manages to match or even surpass strength over time due to its reactivity, in addition to increasing crack resistance, resistance to sulfate and chloride attacks [54,56,59,128]. However, it tends to increase shrinkage when replacing aggregates due to aggregate porosity and reactivity in slag hydration [128].

2.5.2.2 Fly Ash (FA)

Fly ash (FA) is a by-product of the burning of pulverized coal in an electricity generation plant, which melts, cools, and over time hardens after combustion [28,61]. Possessing smooth, spherical-shaped particles, the FA does not react with the superplasticizer, producing a repulsive force, which consequently manages to reduce the dosage of superplasticizer in self-compacting concretes and increase workability [21,28,29,55,61–63,78].

Despite generating a drop in strength in the early ages of concrete due to its low reactivity, small replacements of cement by FA increase mechanical strength over time, which may be due to the pozzolanic activity of the residue [21,28,55,61–63,78].

The residue also acts as a filler, filling the voids of the mixture, increasing the packing of particles, reducing the capillary pores and their connectivity, which consequently reduces the absorption of water in concrete [21,28,62,63,78]. The residue also increases UPV, increases resistivity, and reduces permeability to chlorides [21,28,62,78].

Therefore, due to fly ash's spherical particles and pozzolanicity, this residue is an excellent alternative to cement in self-compacting concrete, including combinations with other residues.

2.5.2.3 Rice husk ash (RHA)

Rice husk ash (RHA) is produced through the combustion of rice husk, generating the ash, fine particle size material rich in silica, with the potential to replace cement, which can acquire pozzolanic activity due to the high silica content. [22,25].

Due to its fine and elongated particles, with a high surface area, the replacement of cement at up to 15% of RHA can increase the absorption of water in the mixture and decrease the spreading value, requiring a readjustment of the mix, water consumption, and superplasticizer for self-compacting concrete, with replacement values above 15% significantly affecting the resistance to segregation [18,19,23,24,64].

Low cement replacements by RHA (up to 15%) manage to keep the compressive strength close to the base mix, with larger replacements with a drop in mechanical strength [18,19,23–25]. However, the mechanical strength of self-compacting concrete depends on combining other materials, with a good dosage that can vary from 20 MPa to over 100 MPa. This demonstrates that mixtures designed by experimental methodologies may not reach the full mechanical potential, especially when the residue replaces a material with similar characteristics. In contrast, methodologies based on particle packing achieve higher mechanical strength results due to a proportioning based on characteristics of all constituent materials [64,65,129].

2.5.2.4 Sugarcane Bagasse Ash (SCBA)

After the sugarcane is crushed to extract the juice, sugarcane bagasse is generated, which can be used as biomass for energy generation when burned in boilers, producing sugarcane

bagasse ash (SCBA) during this process [26,118]. These ashes have a high concentration of amorphous compounds and crystalline silica (SiO_2), and therefore, can be used as supplementary cementitious material with pozzolanic action [26,27,130,131].

SCBA can be used as a viscosity modifier in self-compacting concretes, increasing the resistance to segregation, reducing production costs [26,27]. However, the irregular and porous particles of SCBA absorb part of the mixing water, which reduces the spread and workability of self-compacting concrete, requiring an increase in the superplasticizer content [26,27,66,67].

The mechanical results demonstrate that SCBA does not produce a drop in strength, keeping this close to the values of the control concrete when using a proportion of up to 30% replacement in cement content [26,66,67,118,132]. The pozzolanic reaction of SCBA also increases the resistance to chloride penetration and sulfate attack in concrete by reducing $\text{Ca}(\text{OH})_2$, in addition to decreasing cracking and loss of strength when raising concrete to high temperatures [66,67,132].

2.5.2.5 Recycled Concrete Aggregates (RCA)

Recycled concrete aggregates are generated by demolishing reinforced concrete structures and are crushed to reach the aggregate particle size. During the RCA crushing and washing process, a large part of the fine material from the paste is released from the aggregate, increasing the porosity and water absorption of the RCA, and, if the material is not well processed, these characteristics can increase the contamination of the RCA (e.g., brick, tiles, wood, and soil) [133,134].

Due to the high absorption of these aggregates and the particles considered to be of low sphericity, RCA tends to absorb part of the kneading water of self-compacting concrete. The concrete's workability, yield stress, and plastic viscosity are affected, requiring more water and superplasticizer, increasing the tendency to segregation. Alternatively, a greater amount of fines can be considered [36–39]. Pre-soaking the RCA in water until it reaches saturation before introducing it into the mixture is a way to address this issue, thus avoiding excessive water loss in the mixture, and that the superplasticizer admixture is lost when absorbed by the RCA [37].

The porosity and irregular shape of the RCA particles also affect the packing density of the granular skeleton of the self-compacting concrete, which can interfere with the mixture design by particle packing, and these proportioning methods will not always show the best results when compared to the experimental proportioning [39].

The increase in aggregate content also increases porosity and decreases mechanical strength and carbonation resistance [38,68,69,135]. Therefore, fluidity and strength become opposite characteristics when using recycled aggregates. The increase in the superplasticizer content and optimized proportioning for a minimum amount of fine material is necessary to prevent loss in fresh and hardened self-compacting concrete characteristics.

2.5.2.6 Ornamental Stone Waste (OSW)

Ornamental stone waste (OSW) comes from the cutting and polishing process of marble and granite sheets, and, for the most part, it is discarded in decantation ponds and landfills [136,137]. The tailings generated in the sheet cutting process can be crushed to achieve coarse and fine aggregates, while the polishing residue, due to its high content of fines and crystalline materials, can be used as filler [31–35].

OSW particles, in general, are classified as angular, rough, and with a high surface area, generating an increase in water demand in self-compacting concrete to maintain the workability and fluidity of the mixture, increasing the concrete water absorption. However, when polishing residue is used as filler, the fine granulometry of the residue can fill the voids and reduce the permeability and porosity of the concrete [31–35].

Some studies with ornamental stone residues from marble and granite show a reaction with free Ca(OH)_2 producing hydrated calcium silicate. When compared to other types of fillers, OSW can induce a pozzolanic effect, increasing mechanical strength, despite being classified as non-pozzolanic material [31–34,71,73]. The results in self-compacting concrete show that substitutions of up to 15% can increase workability, segregation resistance, and mechanical strength [32–34]. However, larger substitutions can lead to a loss in the fluidity of

the mixture, demanding more water and/or superplasticizer, which can lead to a tendency to segregation and a drop in mechanical strength [31,33,34,137].

2.6 Discussions

2.6.1 Self-compacting concrete constituents

According to the life cycle assessment data collected by Souza et al. [53], the superplasticizer admixture has superior impact results than all other materials in all the categories mentioned, making it the material with the most significant environmental impact. Thus, due to the low consumption of superplasticizers in conventional concretes, their eco-performance impacts were negligible.

However, self-compacting concretes demand higher consumptions of superplasticizers to meet the mixtures' need for fluidity, spreading, and cohesion. This increase is significant for the environmental impacts associated with SCCs.

The average consumption of each material used in the SCCs of the case study was calculated, as well as the percentages of environmental impacts related to each indicator proposed by Souza et al. [53]. Figure 2.4 shows the influence of each material on the different impact categories. The superplasticizer used in SCCs has a strong influence on environmental impacts, especially in the Primary Energy, Freshwater Aquatic Toxicity, and Marine Toxicity categories, in addition to increase the cost.

Therefore, in SCCs, it is extremely important to reduce cement consumption and the use of natural resources, but also to seek optimized proportions with low consumption of superplasticizers.

Adding residues is highly effective in reducing the environmental impacts related to the replacement material, but they can reduce the workability of SCCs. In this context, to increase eco-efficiency, it is interesting to replace conventional materials with residues that increase the workability of the mixture or those that do not demand higher consumptions of superplasticizers.

Thus, the replacement of conventional materials by fly ash is one of the best alternatives for this type of concrete, while residues with high water absorption or residues with lamellar, rough, and angular particles can be harmful to both the mechanical and eco-efficiency performances of the concretes.

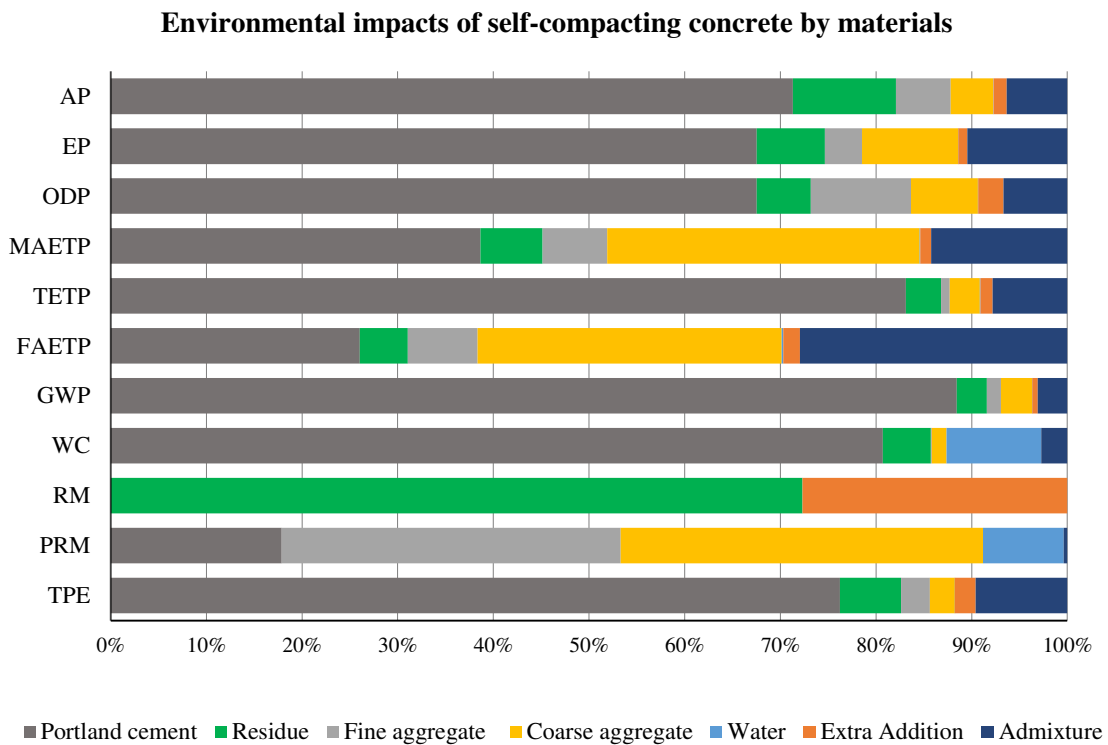


Figure 2.4 - Environmental impacts of self-compacting concrete by constituent materials (TPE - Total Primary Energy; PRM - Primary Raw Material; RM - Recycled Material; WC - Water Consumption; GWP - Global Warming Potential; FAETP - Freshwater Aquatic Ecotoxicity Potential; TETP – Terrestrial Ecotoxicity Potential; MAETP - Marine Ecotoxicity Potential; ODP - Ozone Depletion Potential; EP - Eutrophication Potential; AP - Acidification Potential).

2.6.2 Evaluation of the mixtures of the consulted literature

The works consulted suggest that the strength of SCC is closely related to the fluidity and self-compaction of the mixture. Mixtures that did not reach the spreading and workability specifications present difficulties in densifying, retaining a greater amount of voids, increasing the mixture's porosity, consequently reducing the compressive strength.

Due to the different physical, morphological, mineralogical, and chemical characteristics of the materials, the proportions of each material influence the fresh and hardened characteristics of SCC. Small changes in the proportions of materials can destabilize

the mixture. Even small changes in the mass of materials with different densities can drastically alter the volume of the mix, considerably increasing the proportion of a lower density material.

Regarding physical and morphological characteristics, materials that have particles with lamellar, elongated characteristics and a higher specific surface tend to absorb more water, decreasing workability and density, and consequently, decreasing compressive strength [18]. The drop in compressive strength leads to a drop in the eco-efficiency of the mixture.

However, the particle effect can be compensated for reactive additions, which tend to increase the strength of concrete, increasing its mechanical performance and eco-efficiency. This can be seen in the results of the indicator proposed by Daminelli et al. [52] in Table A.2.2, which demonstrate that the Binder Intensity (BI) tends to decrease with the increase in reactive additions since there is a decrease in binder consumption and an increase or stabilization of mechanical strength. This effect is mainly seen in blends with GGBFS and in some blends of FA, RHA, and SCBA.

On the other hand, inert materials only replace the high exploitation of natural resources. Therefore, BI tends to increase with the decrease in cement consumption and the consequent drop in strength. The replacement of conventional materials by materials that reduce workability also tends to increase the BI. This is the case for RCA and OSW.

It was observed that mixtures with the same proportions of substitutions for the same residue could obtain very different performance results, which is linked to the proportion of materials used and efficient dosage. The mixtures with the best performance and the lowest BIs are from works that used particle packing methods, such as Dinakar [60], which replaced up to 80% of the cement with GGBFS, and Le and Ludwig [64], which replaced up to 40% of the cement by FA and up to 20% by RHA.

According to the BI indicator (Table A.2.2) and the EEP indicator (Table A.2.4), in most studies, mixtures with residues were more eco-efficient than the reference mixtures. The exceptions are the mixtures that had a significant drop in mechanical strength, which indicates the limit of replacement for optimal performance, as in the works of Gill and Siddique [23], Hamza Hasnain et al. [65] and Jain, Gupta, and Chaudhary [70]. However, these same low-strength mixtures have superior indicators when compared to dosages without residues of

similar strength by other authors. Despite the drop in strength of these mixtures, many are still in the classification of structural concrete; however, when their constituents are analyzed, the slight increase in waste may not justify the cost of this low-strength concrete.

Comparing the different residues (Figure 2.5), none of them was much better or worse, regardless of whether active or inert. It demonstrates that the important thing is to have efficient dosages.

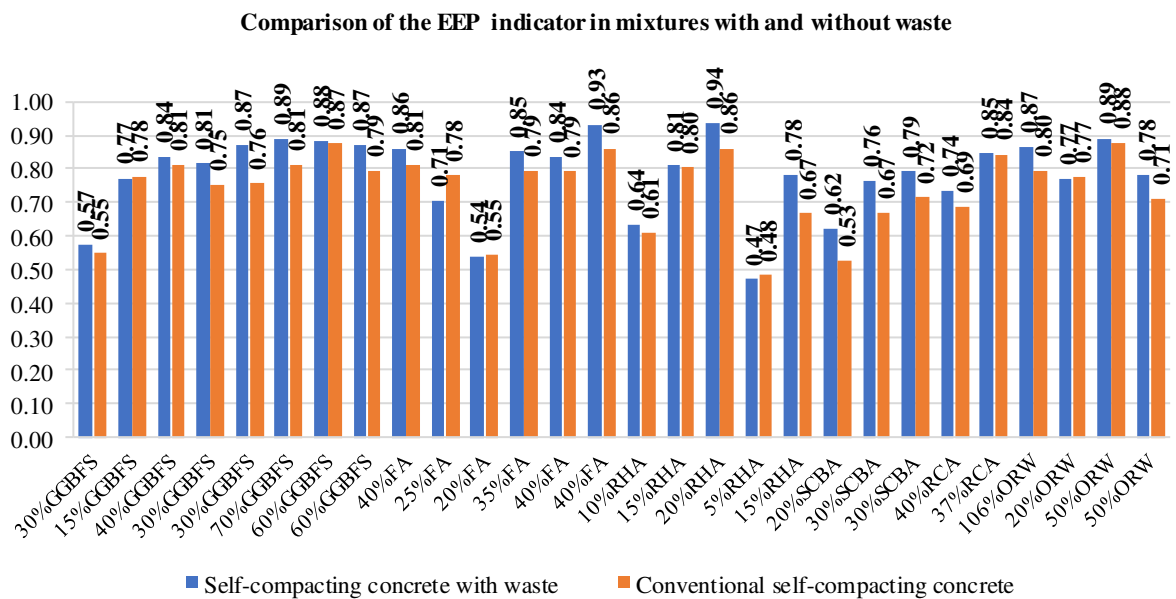


Figure 2.5 – Comparison of the EEP indicator in mixtures with and without waste.

2.7 Conclusion

A literature review was carried out on strategies to increase the eco-efficiency of self-compacting concretes, through efficient dosages and the addition of industrial waste, such as ground granulated blast furnace slag, fly ash, rice husk ash, sugarcane bagasse, recycled concrete aggregates, and ornamental stone waste.

After reviewing the self-compacting concrete dosage methodologies and the characteristics and properties of the self-compacting, concretes incorporating waste, an evaluation of the eco-efficiency of the mixtures produced by the consulted authors was carried out using sustainability indicators.

As noted by other authors, cement remains a material used to manufacture concrete with more significant environmental impacts. However, despite their low consumption compared to other materials, superplasticizer admixtures also have a strong environmental impact on self-compacting concrete. Furthermore, mechanical strength is still a factor of great importance when comparing concretes.

Therefore, to increase the performance of self-compacting concretes, it is possible to reduce cement consumption by replacing it with cementing materials with lower impacts, adding residues to reduce the environmental impacts associated with the exploitation of natural resources, and increasing the performance of mixtures by promoting efficient dosages and selecting materials that promote the workability of self-compacting concrete with minimal consumption of chemical admixtures.

Acknowledgment

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance code 001. The authors also acknowledge the support provided by the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG), and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). Thanks are also due to the Brazilian Research Groups SICon-CNPq/UFV and RECICLOS-CNPq/UFOP.

References

- [1] P.C.C. GOMES, A.R. Barros, Métodos de dosagem de concreto autoadensável, PINI, São Paulo, 2009.
- [2] A.M. Neville, Propriedades do Concreto, 5. ed, Bookman, Porto Alegre, 2016.
- [3] H. Okamura, M. Ouchi, Self-Compacting Concrete, J. Adv. Concr. Technol. 1 (2003) 5–15.
- [4] P.K. Mehta, P.J.M. Monteiro, Concreto: Propriedades e materiais, IBRACON. (2014).
- [5] A. Kefelegn, A. Gebre, Performance of self-compacting concrete used in congested reinforcement structural element, Eng. Struct. 214 (2020) 110665. <https://doi.org/10.1016/j.engstruct.2020.110665>.

- [6] P.J.D. Mendes, J.A.O. Barros, J.M. Sena-Cruz, M. Taheri, Development of a pedestrian bridge with GFRP profiles and fiber reinforced self-compacting concrete deck, *Compos. Struct.* 93 (2011) 2969–2982. <https://doi.org/10.1016/j.compstruct.2011.05.005>.
- [7] Y. Liu, S. Hou, C. Li, H. Zhou, F. Jin, P. Qin, Q. Yang, Study on support time in double-shield TBM tunnel based on self-compacting concrete backfilling material, *Tunn. Undergr. Sp. Technol.* 96 (2020) 103212. <https://doi.org/10.1016/j.tust.2019.103212>.
- [8] X. Pintado, B.E. Barragán, Homogeneity of self-compacting concretes used in tunnel strengthening - A case study, *Tunn. Undergr. Sp. Technol.* 24 (2009) 647–653. <https://doi.org/10.1016/j.tust.2009.06.005>.
- [9] P. Zhu, X. Xu, H. Liu, S. Liu, C. Chen, Z. Jia, Tunnel fire resistance of self-compacting concrete coated with SiO₂ aerogel cement paste under 2.5 h HC fire loading, *Constr. Build. Mater.* 239 (2020) 117857. <https://doi.org/10.1016/j.conbuildmat.2019.117857>.
- [10] A.L.N. Ferraz, Avaliação de retração e fluências do concreto auto-adensável para aplicação em elementos pré-moldados, Tese (doutorado), Universidade de Campinas, 2009.
- [11] Á. Salesa, J.Á. Pérez-Benedicto, L.M. Esteban, R. Vicente-Vas, M. Orna-Carmona, Physico-mechanical properties of multi-recycled self-compacting concrete prepared with precast concrete rejects, *Constr. Build. Mater.* 153 (2017) 364–373. <https://doi.org/10.1016/j.conbuildmat.2017.07.087>.
- [12] N.F. Zamri, R.N. Mohamed, K.S. Elliott, Shear capacity of precast half-joint beams with steel fibre reinforced self-compacting concrete, *Constr. Build. Mater.* 272 (2021) 121813. <https://doi.org/10.1016/j.conbuildmat.2020.121813>.
- [13] P. Lacombe, D. Beaupré, N. Pouliot, Rheology and bonding characteristics of self-leveling concrete as a repair material, *Mater. Struct. Constr.* 32 (1999) 593–600. <https://doi.org/10.1007/bf02480494>.
- [14] E.M. Lisboa, Obtenção do concreto auto-adensável utilizando resíduo do beneficiamento do mármore e granito e estudo de propriedades mecânicas, Dissertação (Mestrado), Universidade Federal de Alagoas, 2004. http://www.repositorio.ufal.br/bitstream/riufal/377/1/EdvaldoMonteiroLisboa_Capa_Cap2.pdf.
- [15] EFNARC, The European Guidelines for Self-Compacting Concrete, *Eur. Guidel. Self Compact. Concr.* (2005) 63. <http://www.efnarc.org/pdf/SCCGuidelinesMay2005.pdf>.
- [16] M.C. da Silva, Dimensionamento de pilar-parede considerando o aumento da resistência à compressão do concreto, Dissertação (mestrado), Universidade Estadual de Maringá, 2018.
- [17] E. Bacarji, R.D. Toledo Filho, E.A.B. Koenders, E.P. Figueiredo, J.L.M.P. Lopes, Sustainability perspective of marble and granite residues as concrete fillers, *Constr. Build. Mater.* 45 (2013) 1–10. <https://doi.org/10.1016/j.conbuildmat.2013.03.032>.

- [18] V. Kannan, K. Ganesan, Chloride and chemical resistance of self compacting concrete containing rice husk ash and metakaolin, *Constr. Build. Mater.* 51 (2014) 225–234. <https://doi.org/10.1016/j.conbuildmat.2013.10.050>.
- [19] M. Safiuddin, J.S. West, K.A. Soudki, Properties of freshly mixed self-consolidating concretes incorporating rice husk ash as a supplementary cementing material, *Constr. Build. Mater.* 30 (2012) 833–842. <https://doi.org/10.1016/j.conbuildmat.2011.12.066>.
- [20] M. Azimi-Pour, H. Eskandari-Naddaf, A. Pakzad, Linear and non-linear SVM prediction for fresh properties and compressive strength of high volume fly ash self-compacting concrete, *Constr. Build. Mater.* 230 (2020) 117021. <https://doi.org/10.1016/j.conbuildmat.2019.117021>.
- [21] P.R. de Matos, M. Foiato, L.R. Prudêncio, Ecological, fresh state and long-term mechanical properties of high-volume fly ash high-performance self-compacting concrete, *Constr. Build. Mater.* 203 (2019) 282–293. <https://doi.org/10.1016/j.conbuildmat.2019.01.074>.
- [22] B. Meko, J.O. Ighalo, O.M. Ofuyatan, Enhancement of self-compactability of fresh self-compacting concrete: A review, *Clean. Mater.* 1 (2021) 100019. <https://doi.org/10.1016/j.clema.2021.100019>.
- [23] A.S. Gill, R. Siddique, Strength and micro-structural properties of self-compacting concrete containing metakaolin and rice husk ash, *Constr. Build. Mater.* 157 (2017) 51–64. <https://doi.org/10.1016/j.conbuildmat.2017.09.088>.
- [24] E. Molaei Raisi, J. Vaseghi Amiri, M.R. Davoodi, Mechanical performance of self-compacting concrete incorporating rice husk ash, *Constr. Build. Mater.* 177 (2018) 148–157. <https://doi.org/10.1016/j.conbuildmat.2018.05.053>.
- [25] R.K. Sandhu, R. Siddique, Influence of rice husk ash (RHA) on the properties of self-compacting concrete: A review, *Constr. Build. Mater.* 153 (2017) 751–764. <https://doi.org/10.1016/j.conbuildmat.2017.07.165>.
- [26] T. Akram, S.A. Memon, H. Obaid, Production of low cost self compacting concrete using bagasse ash, *Constr. Build. Mater.* 23 (2009) 703–712. <https://doi.org/10.1016/j.conbuildmat.2008.02.012>.
- [27] M.A.S. Anjos, T.R. Araújo, R.L.S. Ferreira, E.C. Farias, A.E. Martinelli, Properties of self-leveling mortars incorporating a high-volume of sugar cane bagasse ash as partial Portland cement replacement, *J. Build. Eng.* 32 (2020) 101694. <https://doi.org/10.1016/j.jobbe.2020.101694>.
- [28] N. Singh, P. Kumar, P. Goyal, Reviewing the behaviour of high volume fly ash based self compacting concrete, *J. Build. Eng.* 26 (2019) 100882. <https://doi.org/10.1016/j.jobbe.2019.100882>.

- [29] A.M. Mohammed, D.S. Asaad, A.I. Al-Hadithi, Experimental and statistical evaluation of rheological properties of self-compacting concrete containing fly ash and ground granulated blast furnace slag, *J. King Saud Univ. - Eng. Sci.* (2021). <https://doi.org/10.1016/j.jksues.2020.12.005>.
- [30] P. Li, T. Zhang, X. An, J. Zhang, An enhanced mix design method of self-compacting concrete with fly ash content based on paste rheological threshold theory and material packing characteristics, *Constr. Build. Mater.* 234 (2020) 117380. <https://doi.org/10.1016/j.conbuildmat.2019.117380>.
- [31] M.S. Hameed, A.S.S. Sekar, L. Balamurugan, V. Saraswathy, Self-compacting concrete using Marble Sludge Powder and Crushed Rock Dust, *KSCE J. Civ. Eng.* 16 (2012) 980–988. <https://doi.org/10.1007/s12205-012-1171-y>.
- [32] H.E. Elyamany, A.E.M. Abd Elmoaty, B. Mohamed, Effect of filler types on physical, mechanical and microstructure of self compacting concrete and Flow-able concrete, *Alexandria Eng. J.* 53 (2014) 295–307. <https://doi.org/10.1016/j.aej.2014.03.010>.
- [33] A. Karmegam, A. Kalidass, D. Ulaganathan, Utilization of granite sawing waste in self compacting concrete, *Gradjevinar.* 66 (2014) 997–1006. <https://doi.org/10.14256/JCE.1117.2014>.
- [34] A. Jain, R. Gupta, S. Chaudhary, Performance of self-compacting concrete comprising granite cutting waste as fine aggregate, *Constr. Build. Mater.* 221 (2019) 539–552. <https://doi.org/10.1016/j.conbuildmat.2019.06.104>.
- [35] K. Ostrowski, D. Stefaniuk, Ł. Sadowski, K. Krzywiński, M. Gicala, M. Róžańska, Potential use of granite waste sourced from rock processing for the application as coarse aggregate in high-performance self-compacting concrete, *Constr. Build. Mater.* 238 (2020) 1–14. <https://doi.org/10.1016/j.conbuildmat.2019.117794>.
- [36] I. González-Taboada, B. González-Fonteboa, F. Martínez-Abella, S. Seara-Paz, Analysis of rheological behaviour of self-compacting concrete made with recycled aggregates, *Constr. Build. Mater.* 157 (2017) 18–25. <https://doi.org/10.1016/j.conbuildmat.2017.09.076>.
- [37] S. Seara-Paz, B. González-Fonteboa, J. Eiras-López, M.F. Herrador, Bond behavior between steel reinforcement and recycled concrete, *Mater. Struct. Constr.* 47 (2014) 323–334. <https://doi.org/10.1617/s11527-013-0063-z>.
- [38] V. Revilla-Cuesta, M. Skaf, F. Faleschini, J.M. Manso, V. Ortega-López, Self-compacting concrete manufactured with recycled concrete aggregate: An overview, *J. Clean. Prod.* 262 (2020). <https://doi.org/10.1016/j.jclepro.2020.121362>.
- [39] O. Kebaïli, M. Mouret, N. Arabia, F. Cassagnabere, Adverse effect of the mass substitution of natural aggregates by air-dried recycled concrete aggregates on the self-compacting ability of concrete: Evidence and analysis through an example, *J. Clean. Prod.* 87 (2015) 752–761. <https://doi.org/10.1016/j.jclepro.2014.10.077>.

- [40] S. Reichenbach, B. Kromoser, State of practice of automation in precast concrete production, *J. Build. Eng.* 43 (2021) 102527. <https://doi.org/10.1016/j.jobbe.2021.102527>.
- [41] S. Çankaya, B. Pekey, A comparative life cycle assessment for sustainable cement production in Turkey, *J. Environ. Manage.* 249 (2019). <https://doi.org/10.1016/j.jenvman.2019.109362>.
- [42] J. Lehne, F. Preston, *Making concrete change - Innovation in low-carbon cement and concrete*, 2018.
- [43] R.M. Andrew, Global CO₂ emissions from cement production, 1928-2018, *Earth Syst. Sci. Data.* 11 (2019) 1675–1710. <https://doi.org/10.5194/essd-11-1675-2019>.
- [44] E. Worrell, L. Price, N. Martin, C. Hendriks, L.O. Meida, Carbon dioxide emissions from the global cement industry, *Annu. Rev. Energy Environ.* 26 (2001) 303–329. <https://doi.org/10.1146/annurev.energy.26.1.303>.
- [45] D.C. Reis, P.C.R.A. Abrão, T. Sui, V.M. John, Influence of cement strength class on environmental impact of concrete, *Resour. Conserv. Recycl.* 163 (2020) 105075. <https://doi.org/10.1016/j.resconrec.2020.105075>.
- [46] Z.S. Ali, M. Hosseinpoor, A. Yahia, New aggregate grading models for low-binder self-consolidating and semi-self-consolidating concrete (Eco-SCC and Eco-semi-SCC), *Constr. Build. Mater.* 265 (2020). <https://doi.org/10.1016/j.conbuildmat.2020.120314>.
- [47] J. Opon, M. Henry, An indicator framework for quantifying the sustainability of concrete materials from the perspectives of global sustainable development, *J. Clean. Prod.* 218 (2019) 718–737. <https://doi.org/10.1016/j.jclepro.2019.01.220>.
- [48] M.K. Chauhan, Varun, S. Chaudhary, S. Kumar, Samar, Life cycle assessment of sugar industry: A review, *Renew. Sustain. Energy Rev.* 15 (2011) 3445–3453. <https://doi.org/10.1016/j.rser.2011.04.033>.
- [49] P. Van den Heede, N. De Belie, Environmental impact and life cycle assessment (LCA) of traditional and ‘green’ concretes: Literature review and theoretical calculations, *Cem. Concr. Compos.* 34 (2012) 431–442. <https://doi.org/10.1016/j.cemconcomp.2012.01.004>.
- [50] D.R. Vieira, J.L. Calmon, F.Z. Coelho, Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review, *Constr. Build. Mater.* 124 (2016) 656–666. <https://doi.org/10.1016/j.conbuildmat.2016.07.125>.
- [51] O. Jolliet, M. Margni, R. Charles, S. Humbert, J. Payet, G. Rebitzer, R. Rosenbaum, IMPACT 2002+: A New Life Cycle Impact Assessment Methodology, *Int. J. Life Cycle Assess.* 8 (2003) 324–330. <https://doi.org/10.1007/BF02978505>.

- [52] B.L. Damineli, F.M. Kemeid, P.S. Aguiar, V.M. John, Measuring the eco-efficiency of cement use, *Cem. Concr. Compos.* 32 (2010) 555–562. <https://doi.org/10.1016/j.cemconcomp.2010.07.009>.
- [53] A. Miranda de Souza, G.E. Soares de Lima, G.H. Nalon, M.M. Salgado Lopes, A. Luís de Oliveira Júnior, G.J. Rodrigues Lopes, M. José de Andrade Olivier, L.G. Pedroti, J.C. Lopes Ribeiro, J.M. Franco de Carvalho, Application of the desirability function for the development of new composite eco-efficiency indicators for concrete, *J. Build. Eng.* (2021) 102374. <https://doi.org/10.1016/j.jobe.2021.102374>.
- [54] S. Altoubat, D. Badran, M.T. Junaid, M. Leblouba, Restrained shrinkage behavior of Self-Compacting Concrete containing ground-granulated blast-furnace slag, *Constr. Build. Mater.* 129 (2016) 98–105. <https://doi.org/10.1016/j.conbuildmat.2016.10.115>.
- [55] M. Uysal, M. Sumer, Performance of self-compacting concrete containing different mineral admixtures, *Constr. Build. Mater.* 25 (2011) 4112–4120. <https://doi.org/10.1016/j.conbuildmat.2011.04.032>.
- [56] O.M. Ofuyatan, A.G. Adeniyi, D. Ijie, J.O. Ighalo, J. Oluwafemi, Development of high-performance self compacting concrete using eggshell powder and blast furnace slag as partial cement replacement, *Constr. Build. Mater.* 256 (2020) 119403. <https://doi.org/10.1016/j.conbuildmat.2020.119403>.
- [57] O. Boukendakdji, E.H. Kadri, S. Kenai, Effects of granulated blast furnace slag and superplasticizer type on the fresh properties and compressive strength of self-compacting concrete, *Cem. Concr. Compos.* 34 (2012) 583–590. <https://doi.org/10.1016/j.cemconcomp.2011.08.013>.
- [58] H. Zhao, W. Sun, X. Wu, B. Gao, The properties of the self-compacting concrete with fly ash and ground granulated blast furnace slag mineral admixtures, *J. Clean. Prod.* 95 (2015) 66–74. <https://doi.org/10.1016/j.jclepro.2015.02.050>.
- [59] S. Dadsetan, J. Bai, Mechanical and microstructural properties of self-compacting concrete blended with metakaolin, ground granulated blast-furnace slag and fly ash, *Constr. Build. Mater.* 146 (2017) 658–667. <https://doi.org/10.1016/j.conbuildmat.2017.04.158>.
- [60] P. Dinakar, K.P. Sethy, U.C. Sahoo, Design of self-compacting concrete with ground granulated blast furnace slag, *Mater. Des.* 43 (2013) 161–169. <https://doi.org/10.1016/j.matdes.2012.06.049>.
- [61] F.A. Mustapha, A. Sulaiman, R.N. Mohamed, S.A. Umara, The effect of fly ash and silica fume on self-compacting high-performance concrete, *Mater. Today Proc.* 39 (2019) 965–969. <https://doi.org/10.1016/j.matpr.2020.04.493>.
- [62] A. Jain, R. Gupta, S. Chaudhary, Sustainable development of self-compacting concrete by using granite waste and fly ash, *Constr. Build. Mater.* 262 (2020) 120516. <https://doi.org/10.1016/j.conbuildmat.2020.120516>.

- [63] M. Liu, Self-compacting concrete with different levels of pulverized fuel ash, *Constr. Build. Mater.* 24 (2010) 1245–1252. <https://doi.org/10.1016/j.conbuildmat.2009.12.012>.
- [64] H.T. Le, H.M. Ludwig, Effect of rice husk ash and other mineral admixtures on properties of self-compacting high performance concrete, *Mater. Des.* 89 (2016) 156–166. <https://doi.org/10.1016/j.matdes.2015.09.120>.
- [65] M. Hamza Hasnain, U. Javed, A. Ali, M. Saeed Zafar, Eco-friendly utilization of rice husk ash and bagasse ash blend as partial sand replacement in self-compacting concrete, *Constr. Build. Mater.* 273 (2021) 121753. <https://doi.org/10.1016/j.conbuildmat.2020.121753>.
- [66] D.H. Le, Y.N. Sheen, M.N.T. Lam, Fresh and hardened properties of self-compacting concrete with sugarcane bagasse ash–slag blended cement, *Constr. Build. Mater.* 185 (2018) 138–147. <https://doi.org/10.1016/j.conbuildmat.2018.07.029>.
- [67] L.C. Larissa, M.A. Marcos, M. V. Maria, N. S. L. de Souza, E.C. de Farias, Effect of high temperatures on self-compacting concrete with high levels of sugarcane bagasse ash and metakaolin, *Constr. Build. Mater.* 248 (2020) 118715. <https://doi.org/10.1016/j.conbuildmat.2020.118715>.
- [68] T. Uygunoğlu, I.B. Topçu, A.G. Çelik, Use of waste marble and recycled aggregates in self-compacting concrete for environmental sustainability, *J. Clean. Prod.* 84 (2014) 691–700. <https://doi.org/10.1016/j.jclepro.2014.06.019>.
- [69] B.M. Vinay Kumar, H. Ananthan, K.V.A. Balaji, Experimental studies on utilization of coarse and finer fractions of recycled concrete aggregates in self compacting concrete mixes, *J. Build. Eng.* 9 (2017) 100–108. <https://doi.org/10.1016/j.jobe.2016.11.013>.
- [70] A. Jain, R. Gupta, S. Chaudhary, Sustainable development of self-compacting concrete by using granite waste and fly ash, *Constr. Build. Mater.* 262 (2020). <https://doi.org/10.1016/j.conbuildmat.2020.120516>.
- [71] B.C. Xavier, E. Verzegnassi, A.D. Bortolozzo, S.M. Alves, R.C. Cecche Lintz, L. Andreia Gachet, W.R. Osório, Fresh and Hardened States of Distinctive Self-Compacting Concrete with Marble- and Phyllite-Powder Aggregate Contents, *J. Mater. Civ. Eng.* 32 (2020) 04020065. [https://doi.org/10.1061/\(asce\)mt.1943-5533.0003103](https://doi.org/10.1061/(asce)mt.1943-5533.0003103).
- [72] M. Tennich, A. Kallel, M. Ben Oueddou, Incorporation of fillers from marble and tile wastes in the composition of self-compacting concretes, *Constr. Build. Mater.* 91 (2015) 65–70. <https://doi.org/10.1016/j.conbuildmat.2015.04.052>.
- [73] D.M. Sadek, M.M. El-Attar, H.A. Ali, Reusing of marble and granite powders in self-compacting concrete for sustainable development, *J. Clean. Prod.* 121 (2016) 19–32. <https://doi.org/10.1016/j.jclepro.2016.02.044>.
- [74] A.M. Neville, *Properties of concrete*, Pearson, 2012.

- [75] K.H. Yang, Y.B. Jung, M.S. Cho, S.H. Tae, Effect of supplementary cementitious materials on reduction of CO₂ emissions from concrete, *J. Clean. Prod.* 103 (2015) 774–783. <https://doi.org/10.1016/j.jclepro.2014.03.018>.
- [76] W.J. Long, Y. Gu, J. Liao, F. Xing, Sustainable design and ecological evaluation of low binder self-compacting concrete, *J. Clean. Prod.* 167 (2017) 317–325. <https://doi.org/10.1016/j.jclepro.2017.08.192>.
- [77] T. Ponikiewski, J. Gołaszewski, The influence of high-calcium fly ash on the properties of fresh and hardened self-compacting concrete and high performance self-compacting concrete, *J. Clean. Prod.* 72 (2014) 212–221. <https://doi.org/10.1016/j.jclepro.2014.02.058>.
- [78] P.R. de Matos, R.D. Sakata, L.R. Prudêncio, Eco-efficient low binder high-performance self-compacting concretes, *Constr. Build. Mater.* 225 (2019) 941–955. <https://doi.org/10.1016/j.conbuildmat.2019.07.254>.
- [79] M.B. Ali, R. Saidur, M.S. Hossain, A review on emission analysis in cement industries, *Renew. Sustain. Energy Rev.* 15 (2011) 2252–2261. <https://doi.org/10.1016/j.rser.2011.02.014>.
- [80] C. Shi, Z. Wu, K. Lv, L. Wu, A review on mixture design methods for self-compacting concrete, *Constr. Build. Mater.* 84 (2015) 387–398. <https://doi.org/10.1016/j.conbuildmat.2015.03.079>.
- [81] V.B. Petersson O, Billberg P, A model for self-compacting concrete, in: *Prod. Methods Work. Concr.*, 1st Editio, London, 1996.
- [82] T. Sedran, F. de Larrard, Optimization of self compacting concrete thanks to packing model, *Self-Compacting Concr.* (Stockholm, 13-14 Sept. 1999). (1999) 321–332.
- [83] N. Su, K.C. Hsu, H.W. Chai, A simple mix design method for self-compacting concrete, *Cem. Concr. Res.* 31 (2001) 1799–1807. [https://doi.org/10.1016/S0008-8846\(01\)00566-X](https://doi.org/10.1016/S0008-8846(01)00566-X).
- [84] B.F. Tutikian, Método para dosagem de concreto autoadensável, *Dissertação (Mestrado)*, Universidade Federal do Rio Grande do Sul, 2004.
- [85] P.C.C. GOMES, Optimization and Characterization of High-Strength Self- Compacting Concrete, *Universitat Politècnica de Catalunya*, 2002.
- [86] J. Kanadasan, H.A. Razak, Mix design for self-compacting palm oil clinker concrete based on particle packing, *Mater. Des.* 56 (2014) 9–19. <https://doi.org/10.1016/j.matdes.2013.10.086>.
- [87] C. Hwang, Durability design and performance of self-consolidating lightweight concrete, *19* (2005) 619–626. <https://doi.org/10.1016/j.conbuildmat.2005.01.003>.

- [88] A.W. Saak, H.M. Jennings, S.P. Shah, New Methodology for Designing Self-Compacting Concrete, *ACI Mater. J.* 98 (2001) 429–439. <https://doi.org/10.14359/10841>.
- [89] K.A. de Melo, Contribuição à dosagem de concreto auto-adensável com adição de filler calcário, Dissertação (mestrado), Universidade Federal de Santa Catarina, 2005.
- [90] C. Shi, X. Yang, Design and application of self-compacting lightweight concrete, SCC'2005-China 1st Int. Symp. Des. Perform. Use Self-Consolidating Concr. (2005). <https://books.google.com.br/books?id=T3Zo3x4Xc1kC&lpg=PA55&ots=QtaaEj11x6&lr&hl=pt-BR&pg=PA55#v=onepage&q&f=false>.
- [91] EFNARC, Specification and Guidelines for Self-Compacting Concrete, Rep. from EFNARC. 44 (2002) 32. <https://doi.org/10.953973344>.
- [92] R. Sarkar, Particle size distribution for refractory castables: A review, *InterCeram Int. Ceram. Rev.* 65 (2016) 82–86. <https://doi.org/10.1007/bf03401156>.
- [93] J.E. Funk, D.R. Dinger, Particle size control for high-solids castable refractories, *Am. Ceram. Soc. Bull.* (1994).
- [94] C.C. Furnas, Grading Aggregates - I. - Mathematical Relations for Beds of Broken Solids of Maximum Density, *Ind. Eng. Chem.* 23 (1931) 1052–1058. <https://doi.org/10.1021/ie50261a017>.
- [95] A.H.M. Andreasen, Ueber die Beziehung zwischen Kornabstufung und Zwischenraum in Produkten aus losen Körnern (mit einigen Experimenten), *Kolloid-Zeitschrift.* 50 (1930) 217–228. <https://doi.org/10.1007/BF01422986>.
- [96] R. Vanderlei, Análise experimental do concreto de pós reativos: dosagem e propriedades mecânicas, 2004.
- [97] A.L. de Castro, V.C. Pandolfelli, Revisão: conceitos de dispersão e empacotamento de partículas para a produção de concretos especiais aplicados na construção civil, *Cerâmica.* 55 (2009) 18–32. <https://doi.org/10.1590/s0366-69132009000100003>.
- [98] F.T. Ramal Jr, R.G. Pileggi, J.B. Gallo, V.C. Pandolfelli, A curva de distribuição granulométrica e sua influência na reologia de concretos refratários, *Cerâmica.* 48 (2002) 212–216. <https://doi.org/10.1590/s0366-69132002000400008>.
- [99] X. Wang, K. Wang, P. Taylor, G. Morcou, Assessing particle packing based self-consolidating concrete mix design method, *Constr. Build. Mater.* 70 (2014) 439–452. <https://doi.org/10.1016/j.conbuildmat.2014.08.002>.
- [100] D.K. Ashish, S.K. Verma, Determination of optimum mixture design method for self-compacting concrete: Validation of method with experimental results, *Constr. Build. Mater.* 217 (2019) 664–678. <https://doi.org/10.1016/j.conbuildmat.2019.05.034>.

- [101] N. Sebaibi, M. Benzerzour, Y. Sebaibi, N.-E. Abriak, Composition of self compacting concrete (SCC) using the compressible packing model, the Chinese method and the European standard, *Constr. Build. Mater.* 43 (2013) 382–388. <https://doi.org/10.1016/j.conbuildmat.2013.02.028>.
- [102] Q. Wu, X. An, Development of a mix design method for SCC based on the rheological characteristics of paste, *Constr. Build. Mater.* 53 (2014) 642–651. <https://doi.org/10.1016/j.conbuildmat.2013.12.008>.
- [103] J. Zhang, X. An, D. Nie, Effect of fine aggregate characteristics on the thresholds of self-compacting paste rheological properties, *Constr. Build. Mater.* 116 (2016) 355–365. <https://doi.org/10.1016/j.conbuildmat.2016.04.069>.
- [104] J. Zhang, X. An, Y. Yu, D. Nie, Effects of coarse aggregate content on the paste rheological thresholds of fresh self-compacting concrete, *Constr. Build. Mater.* 208 (2019) 564–576. <https://doi.org/10.1016/j.conbuildmat.2019.02.177>.
- [105] J. Hu, K. Wang, Effect of coarse aggregate characteristics on concrete rheology, *Constr. Build. Mater.* 25 (2011) 1196–1204. <https://doi.org/10.1016/j.conbuildmat.2010.09.035>.
- [106] S. Yang, J. Zhang, X. An, B. Qi, D. Shen, M. Lv, Effects of fly ash and limestone powder on the paste rheological thresholds of self-compacting concrete, *Constr. Build. Mater.* 281 (2021) 122560. <https://doi.org/10.1016/j.conbuildmat.2021.122560>.
- [107] P.P.F. Rodrigues, *Parâmetros de Dosagem de Concreto*, Associação Brasileira de Cimento Portland (ABCP), São Paulo, 1984.
- [108] G.F. Kheder, R.S. Al Jadiri, New method for proportioning self-consolidating concrete based on compressive strength requirements, *ACI Mater. J.* 107 (2010) 490–497. <https://doi.org/10.14359/51663969>.
- [109] Institute AC, *Standard Practice for Selecting Proportions for Normal , Heavyweight , and Mass Concrete (ACI 211 . 1-91)*, 2002.
- [110] B. de Barros Neto, I.S. Scarminio, R.E. Bruns, *Como fazer experimentos: pesquisa e desenvolvimento na ciência e na indústria*, Editora da Unicamp, Campinas, SP, 2001.
- [111] J.I. Ribeiro Júnior, *Métodos estatísticos aplicados à melhoria da qualidade*, 1st ed., Editora UFV, 2012.
- [112] G.E.P. Box, K.B. Wilson, On the Experimental Attainment of Optimum Conditions, *J. R. Stat. Soc. Ser. B.* 13 (1951) 1–45. <http://www.jstor.org/stable/2983966>.
- [113] R.H. Myers, D.C. Montgomery, C.M. Anderson-Cook, *Response surface methodology : process and product optimization using designed experiments*, 3rd ed., John Wiley & Sons, Inc., Hoboken, New Jersey, 2009.

- [114] G. Derringer, R. Suich, Simultaneous Optimization of Several Response Variables, *J. Qual. Technol.* 12 (1980) 214–219. <https://doi.org/10.1080/00224065.1980.11980968>.
- [115] D. Nie, X. An, Optimization of SCC mix at paste level by using numerical method based on a paste rheological threshold theory, *Constr. Build. Mater.* 102 (2016) 428–434. <https://doi.org/10.1016/j.conbuildmat.2015.10.195>.
- [116] A. Kostrzanowska-Siedlarz, J. Gołaszewski, Rheological properties of High Performance Self-Compacting Concrete: Effects of composition and time, *Constr. Build. Mater.* 115 (2016) 705–715. <https://doi.org/10.1016/j.conbuildmat.2016.04.027>.
- [117] A.M. Matos, L. Maia, S. Nunes, P. Milheiro-Oliveira, Design of self-compacting high-performance concrete: Study of mortar phase, *Constr. Build. Mater.* 167 (2018) 617–630. <https://doi.org/10.1016/j.conbuildmat.2018.02.053>.
- [118] J.P. Moretti, S. Nunes, A. Sales, Self-compacting concrete incorporating sugarcane bagasse ash, *Constr. Build. Mater.* 172 (2018) 635–649. <https://doi.org/10.1016/j.conbuildmat.2018.03.277>.
- [119] T. Bouziani, Assessment of fresh properties and compressive strength of self-compacting concrete made with different sand types by mixture design modelling approach, *Constr. Build. Mater.* 49 (2013) 308–314. <https://doi.org/10.1016/j.conbuildmat.2013.08.039>.
- [120] E. Ozbay, A. Oztas, A. Baykasoglu, H. Ozbebek, Investigating mix proportions of high strength self compacting concrete by using Taguchi method, *Constr. Build. Mater.* 23 (2009) 694–702. <https://doi.org/10.1016/j.conbuildmat.2008.02.014>.
- [121] G. Taguchi, *System of experimental design*, UNIBUB, White Plains, NY, 1987.
- [122] M. Sonebi, Medium strength self-compacting concrete containing fly ash: Modelling using factorial experimental plans, *Cem. Concr. Res.* 34 (2004) 1199–1208. <https://doi.org/10.1016/j.cemconres.2003.12.022>.
- [123] F.M. Almeida Filho, B.E. Barragán, J.R. Casas, A.L.H.C. El Debs, Hardened properties of self-compacting concrete - A statistical approach, *Constr. Build. Mater.* 24 (2010) 1608–1615. <https://doi.org/10.1016/j.conbuildmat.2010.02.032>.
- [124] A.A. Abouhussien, A.A.A. Hassan, Application of Statistical Analysis for Mixture Design of High-Strength Self-Consolidating Concrete Containing Metakaolin, *J. Mater. Civ. Eng.* 26 (2014) 04014016. [https://doi.org/10.1061/\(asce\)mt.1943-5533.0000944](https://doi.org/10.1061/(asce)mt.1943-5533.0000944).
- [125] M.G. PIMENTEL, A.L.R. VASCONCELOS, M.D.S. PICANÇO, J.V.B. DE SOUZA, A.N. MACÊDO, Characterization of high furnace slag from industrial waste aiming its use in construction, (2017) 5.
- [126] M. Gesoğlu, E. Güneyisi, E. Özbay, Properties of self-compacting concretes made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag, and silica

fume, *Constr. Build. Mater.* 23 (2009) 1847–1854. <https://doi.org/10.1016/j.conbuildmat.2008.09.015>.

[127] M. Gesoğlu, E. Güneyisi, S.F. Mahmood, H. öznur öz, K. Mermerdaş, Recycling ground granulated blast furnace slag as cold bonded artificial aggregate partially used in self-compacting concrete, *J. Hazard. Mater.* 235–236 (2012) 352–358. <https://doi.org/10.1016/j.jhazmat.2012.08.013>.

[128] M. Valcuende, F. Benito, C. Parra, I. Miñano, Shrinkage of self-compacting concrete made with blast furnace slag as fine aggregate, *Constr. Build. Mater.* 76 (2015) 1–9. <https://doi.org/10.1016/j.conbuildmat.2014.11.029>.

[129] M. Nuruzzaman, J.O. Camargo Casimiro, P.K. Sarker, Fresh and hardened properties of high strength self-compacting concrete using by-product ferronickel slag fine aggregate, *J. Build. Eng.* 32 (2020) 101686. <https://doi.org/10.1016/j.jobe.2020.101686>.

[130] G.C. Cordeiro, L.M. Tavares, R.D. Toledo Filho, Improved pozzolanic activity of sugar cane bagasse ash by selective grinding and classification, *Cem. Concr. Res.* 89 (2016) 269–275. <https://doi.org/10.1016/j.cemconres.2016.08.020>.

[131] G.C. Cordeiro, K.E. Kurtis, Effect of mechanical processing on sugar cane bagasse ash pozzolanicity, *Cem. Concr. Res.* 97 (2017) 41–49. <https://doi.org/10.1016/j.cemconres.2017.03.008>.

[132] S. Rukzon, P. Chindaprasirt, Utilization of bagasse ash in high-strength concrete, *Mater. Des.* 34 (2012) 45–50. <https://doi.org/10.1016/j.matdes.2011.07.045>.

[133] R. V. Silva, J. De Brito, R.K. Dhir, Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production, *Constr. Build. Mater.* 65 (2014) 201–217. <https://doi.org/10.1016/j.conbuildmat.2014.04.117>.

[134] M.S. de Juan, P.A. Gutiérrez, Study on the influence of attached mortar content on the properties of recycled concrete aggregate, *Constr. Build. Mater.* 23 (2009) 872–877. <https://doi.org/10.1016/j.conbuildmat.2008.04.012>.

[135] S. Santos, P. daSilva, J. deBrito, Self-compacting concrete with recycled aggregates – A literature review, *J. Build. Eng.* 22 (2019). <https://doi.org/10.1016/j.jobe.2019.01.001>.

[136] M.K. Degen, G.L. Vieira, L. Calmon, J.G. Uliana, R.S. Bastos, Concretos produzidos com resíduos provenientes do beneficiamento de rochas ornamentais como substituto parcial de cimento, *An. Do 55o Congr. Bras. Concreto CBC2013.* (2013) 1–12.

[137] P. Danish, G. Mohan Ganesh, Study on influence of Metakaolin and waste marble powder on self-compacting concrete – A state of the art review, *Mater. Today Proc.* (2020). <https://doi.org/10.1016/j.matpr.2020.11.629>.

APPENDIX

Table A.2.1 - Constituents proportioning of the self-compacting concretes (in mass).

Id	Reference	Portland cement	Fine aggregate	Coarse aggregate	Water	Admixture (%)	Residue	Extra addition	f _c (MPa)	Slump flow (mm)	BI (kg/MPa)
0%GGBFS	[56]	1.00	1.00	1.50	0.30	0.00	-	-	42.10	-	15.69
10%GGBFS	[56]	1.00	1.11	1.67	0.30	1.22	0.11	-	41.62	590	14.46
20%GGBFS	[56]	1.00	1.25	1.88	0.30	1.38	0.25	-	42.40	575	12.86
30%GGBFS	[56]	1.00	1.43	2.14	0.30	1.57	0.43	-	40.60	560	11.99
0%GGBFS	[57]	1.00	1.86	1.81	0.40	3.40	-	-	67.50	630	7.22
10%GGBFS	[57]	1.00	2.06	2.00	0.44	3.61	0.10	-	63.00	660	6.99
15%GGBFS	[57]	1.00	2.18	2.12	0.47	3.96	0.17	-	61.50	745	6.76
0%GGBFS	[58]	1.00	1.51	2.36	0.35	0.24	-	-	67.70	690	7.21
20%GGBFS	[58]	1.00	1.89	2.95	0.44	0.30	0.25	-	67.70	720	5.76
30%GGBFS	[58]	1.00	2.15	3.37	0.50	0.34	0.43	-	62.00	730	5.50
40%GGBFS	[58]	1.00	2.51	3.93	0.58	0.40	0.67	-	58.50	740	4.99
0%GGBFS	[59]	1.00	2.01	2.19	0.40	1.13	-	0.22	51.50	740	8.45
10%GGBF	[59]	1.00	2.23	2.44	0.44	1.47	0.11	0.25	44.00	750	8.89
20%GGBFS	[59]	1.00	2.51	2.74	0.50	1.91	0.25	0.28	45.00	750	7.71
30%GGBFS	[59]	1.00	2.87	3.13	0.57	2.32	0.43	0.32	55.00	750	5.52
0%GGBFS	[59]	1.00	1.83	2.13	0.45	1.08	-	0.30	51.50	750	8.47
10%GGBF	[59]	1.00	2.03	2.37	0.50	1.36	0.11	0.34	65.00	750	6.03
20%GGBFS	[59]	1.00	2.29	2.66	0.56	1.66	0.25	0.38	69.00	760	5.04
30%GGBFS	[59]	1.00	2.62	3.04	0.64	2.07	0.43	0.43	69.60	750	4.37
0%GGBFS	[54]	1.00	2.45	1.64	0.36	1.58	-	-	69.00	620	6.79
35%GGBFS	[54]	1.00	3.75	2.56	0.55	1.88	0.54	-	61.00	650	4.97
50%GGBFS	[54]	1.00	4.86	3.32	0.72	2.89	1.00	-	65.00	680	3.58
70%GGBFS	[54]	1.00	8.02	5.47	1.20	4.52	2.33	-	62.00	680	2.27
20%GGBFS	[60]	1.00	1.91	2.25	0.32	1.90	0.25	-	94.60	650	4.76
40%GGBFS	[60]	1.00	2.53	2.97	0.44	2.53	0.67	-	92.60	650	3.65
60%GGBFS	[60]	1.00	3.62	4.26	0.78	3.04	1.50	-	73.50	670	3.07
80%GGBFS	[60]	1.00	6.35	7.46	2.24	6.25	4.00	-	48.30	700	2.33
0%GGBFS	[55]	1.00	1.58	1.41	0.33	1.60	-	-	75.90	690	7.62
20%GGBFS	[55]	1.00	1.97	1.76	0.41	2.00	0.25	-	77.90	700	5.94
40%GGBFS	[55]	1.00	2.62	2.34	0.55	2.67	0.67	-	74.80	730	4.64
60%GGBFS	[55]	1.00	3.91	3.50	0.83	4.00	1.50	-	71.60	720	3.24
0%FA	[58]	1.00	1.51	2.36	0.35	0.24	-	-	67.80	690	7.20
20%FA	[58]	1.00	1.89	2.95	0.44	0.30	0.25	-	66.30	725	5.82
30%FA	[58]	1.00	2.15	3.37	0.50	0.34	0.43	-	58.20	745	5.76
40%FA	[58]	1.00	2.51	3.93	0.58	0.40	0.67	-	55.50	760	5.15
0%FA	[61]	1.00	1.36	1.42	0.32	2.60	-	-	78.30	550	7.73
25%FA	[61]	1.00	1.67	1.90	0.33	2.67	0.33	-	51.11	640	9.33
0%FA	[62]	1.00	1.55	1.46	0.37	1.35	-	-	39.00	700	14.50
20%FA	[62]	1.00	1.93	1.82	0.46	0.95	0.25	-	31.00	675	14.43
30%FA	[62]	1.00	2.21	2.08	0.53	0.75	0.43	-	24.50	685	15.87
0%FA	[55]	1.00	1.58	1.41	0.33	1.60	-	-	75.90	690	7.62
15%FA	[55]	1.00	1.85	1.63	0.39	1.88	0.18	-	74.20	710	6.60
25%FA	[55]	1.00	2.15	1.83	0.44	2.14	0.33	-	73.40	740	5.82
35%FA	[55]	1.00	2.46	2.08	0.51	2.46	0.54	-	67.50	750	5.48
0%FA	[63]	1.00	1.38	1.71	0.33	1.10	-	-	73.30	720	7.75
20%FA	[63]	1.00	1.70	2.11	0.40	1.06	0.29	-	69.70	700	6.46

Id	Reference	Portland cement	Fine aggregate	Coarse aggregate	Water	Admixture (%)	Residue	Extra addition	f _c (MPa)	Slump flow (mm)	BI (kg/MPa)
40%FA	[63]	1.00	2.23	2.77	0.52	1.11	0.49	-	58.50	705	6.00
60%FA	[63]	1.00	3.30	4.11	0.76	1.43	1.10	-	37.20	715	6.38
80%FA	[63]	1.00	6.46	8.03	1.45	2.55	2.92	-	16.00	730	7.57
0%FA	[64]	1.00	1.26	1.55	0.26	2.50	-	-	112.00	790	5.56
20%FA	[64]	1.00	1.64	2.01	0.32	3.25	0.25	-	112.00	820	4.28
40%FA	[64]	1.00	2.28	2.79	0.44	4.50	0.67	-	111.00	780	3.11
0%RHA	[23]	1.00	1.88	1.40	0.44	1.50	-	-	41.40	680	12.50
10%RHA	[23]	1.00	1.69	1.40	0.44	1.50	0.19	-	43.40	690	11.79
20%RHA	[23]	1.00	1.50	1.40	0.44	1.50	0.38	-	36.20	675	13.98
30%RHA	[23]	1.00	1.31	1.40	0.44	1.50	0.56	-	30.30	650	16.52
0%RHA	[24]	1.00	2.36	2.15	0.50	1.25	-	0.61	53.40	740	7.08
5%RHA	[24]	1.00	2.49	2.27	0.53	1.43	0.05	0.64	57.70	720	6.21
10%RHA	[24]	1.00	2.62	2.39	0.56	1.67	0.11	0.68	54.80	700	6.17
15%RHA	[24]	1.00	2.78	2.53	0.59	2.45	0.18	0.72	50.30	670	6.32
20%RHA	[24]	1.00	2.95	2.69	0.63	3.19	0.25	0.76	47.50	650	6.28
0%RHA	[64]	1.00	1.26	1.55	0.26	2.50	-	-	112.00	790	5.56
5%RHA	[64]	1.00	1.77	2.17	0.35	3.49	0.07	0.27	112.00	800	3.97
10%RHA	[64]	1.00	1.91	2.34	0.37	3.78	0.14	0.29	117.00	780	3.51
15%RHA	[64]	1.00	2.08	2.55	0.40	4.11	0.23	0.31	118.00	730	3.20
20%RHA	[64]	1.00	2.28	2.79	0.44	4.50	0.33	0.33	117.00	705	2.95
0%RHA	[65]	1.00	2.35	2.93	0.40	1.70	-	-	26.64	740	14.40
5%RHA	[65]	1.00	2.12	2.93	0.40	1.70	0.12	0.12	26.08	720	14.60
10%RHA	[65]	1.00	1.88	2.93	0.40	1.70	0.24	0.24	20.08	685	18.83
15%RHA	[65]	1.00	1.65	2.93	0.40	1.70	0.35	0.35	15.22	660	24.66
0%RHA	[18]	1.00	2.20	2.00	0.55	2.00	-	-	41.00	740	10.27
5%RHA	[18]	1.00	2.32	2.11	0.58	2.11	0.05	-	43.50	700	9.17
10%RHA	[18]	1.00	2.44	2.22	0.61	2.22	0.11	-	47.90	670	7.87
15%RHA	[18]	1.00	2.59	2.35	0.65	2.35	0.18	-	51.00	615	6.96
20%RHA	[18]	1.00	2.75	2.50	0.69	2.50	0.25	-	44.20	580	7.54
25%RHA	[18]	1.00	2.93	2.67	0.73	2.67	0.33	-	42.00	550	7.42
30%RHA	[18]	1.00	3.14	2.86	0.79	2.86	0.43	-	37.00	490	7.84
5%SCBA	[26]	1.00	1.75	1.50	0.45	2.50	0.05	-	36.25	760	14.04
5%SCBA	[26]	1.00	1.75	1.50	0.45	3.00	0.05	-	35.00	780	14.51
5%SCBA	[26]	1.00	1.75	1.50	0.45	3.50	0.05	-	25.63	820	19.78
5%SCBA	[26]	1.00	1.75	1.50	0.45	4.00	0.05	-	25.00	820	20.23
10%SCBA	[26]	1.00	1.75	1.50	0.45	2.50	0.10	-	40.00	750	12.60
10%SCBA	[26]	1.00	1.75	1.50	0.45	3.00	0.10	-	40.63	770	12.38
10%SCBA	[26]	1.00	1.75	1.50	0.45	3.50	0.10	-	30.00	780	16.73
10%SCBA	[26]	1.00	1.75	1.50	0.45	4.00	0.10	-	26.88	790	18.63
15%SCBA	[26]	1.00	1.75	1.50	0.45	2.50	0.15	-	43.75	720	11.41
15%SCBA	[26]	1.00	1.75	1.50	0.45	3.00	0.15	-	43.13	760	11.55
15%SCBA	[26]	1.00	1.75	1.50	0.45	3.50	0.15	-	30.63	800	16.23
15%SCBA	[26]	1.00	1.75	1.50	0.45	4.00	0.15	-	28.75	780	17.25
20%SCBA	[26]	1.00	1.75	1.50	0.45	2.50	0.20	-	43.13	600	11.46
20%SCBA	[26]	1.00	1.75	1.50	0.45	3.00	0.20	-	42.50	670	11.61
20%SCBA	[26]	1.00	1.75	1.50	0.45	3.50	0.20	-	28.75	670	17.12
20%SCBA	[26]	1.00	1.75	1.50	0.45	4.00	0.20	-	27.50	680	17.86
0%SCBA	[66]	1.00	1.91	1.87	0.58	1.80	-	0.29	40.13	671	10.45
10%SCBA	[66]	1.00	2.12	2.08	0.64	2.00	0.11	0.32	39.38	625	9.56
20%SCBA	[66]	1.00	2.38	2.34	0.72	2.25	0.25	0.36	45.00	611	7.42

Id	Reference	Portland cement	Fine aggregate	Coarse aggregate	Water	Admixture (%)	Residue	Extra addition	f _c (MPa)	Slump flow (mm)	BI (kg/MPa)
30%SCBA	[66]	1.00	2.73	2.67	0.83	2.57	0.43	0.41	41.88	584	6.96
0%SCBA	[67]	1.00	1.66	2.16	0.48	0.52	-	-	47.49	740	9.74
30%SCBA	[67]	1.00	2.34	3.09	0.69	1.90	0.43	-	49.76	717	6.45
0%RCA	[69]	1.00	1.92	1.70	0.48	1.40	0.00	0.33	43.00	710	10.33
20%RCA	[69]	1.00	1.92	1.36	0.48	1.40	0.30	0.33	48.00	690	9.28
20%RCA	[69]	1.00	1.54	1.70	0.48	1.40	0.33	0.33	46.00	705	9.69
40%RCA	[69]	1.00	1.54	1.36	0.48	1.40	0.63	0.33	47.00	635	9.51
31%RCA	[68]	1.00	2.06	-	0.40	3.09	2.86	0.29	54.00	500	6.88
34%RCA	[68]	1.00	2.02	-	0.44	2.71	2.81	0.29	53.50	545	6.95
37%RCA	[68]	1.00	1.98	-	0.48	2.31	2.75	0.29	53.40	550	6.96
40%RCA	[68]	1.00	1.94	-	0.51	1.94	2.69	0.29	51.70	580	7.19
106%OSW	[68]	1.00	2.06	-	0.40	3.09	3.17	0.29	53.60	530	6.79
104%OSW	[68]	1.00	2.02	-	0.44	2.71	3.11	0.29	50.00	550	7.28
102%OSW	[68]	1.00	1.98	-	0.48	2.31	3.04	0.29	42.00	625	8.67
100%OSW	[68]	1.00	1.94	-	0.51	1.94	2.98	0.29	38.00	635	9.59
0%OSW	[70]	1.00	2.50	2.28	0.58	2.11	0.00	-	52.50	700	7.31
20%OSW	[70]	1.00	1.24	2.28	0.58	1.80	0.31	-	55.00	705	7.98
40%OSW	[70]	1.00	0.93	2.28	0.58	2.11	0.62	-	51.40	695	8.51
60%OSW	[70]	1.00	0.62	2.28	0.58	2.81	0.93	-	43.00	715	10.12
80%OSW	[70]	1.00	0.31	2.28	0.58	3.44	1.24	-	32.50	670	13.33
20%OSW	[71]	1.00	2.63	2.09	0.54	1.40	0.20	-	76.25	740	5.02
40%OSW	[71]	1.00	2.63	2.09	0.54	1.40	0.40	-	76.25	715	4.89
50%OSW	[71]	1.00	2.63	2.09	0.54	1.40	0.50	-	77.50	735	4.74
50%OSW	[72]	1.00	2.26	2.28	0.50	1.20	0.57	-	43.88	650	8.62
0%OSW	[73]	1.00	1.36	1.36	0.30	1.38	-	-	61.80	765	10.10
50%OSW	[73]	1.00	2.02	2.02	0.45	2.15	0.50	-	39.00	650	10.69
50%OSW	[73]	1.00	2.00	2.00	0.45	2.03	0.50	-	51.50	750	8.13
50%OSW	[73]	1.00	2.01	2.01	0.45	2.08	0.50	-	55.10	740	7.58

Table A.2.2 - Ratios between the environmental impacts of each concrete mixture and its compressive strength.

Identification	Reference	TPE/f _c	PRM/fc	RM/fc	WC/fc	GWP/fc	FAETP/fc	TETP/fc	MAETP/fc	ODP/fc	EP/fc	AP/fc
		MJ/(m ³ .MPa)	kg/(m ³ .MPa)	kg/(m ³ .MPa)	kg H ₂ O /(m ³ .MPa)	kg CO ₂ eq /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg (PO ₄) ⁻³ /(m ³ .MPa)	kg (SO ₂) /(m ³ .MPa)
0%GGBFS	[56]	68.88	59.62	0.00	65.72	14.33	0.13	0.019	514.69	3.69E-07	3.58E-03	2.62E-02
10%GGBFS	[56]	70.70	59.15	1.61	65.46	13.80	0.17	0.019	572.91	3.66E-07	3.81E-03	2.83E-02
20%GGBFS	[56]	66.52	57.10	3.22	62.58	12.68	0.16	0.017	559.84	3.37E-07	3.70E-03	2.87E-02
30%GGBFS	[56]	66.36	58.59	5.14	63.53	12.29	0.17	0.016	581.92	3.29E-07	3.82E-03	3.09E-02
0%GGBFS	[57]	38.44	36.86	0.00	32.54	7.03	0.12	0.010	347.03	2.05E-07	2.07E-03	1.41E-02
10%GGBFS	[57]	38.94	38.74	0.73	33.63	6.99	0.12	0.010	361.92	2.05E-07	2.15E-03	1.52E-02
15%GGBFS	[57]	39.05	39.29	1.12	33.86	6.89	0.13	0.010	370.29	2.04E-07	2.19E-03	1.57E-02
0%GGBFS	[58]	32.82	37.65	0.00	30.90	6.74	0.08	0.009	296.71	1.83E-07	1.78E-03	1.27E-02
20%GGBFS	[58]	28.99	36.15	1.44	28.66	5.71	0.08	0.007	284.26	1.57E-07	1.68E-03	1.30E-02
30%GGBFS	[58]	29.57	38.66	2.36	30.08	5.68	0.08	0.007	303.61	1.58E-07	1.77E-03	1.43E-02
40%GGBFS	[58]	29.13	40.11	3.33	30.60	5.42	0.09	0.007	314.60	1.52E-07	1.82E-03	1.54E-02
0%GGBFS	[59]	41.05	47.40	1.89	37.02	8.04	0.11	0.011	369.00	2.31E-07	2.21E-03	1.57E-02
10%GGBF	[59]	45.88	54.44	3.19	41.89	8.73	0.13	0.012	429.66	2.54E-07	2.54E-03	1.87E-02
20%GGBFS	[59]	42.74	52.21	4.08	39.56	7.87	0.13	0.011	417.93	2.32E-07	2.44E-03	1.86E-02
30%GGBFS	[59]	33.06	41.89	4.12	31.18	5.89	0.11	0.008	337.65	1.77E-07	1.95E-03	1.54E-02
0%GGBFS	[59]	41.06	45.90	2.57	37.48	8.04	0.11	0.011	361.70	2.29E-07	2.19E-03	1.56E-02
10%GGBF	[59]	30.98	35.66	2.71	28.70	5.91	0.09	0.008	284.00	1.70E-07	1.70E-03	1.26E-02
20%GGBFS	[59]	27.66	32.93	3.18	26.09	5.12	0.08	0.007	264.11	1.50E-07	1.57E-03	1.20E-02
30%GGBFS	[59]	25.94	32.00	3.77	24.94	4.64	0.08	0.006	258.94	1.38E-07	1.52E-03	1.21E-02
0%GGBFS	[54]	33.34	37.05	0.00	29.54	6.44	0.09	0.009	282.57	1.86E-07	1.78E-03	1.27E-02
35%GGBFS	[54]	29.87	39.15	2.69	29.07	5.33	0.09	0.007	288.36	1.59E-07	1.78E-03	1.47E-02
50%GGBFS	[54]	25.58	35.62	3.58	25.71	4.26	0.08	0.006	266.68	1.32E-07	1.61E-03	1.41E-02
70%GGBFS	[54]	22.83	35.72	5.30	24.79	3.42	0.08	0.004	264.94	1.11E-07	1.58E-03	1.52E-02
20%GGBFS	[60]	25.60	26.17	1.19	23.47	4.77	0.07	0.007	234.56	1.34E-07	1.45E-03	1.10E-02
40%GGBFS	[60]	22.99	25.42	2.43	22.18	4.02	0.07	0.005	229.00	1.15E-07	1.39E-03	1.16E-02
60%GGBFS	[60]	24.30	29.73	4.60	25.87	3.95	0.08	0.005	262.50	1.14E-07	1.60E-03	1.47E-02
80%GGBFS	[60]	30.60	39.92	9.33	37.30	4.31	0.11	0.005	358.60	1.26E-07	2.23E-03	2.27E-02
0%GGBFS	[55]	36.81	33.09	0.00	32.89	7.16	0.09	0.010	293.46	1.97E-07	1.94E-03	1.37E-02
20%GGBFS	[55]	31.97	30.69	1.49	29.80	5.93	0.08	0.008	273.28	1.66E-07	1.78E-03	1.37E-02

Identification	Reference	TPE/f _c	PRM/f _c	RM/f _c	WC/f _c	GWP/f _c	FAETP/f _c	TETP/f _c	MAETP/f _c	ODP/f _c	EP/f _c	AP/f _c
		MJ/(m ³ .MPa)	kg/(m ³ .MPa)	kg/(m ³ .MPa)	kg H ₂ O /(m ³ .MPa)	kg CO ₂ eq /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg (PO ₄) ⁻³ /(m ³ .MPa)	kg (SO ₂) /(m ³ .MPa)
40%GGBFS	[55]	29.24	30.34	3.10	28.70	5.09	0.08	0.007	271.43	1.45E-07	1.74E-03	1.47E-02
60%GGBFS	[55]	26.30	30.01	4.85	27.53	4.17	0.09	0.006	269.71	1.22E-07	1.71E-03	1.57E-02
0%FA	[58]	32.77	37.59	0.00	30.85	6.73	0.08	0.009	296.25	1.83E-07	1.78E-03	1.26E-02
20%FA	[58]	27.59	36.51	1.45	25.58	5.52	0.08	0.007	273.28	1.59E-07	1.51E-03	1.06E-02
30%FA	[58]	28.12	40.52	2.47	25.81	5.53	0.09	0.008	294.73	1.66E-07	1.55E-03	1.08E-02
40%FA	[58]	26.06	41.37	3.43	23.60	5.01	0.09	0.007	291.88	1.58E-07	1.45E-03	1.00E-02
0%FA	[61]	39.08	31.88	0.00	33.72	7.36	0.11	0.010	321.04	2.05E-07	2.07E-03	1.43E-02
25%FA	[61]	49.17	45.96	3.11	41.03	9.01	0.15	0.013	433.95	2.65E-07	2.60E-03	1.79E-02
0%FA	[62]	69.11	63.59	0.00	62.92	13.58	0.16	0.019	549.94	3.72E-07	3.63E-03	2.59E-02
20%FA	[62]	69.67	75.38	3.61	63.79	13.58	0.17	0.019	584.07	3.89E-07	3.66E-03	2.62E-02
30%FA	[62]	77.72	92.47	6.82	71.20	15.01	0.20	0.021	676.26	4.44E-07	4.09E-03	2.93E-02
0%FA	[55]	36.81	33.09	0.00	32.89	7.16	0.09	0.010	293.46	1.97E-07	1.94E-03	1.37E-02
15%FA	[55]	33.05	32.27	1.17	29.01	6.27	0.09	0.009	276.33	1.80E-07	1.74E-03	1.23E-02
25%FA	[55]	30.11	31.64	1.95	26.01	5.59	0.09	0.008	261.75	1.67E-07	1.59E-03	1.11E-02
35%FA	[55]	29.51	33.26	2.96	25.04	5.33	0.09	0.008	268.05	1.66E-07	1.56E-03	1.08E-02
0%FA	[63]	36.48	34.35	0.00	33.26	7.25	0.09	0.010	300.61	1.97E-07	1.93E-03	1.37E-02
20%FA	[63]	31.50	33.78	1.87	28.29	6.11	0.08	0.008	276.56	1.75E-07	1.67E-03	1.18E-02
40%FA	[63]	30.37	39.24	2.92	27.15	5.78	0.09	0.008	296.13	1.75E-07	1.64E-03	1.14E-02
60%FA	[63]	35.55	58.57	7.00	30.79	6.38	0.13	0.009	405.39	2.18E-07	1.96E-03	1.34E-02
80%FA	[63]	54.09	128.55	22.13	43.41	8.44	0.28	0.013	803.82	3.74E-07	3.10E-03	2.02E-02
0%FA	[64]	27.99	22.79	0.00	23.93	5.30	0.08	0.007	233.61	1.47E-07	1.49E-03	1.03E-02
20%FA	[64]	23.04	21.44	1.07	18.95	4.17	0.07	0.006	210.35	1.23E-07	1.23E-03	8.37E-03
40%FA	[64]	18.58	20.35	2.08	14.43	3.15	0.07	0.005	190.10	1.02E-07	1.01E-03	6.65E-03
0%RHA	[23]	60.37	59.09	0.00	55.24	11.76	0.15	0.016	481.85	3.28E-07	3.18E-03	2.27E-02
10%RHA	[23]	57.94	53.52	2.21	52.09	11.27	0.14	0.015	482.36	3.16E-07	3.10E-03	2.20E-02
20%RHA	[23]	69.88	60.82	5.24	61.75	13.57	0.16	0.019	604.93	3.83E-07	3.81E-03	2.67E-02
30%RHA	[23]	83.97	68.76	9.29	72.94	16.29	0.19	0.022	753.82	4.62E-07	4.65E-03	3.24E-02
0%RHA	[24]	35.54	42.65	4.33	31.78	6.81	0.10	0.009	314.29	2.03E-07	1.88E-03	1.36E-02
5%RHA	[24]	31.78	39.05	4.32	28.12	6.03	0.09	0.008	290.81	1.83E-07	1.70E-03	1.22E-02
10%RHA	[24]	32.34	40.66	4.88	28.26	6.07	0.09	0.008	306.76	1.88E-07	1.75E-03	1.24E-02
15%RHA	[24]	34.79	43.77	5.66	29.49	6.36	0.11	0.009	345.39	2.02E-07	1.91E-03	1.33E-02

Identification	Reference	TPE/f _c	PRM/f _c	RM/f _c	WC/f _c	GWP/f _c	FAETP/f _c	TETP/f _c	MAETP/f _c	ODP/f _c	EP/f _c	AP/f _c
		MJ/(m ³ .MPa)	kg/(m ³ .MPa)	kg/(m ³ .MPa)	kg H ₂ O /(m ³ .MPa)	kg CO ₂ eq /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg (PO ₄) ⁻³ /(m ³ .MPa)	kg (SO ₂) /(m ³ .MPa)
20%RHA	[24]	36.17	45.81	6.36	29.83	6.45	0.12	0.009	374.71	2.10E-07	2.01E-03	1.38E-02
0%RHA	[64]	27.99	22.79	0.00	23.93	5.30	0.08	0.007	233.61	1.47E-07	1.49E-03	1.03E-02
5%RHA	[64]	21.89	21.11	1.32	17.76	3.92	0.07	0.006	208.05	1.18E-07	1.19E-03	7.98E-03
10%RHA	[64]	19.87	19.91	1.51	15.88	3.52	0.07	0.005	197.14	1.08E-07	1.09E-03	7.28E-03
15%RHA	[64]	18.64	19.43	1.73	14.66	3.27	0.07	0.005	193.37	1.03E-07	1.04E-03	6.86E-03
20%RHA	[64]	17.74	19.30	1.97	13.69	3.07	0.07	0.005	192.87	9.91E-08	1.00E-03	6.56E-03
0%RHA	[65]	72.31	96.50	0.00	63.99	13.97	0.23	0.019	747.69	4.14E-07	4.05E-03	2.78E-02
5%RHA	[65]	75.51	94.42	3.44	64.88	14.49	0.23	0.020	806.70	4.31E-07	4.30E-03	2.92E-02
10%RHA	[65]	100.19	117.31	8.86	83.66	19.11	0.30	0.027	1102.83	5.71E-07	5.79E-03	3.90E-02
15%RHA	[65]	134.91	147.86	17.41	109.56	25.58	0.40	0.036	1526.36	7.68E-07	7.90E-03	5.28E-02
0%RHA	[18]	51.57	59.28	0.00	47.05	9.85	0.15	0.014	467.03	2.86E-07	2.79E-03	1.95E-02
5%RHA	[18]	46.71	55.24	0.48	42.37	8.88	0.14	0.012	436.53	2.61E-07	2.55E-03	1.77E-02
10%RHA	[18]	40.70	49.59	0.87	36.70	7.69	0.12	0.011	393.13	2.30E-07	2.25E-03	1.55E-02
15%RHA	[18]	36.62	46.04	1.23	32.80	6.88	0.11	0.010	366.15	2.09E-07	2.05E-03	1.40E-02
20%RHA	[18]	40.41	52.51	1.89	35.94	7.55	0.13	0.011	418.94	2.33E-07	2.29E-03	1.56E-02
25%RHA	[18]	40.60	54.61	2.47	35.82	7.53	0.13	0.011	437.18	2.36E-07	2.33E-03	1.57E-02
30%RHA	[18]	43.92	61.27	3.36	38.41	8.08	0.15	0.011	492.08	2.59E-07	2.55E-03	1.71E-02
5%SCBA	[26]	71.86	66.36	0.70	63.08	13.50	0.20	0.019	608.76	3.84E-07	3.83E-03	2.66E-02
5%SCBA	[26]	76.05	68.64	0.73	65.62	14.05	0.22	0.020	653.38	4.04E-07	4.06E-03	2.80E-02
5%SCBA	[26]	106.07	93.65	0.99	90.02	19.29	0.32	0.028	923.54	5.60E-07	5.68E-03	3.88E-02
5%SCBA	[26]	110.98	95.87	1.01	92.68	19.88	0.35	0.029	978.37	5.82E-07	5.96E-03	4.03E-02
10%SCBA	[26]	65.05	59.55	1.26	56.60	12.18	0.18	0.017	557.20	3.48E-07	3.48E-03	2.41E-02
10%SCBA	[26]	65.43	58.56	1.24	55.98	12.06	0.19	0.017	568.13	3.48E-07	3.51E-03	2.41E-02
10%SCBA	[26]	90.47	79.21	1.67	76.14	16.41	0.27	0.024	795.65	4.78E-07	4.86E-03	3.31E-02
10%SCBA	[26]	103.07	88.31	1.86	85.37	18.42	0.32	0.027	917.39	5.41E-07	5.55E-03	3.75E-02
15%SCBA	[26]	59.41	53.91	1.71	51.25	11.10	0.16	0.016	514.38	3.18E-07	3.19E-03	2.21E-02
15%SCBA	[26]	61.56	54.63	1.73	52.23	11.32	0.17	0.016	540.02	3.28E-07	3.31E-03	2.27E-02
15%SCBA	[26]	88.50	76.84	2.43	73.87	16.02	0.26	0.023	785.94	4.68E-07	4.77E-03	3.25E-02
15%SCBA	[26]	96.19	81.76	2.59	79.03	17.15	0.30	0.025	864.23	5.05E-07	5.19E-03	3.51E-02
20%SCBA	[26]	60.21	54.17	2.29	51.49	11.22	0.16	0.016	526.75	3.23E-07	3.24E-03	2.24E-02
20%SCBA	[26]	62.39	54.90	2.32	52.48	11.44	0.18	0.016	552.76	3.32E-07	3.37E-03	2.31E-02

Identification	Reference	TPE/fc	PRM/fc	RM/fc	WC/fc	GWP/fc	FAETP/fc	TETP/fc	MAETP/fc	ODP/fc	EP/fc	AP/fc
		MJ/(m ³ .MPa)	kg/(m ³ .MPa)	kg/(m ³ .MPa)	kg H ₂ O /(m ³ .MPa)	kg CO ₂ eq /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg (PO ₄) ⁻³ /(m ³ .MPa)	kg (SO ₂) /(m ³ .MPa)
20%SCBA	[26]	94.14	81.07	3.42	77.93	17.00	0.28	0.025	844.01	4.98E-07	5.09E-03	3.46E-02
20%SCBA	[26]	100.41	84.66	3.57	81.84	17.86	0.31	0.026	910.36	5.28E-07	5.44E-03	3.67E-02
0%SCBA	[66]	52.84	56.15	2.99	47.97	9.97	0.15	0.014	456.98	2.91E-07	2.79E-03	1.96E-02
10%SCBA	[66]	50.21	56.02	4.10	44.70	9.32	0.14	0.013	462.36	2.80E-07	2.70E-03	1.87E-02
20%SCBA	[66]	40.76	47.98	4.50	35.46	7.43	0.12	0.011	401.67	2.30E-07	2.23E-03	1.53E-02
30%SCBA	[66]	40.42	50.44	5.82	34.21	7.20	0.13	0.010	428.54	2.32E-07	2.26E-03	1.53E-02
0%SCBA	[67]	44.98	51.68	0.00	43.08	9.12	0.11	0.012	397.38	2.51E-07	2.43E-03	1.73E-02
30%SCBA	[67]	35.29	46.04	2.78	30.64	6.62	0.11	0.009	395.44	2.02E-07	2.03E-03	1.37E-02
0%RCA	[69]	51.31	52.90	3.44	46.10	9.78	0.13	0.014	425.75	2.84E-07	2.68E-03	1.91E-02
20%RCA	[69]	46.00	44.36	5.91	41.30	8.76	0.12	0.012	367.89	2.55E-07	2.39E-03	1.71E-02
20%RCA	[69]	47.97	45.92	6.39	43.25	9.17	0.13	0.013	404.26	2.64E-07	2.52E-03	1.78E-02
40%RCA	[69]	46.97	41.81	9.17	42.33	8.97	0.12	0.013	381.78	2.58E-07	2.46E-03	1.74E-02
31%RCA	[68]	37.00	24.00	21.66	30.45	6.66	0.11	0.010	302.12	2.09E-07	1.99E-03	1.35E-02
34%RCA	[68]	36.69	24.19	21.48	30.86	6.68	0.11	0.010	294.63	2.08E-07	1.96E-03	1.35E-02
37%RCA	[68]	36.01	24.19	21.13	31.00	6.65	0.10	0.010	283.85	2.05E-07	1.92E-03	1.33E-02
40%RCA	[68]	36.52	24.96	21.43	32.15	6.82	0.10	0.010	282.50	2.08E-07	1.94E-03	1.35E-02
106%OSW	[68]	35.77	23.68	23.45	32.33	6.43	0.08	0.009	229.48	1.89E-07	1.77E-03	1.29E-02
104%OSW	[68]	37.69	25.36	24.70	34.74	6.86	0.08	0.010	236.70	2.00E-07	1.86E-03	1.36E-02
102%OSW	[68]	43.99	30.16	28.87	41.44	8.11	0.09	0.011	269.60	2.34E-07	2.16E-03	1.60E-02
100%OSW	[68]	47.75	33.30	31.33	45.93	8.92	0.09	0.013	285.71	2.55E-07	2.33E-03	1.74E-02
0%OSW	[70]	37.22	46.61	0.00	33.81	7.07	0.11	0.010	354.44	2.10E-07	2.04E-03	1.41E-02
20%OSW	[70]	39.17	40.76	2.47	36.99	7.61	0.11	0.011	361.19	2.11E-07	2.13E-03	1.46E-02
40%OSW	[70]	42.20	40.86	5.26	39.87	8.13	0.12	0.011	389.48	2.23E-07	2.30E-03	1.56E-02
60%OSW	[70]	51.70	45.54	9.39	48.18	9.76	0.16	0.014	481.69	2.68E-07	2.82E-03	1.89E-02
80%OSW	[70]	69.80	55.94	16.48	64.38	12.94	0.23	0.019	655.17	3.55E-07	3.81E-03	2.51E-02
20%OSW	[71]	24.68	31.51	1.00	22.89	4.80	0.07	0.007	225.41	1.41E-07	1.34E-03	9.48E-03
40%OSW	[71]	24.02	30.66	1.95	22.38	4.67	0.07	0.006	219.33	1.37E-07	1.30E-03	9.23E-03
50%OSW	[71]	23.32	29.76	2.37	21.77	4.53	0.06	0.006	212.92	1.33E-07	1.27E-03	8.96E-03
50%OSW	[72]	41.79	52.16	4.93	39.24	8.21	0.12	0.011	388.39	2.37E-07	2.28E-03	1.61E-02
0%OSW	[73]	48.02	40.79	0.00	43.13	9.44	0.11	0.013	373.71	2.55E-07	2.51E-03	1.79E-02
50%OSW	[73]	53.93	58.83	5.35	48.56	10.27	0.16	0.014	489.24	2.97E-07	2.92E-03	2.03E-02

Identification	Reference	TPE/f _c	PRM/f _c	RM/f _c	WC/f _c	GWP/f _c	FAETP/f _c	TETP/f _c	MAETP/f _c	ODP/f _c	EP/f _c	AP/f _c
		MJ/(m ³ .MPa)	kg/(m ³ .MPa)	kg/(m ³ .MPa)	kg H ₂ O /(m ³ .MPa)	kg CO ₂ eq /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg (PO ₄) ⁻³ /(m ³ .MPa)	kg (SO ₂) /(m ³ .MPa)
50%OSW	[73]	40.75	44.52	4.07	36.86	7.79	0.12	0.011	367.66	2.25E-07	2.20E-03	1.53E-02
50%OSW	[73]	38.07	41.64	3.79	34.37	7.27	0.11	0.010	344.55	2.10E-07	2.06E-03	1.43E-02

Notes: TPE - Total Primary Energy; PRM - Primary Raw Material; RM - Recycled Material; WC - Water Consumption; GWP – Global Warming Potential; FAETP - Freshwater Aquatic Ecotoxicity Potential; TETP - Terrestrial Ecotoxicity Potential; MAETP - Marine Ecotoxicity Potential; ODP - Ozone Depletion Potential; EP - Eutrophication Potential; AP - Acidification Potential.

Table A.2.3 - Values of individual desirability and values of environmental indicators of each concrete.

Identification	Reference	Individual desirability											Composite indicators					
		TPE	PRM	RM	WC	GWP	FAETP	TETP	MAETP	ODP	EP	AP	EIR	MIR	GGR	EPR	AEO	EEP
0%GGBFS	[56]	0.56	0.69	0.00	0.46	0.50	0.80	0.53	0.76	0.60	0.63	0.58	0.56	0.38	0.50	0.70	0.60	0.55
10%GGBFS	[56]	0.55	0.69	0.05	0.46	0.52	0.69	0.54	0.71	0.60	0.59	0.53	0.55	0.40	0.52	0.65	0.57	0.54
20%GGBFS	[56]	0.58	0.71	0.10	0.49	0.57	0.70	0.59	0.72	0.64	0.61	0.52	0.58	0.43	0.57	0.67	0.59	0.57
30%GGBFS	[56]	0.59	0.69	0.16	0.48	0.59	0.68	0.61	0.71	0.66	0.59	0.47	0.59	0.45	0.59	0.67	0.57	0.57
0%GGBFS	[57]	0.82	0.86	0.00	0.80	0.82	0.83	0.82	0.88	0.84	0.84	0.84	0.82	0.56	0.82	0.84	0.84	0.78
10%GGBFS	[57]	0.82	0.85	0.02	0.79	0.83	0.82	0.82	0.87	0.84	0.83	0.81	0.82	0.55	0.83	0.84	0.83	0.77
15%GGBFS	[57]	0.82	0.84	0.04	0.79	0.83	0.81	0.83	0.87	0.84	0.83	0.80	0.82	0.56	0.83	0.83	0.82	0.77
0%GGBFS	[58]	0.87	0.86	0.00	0.82	0.84	0.95	0.85	0.92	0.87	0.89	0.87	0.87	0.56	0.84	0.91	0.88	0.81
20%GGBFS	[58]	0.90	0.87	0.05	0.84	0.88	0.96	0.90	0.93	0.91	0.90	0.86	0.90	0.59	0.88	0.93	0.89	0.84
30%GGBFS	[58]	0.90	0.85	0.08	0.83	0.88	0.94	0.90	0.92	0.91	0.89	0.83	0.90	0.58	0.88	0.92	0.88	0.83
40%GGBFS	[58]	0.90	0.84	0.11	0.82	0.90	0.93	0.92	0.91	0.92	0.88	0.81	0.90	0.59	0.90	0.92	0.87	0.84
0%GGBFS	[59]	0.80	0.78	0.06	0.76	0.78	0.87	0.79	0.87	0.80	0.83	0.80	0.80	0.53	0.78	0.84	0.81	0.75
10%GGBF	[59]	0.76	0.73	0.10	0.71	0.75	0.80	0.76	0.82	0.77	0.78	0.74	0.76	0.51	0.75	0.80	0.76	0.72
20%GGBFS	[59]	0.79	0.74	0.13	0.73	0.79	0.81	0.80	0.83	0.80	0.79	0.74	0.79	0.53	0.79	0.81	0.78	0.74
30%GGBFS	[59]	0.87	0.82	0.13	0.82	0.87	0.88	0.89	0.89	0.88	0.86	0.81	0.87	0.59	0.87	0.88	0.85	0.81
0%GGBFS	[59]	0.80	0.79	0.08	0.75	0.78	0.87	0.79	0.87	0.81	0.83	0.80	0.80	0.54	0.78	0.85	0.81	0.76
10%GGBF	[59]	0.89	0.87	0.09	0.84	0.87	0.94	0.89	0.93	0.89	0.90	0.87	0.89	0.60	0.87	0.92	0.89	0.83
20%GGBFS	[59]	0.92	0.89	0.10	0.87	0.91	0.95	0.92	0.94	0.92	0.92	0.88	0.92	0.62	0.91	0.94	0.91	0.86
30%GGBFS	[59]	0.93	0.90	0.12	0.88	0.93	0.95	0.94	0.95	0.94	0.93	0.88	0.93	0.63	0.93	0.95	0.92	0.87
0%GGBFS	[54]	0.87	0.86	0.00	0.83	0.85	0.93	0.86	0.93	0.87	0.89	0.87	0.87	0.57	0.85	0.91	0.87	0.81
35%GGBFS	[54]	0.90	0.85	0.09	0.84	0.90	0.93	0.91	0.93	0.91	0.89	0.82	0.90	0.59	0.90	0.92	0.87	0.84
50%GGBFS	[54]	0.93	0.87	0.11	0.87	0.95	0.95	0.96	0.94	0.95	0.91	0.84	0.93	0.62	0.95	0.95	0.90	0.87

Identification	Reference	Individual desirability											Composite indicators					
		TPE	PRM	RM	WC	GWP	FAETP	TETP	MAETP	ODP	EP	AP	EIR	MIR	GGR	EPR	AEO	EEP
70%GGBFS	[54]	0.96	0.87	0.17	0.88	0.98	0.95	1.00	0.94	0.98	0.92	0.81	0.96	0.64	0.98	0.96	0.90	0.89
20%GGBFS	[60]	0.93	0.95	0.04	0.90	0.92	0.98	0.93	0.97	0.95	0.94	0.90	0.93	0.63	0.92	0.96	0.93	0.87
40%GGBFS	[60]	0.96	0.95	0.08	0.91	0.96	0.98	0.97	0.97	0.98	0.94	0.89	0.96	0.65	0.96	0.97	0.94	0.89
60%GGBFS	[60]	0.94	0.92	0.15	0.87	0.96	0.95	0.98	0.95	0.98	0.91	0.82	0.94	0.65	0.96	0.96	0.90	0.88
80%GGBFS	[60]	0.89	0.84	0.30	0.75	0.94	0.86	0.97	0.87	0.96	0.82	0.65	0.89	0.63	0.94	0.90	0.81	0.84
0%GGBFS	[55]	0.84	0.89	0.00	0.80	0.82	0.92	0.83	0.92	0.85	0.86	0.84	0.84	0.56	0.82	0.89	0.85	0.79
20%GGBFS	[55]	0.88	0.91	0.05	0.83	0.87	0.94	0.88	0.94	0.90	0.89	0.84	0.88	0.60	0.87	0.92	0.88	0.83
40%GGBFS	[55]	0.90	0.91	0.10	0.84	0.91	0.94	0.92	0.94	0.93	0.89	0.82	0.90	0.62	0.91	0.93	0.88	0.85
60%GGBFS	[55]	0.93	0.92	0.15	0.86	0.95	0.94	0.96	0.94	0.97	0.90	0.80	0.93	0.64	0.95	0.95	0.89	0.87
0%FA	[58]	0.87	0.86	0.00	0.82	0.84	0.95	0.85	0.92	0.87	0.89	0.87	0.87	0.56	0.84	0.91	0.88	0.81
20%FA	[58]	0.92	0.87	0.05	0.88	0.89	0.96	0.90	0.94	0.91	0.93	0.91	0.92	0.60	0.89	0.93	0.92	0.85
30%FA	[58]	0.91	0.83	0.08	0.87	0.89	0.94	0.90	0.92	0.90	0.92	0.91	0.91	0.60	0.89	0.92	0.91	0.85
40%FA	[58]	0.93	0.83	0.11	0.90	0.91	0.93	0.92	0.92	0.91	0.93	0.93	0.93	0.61	0.91	0.93	0.92	0.86
0%FA	[61]	0.82	0.90	0.00	0.79	0.81	0.87	0.81	0.90	0.84	0.85	0.83	0.82	0.56	0.81	0.86	0.84	0.78
25%FA	[61]	0.73	0.79	0.10	0.71	0.74	0.75	0.73	0.82	0.75	0.77	0.75	0.73	0.54	0.74	0.77	0.76	0.71
0%FA	[62]	0.56	0.66	0.00	0.49	0.53	0.70	0.55	0.73	0.59	0.62	0.58	0.56	0.38	0.53	0.66	0.60	0.55
20%FA	[62]	0.56	0.56	0.12	0.48	0.53	0.68	0.55	0.71	0.57	0.61	0.57	0.56	0.39	0.53	0.64	0.58	0.54
30%FA	[62]	0.49	0.43	0.22	0.40	0.47	0.59	0.48	0.64	0.48	0.55	0.51	0.49	0.35	0.47	0.57	0.51	0.48
0%FA	[55]	0.84	0.89	0.00	0.80	0.82	0.92	0.83	0.92	0.85	0.86	0.84	0.84	0.56	0.82	0.89	0.85	0.79
15%FA	[55]	0.87	0.90	0.04	0.84	0.86	0.93	0.86	0.94	0.88	0.89	0.88	0.87	0.59	0.86	0.91	0.88	0.82
25%FA	[55]	0.89	0.90	0.06	0.87	0.89	0.94	0.89	0.95	0.90	0.92	0.90	0.89	0.61	0.89	0.92	0.91	0.84
35%FA	[55]	0.90	0.89	0.09	0.88	0.90	0.92	0.90	0.94	0.90	0.92	0.91	0.90	0.62	0.90	0.92	0.91	0.85
0%FA	[63]	0.84	0.88	0.00	0.80	0.81	0.93	0.83	0.92	0.85	0.86	0.84	0.84	0.56	0.81	0.89	0.85	0.79
20%FA	[63]	0.88	0.89	0.06	0.85	0.86	0.94	0.87	0.94	0.89	0.90	0.89	0.88	0.60	0.86	0.92	0.89	0.83
40%FA	[63]	0.89	0.84	0.09	0.86	0.88	0.92	0.88	0.92	0.89	0.91	0.89	0.89	0.60	0.88	0.91	0.90	0.84
60%FA	[63]	0.85	0.69	0.22	0.82	0.85	0.80	0.85	0.84	0.82	0.86	0.85	0.85	0.58	0.85	0.83	0.85	0.79
80%FA	[63]	0.69	0.15	0.71	0.69	0.76	0.36	0.72	0.54	0.59	0.70	0.71	0.69	0.52	0.76	0.54	0.66	0.63
0%FA	[64]	0.91	0.97	0.00	0.89	0.90	0.96	0.90	0.97	0.93	0.93	0.92	0.91	0.62	0.90	0.94	0.93	0.86
20%FA	[64]	0.95	0.98	0.03	0.95	0.95	0.98	0.95	0.98	0.96	0.97	0.96	0.95	0.65	0.95	0.97	0.96	0.90
40%FA	[64]	0.99	0.99	0.07	0.99	1.00	0.98	0.99	1.00	0.99	1.00	1.00	0.99	0.68	1.00	0.99	1.00	0.93
0%RHA	[23]	0.64	0.69	0.00	0.57	0.61	0.75	0.63	0.78	0.66	0.69	0.65	0.64	0.42	0.61	0.72	0.66	0.61
10%RHA	[23]	0.66	0.73	0.07	0.60	0.64	0.78	0.65	0.78	0.68	0.70	0.67	0.66	0.47	0.64	0.74	0.68	0.64

Identification	Reference	Individual desirability											Composite indicators					
		TPE	PRM	RM	WC	GWP	FAETP	TETP	MAETP	ODP	EP	AP	EIR	MIR	GGR	EPR	AEO	EEP
20%RHA	[23]	0.55	0.68	0.17	0.50	0.53	0.70	0.54	0.69	0.58	0.59	0.56	0.55	0.45	0.53	0.65	0.58	0.55
30%RHA	[23]	0.43	0.62	0.30	0.38	0.41	0.61	0.42	0.58	0.46	0.47	0.44	0.43	0.43	0.41	0.54	0.46	0.45
0%RHA	[24]	0.85	0.82	0.14	0.81	0.83	0.91	0.85	0.91	0.84	0.87	0.85	0.85	0.59	0.83	0.89	0.86	0.80
5%RHA	[24]	0.88	0.85	0.14	0.85	0.87	0.93	0.88	0.92	0.87	0.90	0.88	0.88	0.61	0.87	0.91	0.88	0.83
10%RHA	[24]	0.88	0.83	0.16	0.85	0.87	0.91	0.87	0.91	0.87	0.89	0.87	0.88	0.61	0.87	0.90	0.88	0.83
15%RHA	[24]	0.85	0.81	0.18	0.84	0.85	0.87	0.86	0.88	0.85	0.87	0.85	0.85	0.61	0.85	0.87	0.86	0.81
20%RHA	[24]	0.84	0.79	0.20	0.83	0.85	0.83	0.85	0.86	0.83	0.85	0.84	0.84	0.61	0.85	0.85	0.84	0.80
0%RHA	[64]	0.91	0.97	0.00	0.89	0.90	0.96	0.90	0.97	0.93	0.93	0.92	0.91	0.62	0.90	0.94	0.93	0.86
5%RHA	[64]	0.96	0.99	0.04	0.96	0.96	0.98	0.96	0.99	0.97	0.97	0.97	0.96	0.66	0.96	0.97	0.97	0.91
10%RHA	[64]	0.98	1.00	0.05	0.98	0.98	0.99	0.98	0.99	0.99	0.99	0.98	0.98	0.67	0.98	0.99	0.99	0.92
15%RHA	[64]	0.99	1.00	0.06	0.99	0.99	1.00	0.99	1.00	0.99	0.99	0.99	0.99	0.68	0.99	0.99	0.99	0.93
20%RHA	[64]	1.00	1.00	0.06	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.69	1.00	1.00	1.00	0.94
0%RHA	[65]	0.53	0.40	0.00	0.48	0.52	0.50	0.53	0.58	0.53	0.56	0.54	0.53	0.29	0.52	0.54	0.54	0.48
5%RHA	[65]	0.51	0.42	0.11	0.47	0.49	0.49	0.50	0.54	0.50	0.52	0.51	0.51	0.33	0.49	0.51	0.51	0.47
10%RHA	[65]	0.30	0.24	0.28	0.27	0.29	0.28	0.29	0.32	0.29	0.31	0.30	0.30	0.26	0.29	0.30	0.30	0.29
15%RHA	[65]	0.00	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.04
0%RHA	[18]	0.71	0.69	0.00	0.65	0.70	0.75	0.70	0.79	0.72	0.74	0.72	0.71	0.45	0.70	0.75	0.73	0.67
5%RHA	[18]	0.75	0.72	0.02	0.70	0.74	0.78	0.75	0.82	0.76	0.78	0.76	0.75	0.48	0.74	0.78	0.76	0.70
10%RHA	[18]	0.80	0.76	0.03	0.76	0.79	0.83	0.80	0.85	0.80	0.82	0.81	0.80	0.52	0.79	0.82	0.81	0.75
15%RHA	[18]	0.84	0.79	0.04	0.80	0.83	0.85	0.83	0.87	0.84	0.85	0.84	0.84	0.54	0.83	0.85	0.84	0.78
20%RHA	[18]	0.81	0.74	0.06	0.77	0.80	0.81	0.80	0.83	0.80	0.81	0.80	0.81	0.52	0.80	0.81	0.81	0.75
25%RHA	[18]	0.80	0.73	0.08	0.77	0.80	0.79	0.80	0.82	0.79	0.81	0.80	0.80	0.52	0.80	0.80	0.80	0.75
30%RHA	[18]	0.78	0.67	0.11	0.74	0.78	0.75	0.78	0.77	0.76	0.78	0.77	0.78	0.51	0.78	0.77	0.77	0.72
5%SCBA	[26]	0.54	0.63	0.02	0.48	0.54	0.60	0.53	0.69	0.57	0.59	0.57	0.54	0.38	0.54	0.61	0.58	0.53
5%SCBA	[26]	0.50	0.62	0.02	0.46	0.51	0.54	0.50	0.65	0.54	0.56	0.54	0.50	0.37	0.51	0.56	0.55	0.50
5%SCBA	[26]	0.25	0.42	0.03	0.20	0.28	0.24	0.25	0.45	0.31	0.32	0.30	0.25	0.22	0.28	0.31	0.31	0.27
5%SCBA	[26]	0.20	0.40	0.03	0.18	0.25	0.16	0.22	0.41	0.28	0.28	0.27	0.20	0.20	0.25	0.26	0.28	0.24
10%SCBA	[26]	0.60	0.69	0.04	0.55	0.59	0.66	0.59	0.73	0.63	0.64	0.62	0.60	0.43	0.59	0.66	0.63	0.58
10%SCBA	[26]	0.59	0.69	0.04	0.56	0.60	0.63	0.59	0.72	0.63	0.64	0.62	0.59	0.43	0.60	0.65	0.63	0.58
10%SCBA	[26]	0.38	0.53	0.05	0.35	0.41	0.38	0.38	0.55	0.43	0.44	0.42	0.38	0.31	0.41	0.44	0.43	0.39
10%SCBA	[26]	0.27	0.46	0.06	0.25	0.32	0.23	0.28	0.46	0.34	0.34	0.33	0.27	0.26	0.32	0.32	0.34	0.30
15%SCBA	[26]	0.64	0.73	0.05	0.61	0.64	0.71	0.64	0.76	0.67	0.68	0.66	0.64	0.46	0.64	0.70	0.67	0.63

Identification	Reference	Individual desirability											Composite indicators					
		TPE	PRM	RM	WC	GWP	FAETP	TETP	MAETP	ODP	EP	AP	EIR	MIR	GGR	EPR	AEO	EEP
15%SCBA	[26]	0.63	0.73	0.06	0.60	0.63	0.67	0.62	0.74	0.66	0.67	0.65	0.63	0.46	0.63	0.68	0.66	0.61
15%SCBA	[26]	0.40	0.55	0.08	0.37	0.42	0.41	0.40	0.55	0.45	0.45	0.44	0.40	0.33	0.42	0.45	0.45	0.41
15%SCBA	[26]	0.33	0.51	0.08	0.32	0.37	0.30	0.34	0.50	0.39	0.39	0.38	0.33	0.31	0.37	0.38	0.39	0.36
20%SCBA	[26]	0.64	0.73	0.07	0.61	0.64	0.71	0.63	0.75	0.67	0.68	0.66	0.64	0.47	0.64	0.70	0.67	0.62
20%SCBA	[26]	0.62	0.72	0.07	0.60	0.63	0.67	0.62	0.73	0.65	0.66	0.64	0.62	0.46	0.63	0.67	0.65	0.61
20%SCBA	[26]	0.35	0.52	0.11	0.33	0.38	0.36	0.36	0.51	0.40	0.41	0.39	0.35	0.32	0.38	0.41	0.40	0.37
20%SCBA	[26]	0.29	0.49	0.11	0.29	0.34	0.27	0.31	0.46	0.36	0.36	0.35	0.29	0.30	0.34	0.35	0.35	0.33
0%SCBA	[66]	0.70	0.71	0.10	0.64	0.69	0.76	0.69	0.80	0.71	0.74	0.72	0.70	0.48	0.69	0.75	0.72	0.67
10%SCBA	[66]	0.72	0.71	0.13	0.68	0.72	0.76	0.72	0.80	0.73	0.75	0.74	0.72	0.51	0.72	0.76	0.74	0.69
20%SCBA	[66]	0.80	0.78	0.14	0.77	0.81	0.83	0.80	0.84	0.80	0.82	0.81	0.80	0.56	0.81	0.82	0.81	0.76
30%SCBA	[66]	0.81	0.76	0.19	0.79	0.82	0.81	0.81	0.82	0.80	0.82	0.81	0.81	0.58	0.82	0.81	0.81	0.76
0%SCBA	[67]	0.77	0.75	0.00	0.69	0.73	0.86	0.75	0.84	0.77	0.79	0.77	0.77	0.48	0.73	0.82	0.78	0.72
30%SCBA	[67]	0.85	0.79	0.09	0.82	0.84	0.86	0.84	0.85	0.85	0.85	0.85	0.85	0.57	0.84	0.85	0.85	0.79
0%RCA	[69]	0.71	0.74	0.11	0.66	0.70	0.80	0.71	0.82	0.72	0.76	0.73	0.71	0.50	0.70	0.78	0.74	0.69
20%RCA	[69]	0.76	0.81	0.19	0.71	0.75	0.85	0.75	0.87	0.77	0.80	0.77	0.76	0.57	0.75	0.82	0.78	0.74
20%RCA	[69]	0.74	0.79	0.20	0.69	0.73	0.81	0.73	0.84	0.75	0.78	0.76	0.74	0.56	0.73	0.80	0.76	0.72
40%RCA	[69]	0.75	0.82	0.29	0.70	0.74	0.83	0.74	0.86	0.76	0.79	0.77	0.75	0.61	0.74	0.81	0.77	0.74
31%RCA	[68]	0.84	0.96	0.69	0.83	0.84	0.85	0.83	0.92	0.84	0.86	0.85	0.84	0.83	0.84	0.86	0.85	0.84
34%RCA	[68]	0.84	0.96	0.69	0.82	0.84	0.86	0.83	0.92	0.84	0.86	0.85	0.84	0.82	0.84	0.87	0.85	0.84
37%RCA	[68]	0.84	0.96	0.67	0.82	0.84	0.88	0.83	0.93	0.84	0.87	0.85	0.84	0.82	0.84	0.88	0.85	0.85
40%RCA	[68]	0.84	0.96	0.68	0.81	0.83	0.89	0.83	0.93	0.84	0.86	0.85	0.84	0.82	0.83	0.88	0.85	0.84
106%OSW	[68]	0.85	0.97	0.75	0.81	0.85	0.94	0.84	0.97	0.87	0.89	0.86	0.85	0.84	0.85	0.92	0.87	0.87
104%OSW	[68]	0.83	0.95	0.79	0.78	0.83	0.94	0.83	0.97	0.85	0.88	0.85	0.83	0.84	0.83	0.91	0.86	0.85
102%OSW	[68]	0.78	0.92	0.92	0.71	0.78	0.92	0.77	0.94	0.80	0.83	0.80	0.78	0.85	0.78	0.88	0.81	0.82
100%OSW	[68]	0.74	0.89	1.00	0.66	0.74	0.91	0.74	0.93	0.77	0.81	0.77	0.74	0.85	0.74	0.86	0.78	0.80
0%OSW	[70]	0.83	0.79	0.00	0.79	0.82	0.85	0.83	0.88	0.83	0.85	0.84	0.83	0.53	0.82	0.85	0.84	0.77
20%OSW	[70]	0.82	0.83	0.08	0.76	0.80	0.86	0.80	0.87	0.83	0.84	0.83	0.82	0.56	0.80	0.84	0.83	0.77
40%OSW	[70]	0.79	0.83	0.17	0.73	0.77	0.82	0.78	0.85	0.81	0.81	0.80	0.79	0.58	0.77	0.82	0.81	0.75
60%OSW	[70]	0.71	0.80	0.30	0.64	0.70	0.71	0.70	0.78	0.75	0.74	0.73	0.71	0.58	0.70	0.73	0.74	0.69
80%OSW	[70]	0.56	0.72	0.53	0.47	0.56	0.52	0.54	0.65	0.62	0.59	0.60	0.56	0.57	0.56	0.57	0.60	0.57
20%OSW	[71]	0.94	0.91	0.03	0.90	0.92	0.99	0.93	0.97	0.94	0.95	0.94	0.94	0.61	0.92	0.96	0.94	0.88
40%OSW	[71]	0.95	0.91	0.06	0.91	0.93	0.99	0.94	0.98	0.94	0.96	0.94	0.95	0.63	0.93	0.97	0.95	0.88

Identification	Reference	Individual desirability											Composite indicators					
		TPE	PRM	RM	WC	GWP	FAETP	TETP	MAETP	ODP	EP	AP	EIR	MIR	GGR	EPR	AEO	EEP
50%OSW	[71]	0.95	0.92	0.08	0.92	0.93	1.00	0.94	0.98	0.95	0.96	0.95	0.95	0.64	0.93	0.98	0.95	0.89
50%OSW	[72]	0.79	0.74	0.16	0.73	0.77	0.85	0.78	0.85	0.79	0.82	0.79	0.79	0.55	0.77	0.83	0.80	0.75
0%OSW	[73]	0.74	0.83	0.00	0.69	0.72	0.86	0.73	0.86	0.77	0.78	0.75	0.74	0.51	0.72	0.82	0.77	0.71
50%OSW	[73]	0.69	0.69	0.17	0.64	0.68	0.72	0.68	0.78	0.70	0.72	0.70	0.69	0.50	0.68	0.73	0.71	0.66
50%OSW	[73]	0.80	0.80	0.13	0.76	0.79	0.84	0.79	0.87	0.81	0.83	0.81	0.80	0.56	0.79	0.84	0.82	0.76
50%OSW	[73]	0.83	0.83	0.12	0.78	0.81	0.87	0.82	0.88	0.83	0.85	0.83	0.83	0.58	0.81	0.86	0.84	0.78

Notes: EIR - Energy Negative Impacts Reduction; MIR - Material Impacts Reduction; GGR - Greenhouse Gases Reduction; EPR - Ecotoxicity Potential Reduction; AEO - Acidification, Eutrophication, and Ozone Abatement; EEP - Eco-Efficiency Potential.

CHAPTER 3 - Influence of filler/cement and powder/total ratio on the mixture design of self-compacting sand-concretes containing waste from the ornamental stone industry

Abstract

The ornamental stone industry generates a large volume of waste from the rock cutting and polishing process that can cause significant environmental impacts if disposed of incorrectly. The present work seeks to evaluate the effects of incorporating a high concentration of waste from the processing of ornamental rocks as a filler in self-compacting microconcrete by evaluating its eco-efficiency and physical-chemical, mechanical, and microstructural properties. The dosage of the concretes was done by the compressible packing method to obtain the limits of the filler/cement and fines/total solids ratios for the production of mixtures, following a central composite rotational statistical experimental design. Response surfaces and desirability analyses demonstrate that although the inert residue reduces the mechanical strength, it is a very effective filler for use in self-compacting microconcretes, capable of reducing the cement content and consequently the embodied CO₂ emissions, delivering matrices consistently more eco-efficient for conventional mechanical strengths.

Keywords: Self-compacting concrete. Eco-efficient concrete. Sustainability. Ornamental rock waste. Sand-concrete.

3.1 Introduction

Brazil is one of the largest producers and exporters of ornamental stones, producing in 2019 more than 9 million tonnes [1]. The ornamental stone industry generates about 40% of raw material losses in cutting and polishing the plates. Despite being classified as non-hazardous and inert, if incorrectly discarded, this residue can cause environmental problems such as silting of rivers, pollution of water sources and diseases to the population due to the fine particles [2,3]. In this sense, solid waste management regulations have been created to promote the correct waste disposal and recycling, pressuring the generating sectors to provide solutions [4,5].

Using these wastes in civil construction is a viable alternative since this sector consumes a large volume of natural resources and is prone to absorb solid waste [6]. Due to its particle size distribution (PSD) with a high content of fines and superfines, ornamental stone waste (OSW) as a filler in concrete adds commercial value to the waste and the product generated. Cement is responsible for approximately 5% to 7% of the global CO₂ emissions, and its partial replacement by OSW can improve concrete's physical and environmental characteristics by reducing cement consumption and hydration heat, especially in large quantities [7–16].

Thus, using filler is recommended mainly in concretes that demand a high content of fines in the mixture, such as in microconcrete, where the maximum dimension of the aggregates is limited, and self-compacting concrete (SCC), which can flow and densify by the action of gravity under its weight, filling the spaces of the formworks even in the presence of a dense rebar arrangement, maintaining its homogeneity without the need for any mechanical compaction [8,17–20]. To ensure such properties, superplasticizer admixtures are used, which increase the fluidity, demanding a high volume of fines to maintain the mixture stability, guaranteeing a moderate viscosity and cohesion, preventing bleeding and aggregates segregation [21].

Research on incorporating ornamental stone waste in self-compacting concrete has shown satisfactory results. Xavier [22] produced self-compacting concrete mixes containing up to 50% OSW filler addition by cement content and achieved up to 61.5 MPa of compressive strength at 28 days, without compromising the requirements of flowability, stability and passing ability. Cavalcante et al. [23], demonstrated that adding up to 65% of OSW by cement content

can improve the cohesion of self-compacting concrete and prevent exudation and segregation. Savadkoobi e Reisi [24], produced reactive powder concretes by replacing silica sand with granite residue and concluded that substitutions by up to 30% increase compressive strength by 78% and reduce water absorption by up to 75% while maintaining workability adjustment through the dosage of superplasticizers. Franco de Carvalho et al. [25] used PSD curves based on particle packing method to produce sand-concretes with low-cost supplementary cementing materials, such as quartzite and quartz mining residue, and even the mixtures with 60% of cement replacement showed a compressive strength of 60 MPa at 28 days. Lozano-Lunar et al. [26] replaced up to 40% of the volume of fine aggregates and filler by granite mud in the production of self-compacting mortars, and the incorporation of this residue did not affect the hydration phases of the cement, and, despite the morphology of the particles increasing the incorporation of water in the mixture, affecting the porosity, strength and durability of the mixture, the use of the residue proved to be feasible.

Despite numerous works involving OSW in concrete, there is still no consensus on the ideal percentage of addition or the maximum cement replacement by residue for an economically and sustainably viable cement-based composite. In addition, no studies were found on self-compacting microconcrete with high residue incorporation and dosages with filler consumption higher than cement consumption. Therefore, the present study aims to incorporate high levels of OSW as a filler in self-compacting microconcretes, analyzing its properties in the fresh and hardened state and subsequently quantifying the environmental performance of the composites obtained through indicators proposed in the literature.

3.2 Experimental program

3.2.1 Materials

The binder used was a Brazilian high early strength Portland cement (PC) CPV-ARI (equivalent to ASTM type III), indicated for use in manufacturing prefabricated elements, as it requires shorter curing times. Additionally, this binder does not have significant quantities of supplementary cementing materials, reducing the interference of the additions used in the study. Two conventional aggregates were used: natural quartz river sand (R-Sand) and manufactured gneiss sand (M-Sand), both from the region of Viçosa, Minas Gerais State, Brazil. The proportion 1:3 (R-Sand/M-Sand) was fitted according to the modified Andreassen curve [27].

OSW from a Company located in Cachoeiro de Itapemirim, Espírito Santo State, Brazil, was used as a filler. A commercial superplasticizer admixture based on polycarboxylate ether (PCE) was used. Tables 3.1 and 3.2 show the physical properties of the materials and the chemical properties of OSW, respectively. Figure 3.1 shows the PSD curves of the materials.

Table 3.1 – Specific surface area of the powder fraction components and specific densities of the materials used in this research.

Material	Specific density (g/cm³)	Specific surface area (Blaine), cm²/g
PC	3.15	2135.81
OSW	2.60	2996.11
M-sand	2.86	-
R-sand	2.63	-
Superplasticizer	1.09	-

Table 3.2 – Chemical composition of OSW.

Compound	OSW
SiO ₂ content, %	74.5
CO ₂ content, %	8.1
Al ₂ O ₃ content, %	5.3
CaO content, %	5.0
MgO content, %	3.5
Na ₂ O content, %	1.7
K ₂ O content, %	1.0
Fe ₂ O ₃ content, %	0.6
TiO ₂ content, %	0.1
Other oxides, %	0.1

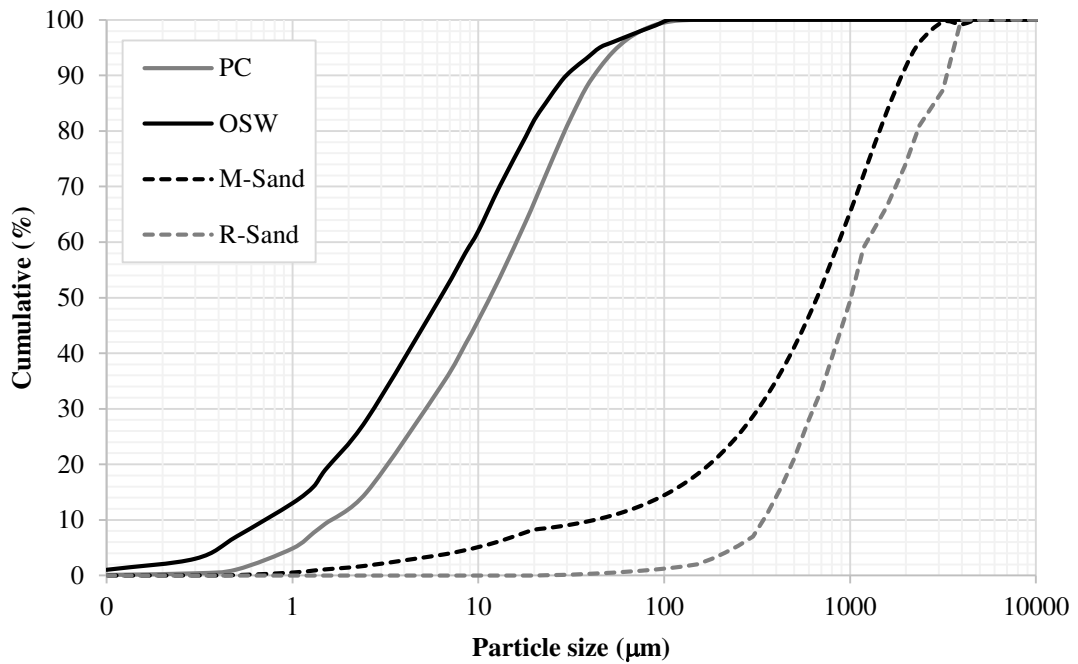


Figure 3.1 – Particle size distribution curves.

3.2.2 Experimental design

The microconcrete dosage was designed to present a high packing density using the modified Andreassen methodology [27] and following the EFNARC prescriptions [20] for the mixtures proportioning. To obtain superfluid concrete with the self-compacting ability for producing slender and densely reinforced pieces, coarse aggregates were not used. PSD curves were obtained by varying cement, filler, and sand contents, meeting the EFNARC recommendations [20] and comparing them to the modified Andreassen packing curve [27].

The Andreassen packing curve modified by Funk and Dinger is obtained using Equation 3.1 [27], where $CPFT$ is the accumulated percentage of particles with a diameter smaller than D (in volume); D is the particle size; D_L is the diameter of the largest particle; D_S is the diameter of the smallest particle; and q is the distribution coefficient (q -value).

Equation 3.1

$$CPFT (\%) = 100 \left(\frac{D^q - D_S^q}{D_L^q - D_S^q} \right)$$

The distribution coefficient q must be between 0.20 and 0.30 to obtain good flowability and densification. Values close to 0.20 led to more workable mixtures when increasing the fines content, reducing interference of the larger grains, causing only the force of the matrix to appear in the system [28–31]. The distribution coefficient should be between 0.20 and 0.23 to keep the proportion of fines above 40% by volume of solids according to EFNARC recommendations [20], and therefore, 0.20 was defined to achieve maximum flowability.

Once the dosage limits were established, the volume ratio filler/cement (f/c) was defined between 0 and 200%, and the volume ratio powder/total solids (V_p/V_t) between 35% and 45%, where the "powder" fraction corresponds to cement plus filler. With these minimum and maximum relationships being independent of each other, a second-order composite project was carried out (as illustrated in Figure 3.2 and presented in Table 3.3). The water/powder ratio by volume was set at 1.09 for a spread between 270 mm and 320 mm in an adapted mini-slump test to obtain stable mixtures. The mixtures that did not reach the spreading limit had the superplasticizer content adjusted to achieve a low yield strength and sufficient viscosity for the mixture to flow. The superplasticizer content was diluted and accounted into the total mixing water volume. Table 3.4 shows the proportions of the mixtures by volume of solids and the consumptions per cubic meter of microconcrete. Figure 3.3 shows the PSD curves of each mixture.

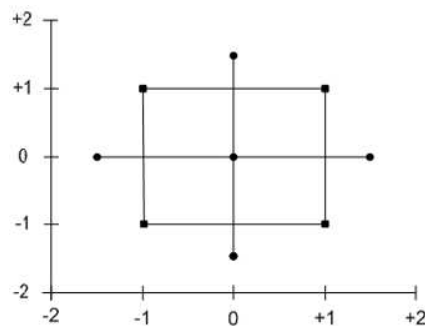


Figure 3.2 – Second-order composite project.

Table 3.3 - Levels of variables used in microconcrete.

Proportions	-1.4142	-1	0	1	1.4142
Filler/cement (f/c)	0	0.29	1	1.71	2
Powder/total solids (V_p/V_t)	0.35	0.3646	0.4	0.4354	0.45

Table 3.4 – Microconcretes proportioning (PC – Portland cement; OSW – ornamental stone waste; M-Sand – gneiss mining sand; R-Sand – river quartz sand; W-water; SP - superplasticizer).

Trat	f/c	Vp/Vt	Proportions (%)				Consumptions (kg/m ³)					
			PC	OSW	M-Sand	R-Sand	PC	OSW	M-Sand	R-Sand	W	SP
200F40P	1.4142	0	13	27	45	15	289.53	489.98	894.80	274.78	304.01	8.69
171F36P	1	-1	13.47	22.99	47.65	15.88	300.57	434.17	973.69	299.00	284.79	8.69
171F44P	1	1	16.08	27.45	42.35	14.12	340.08	491.24	820.04	251.82	322.22	8.69
100F35P	0	-1.4142	17.5	17.5	48.75	16.25	395.02	334.25	1007.66	309.43	276.52	13.03
100F40P	0	0	20	20	45	15	434.30	367.48	894.80	274.78	304.01	13.03
100F45P	0	1.4142	22.5	22.5	41.25	13.75	470.70	398.28	790.21	242.66	329.49	8.69
29F36P	-1	-1	28.20	8.26	47.65	15.88	629.36	155.97	973.69	299.00	284.79	13.03
29F44P	-1	1	33.67	9.86	42.35	14.12	712.08	176.47	820.04	251.82	322.22	8.69
0F44P	-1.4142	0	40	0	45	15	868.60	0.00	894.80	274.78	304.01	8.69

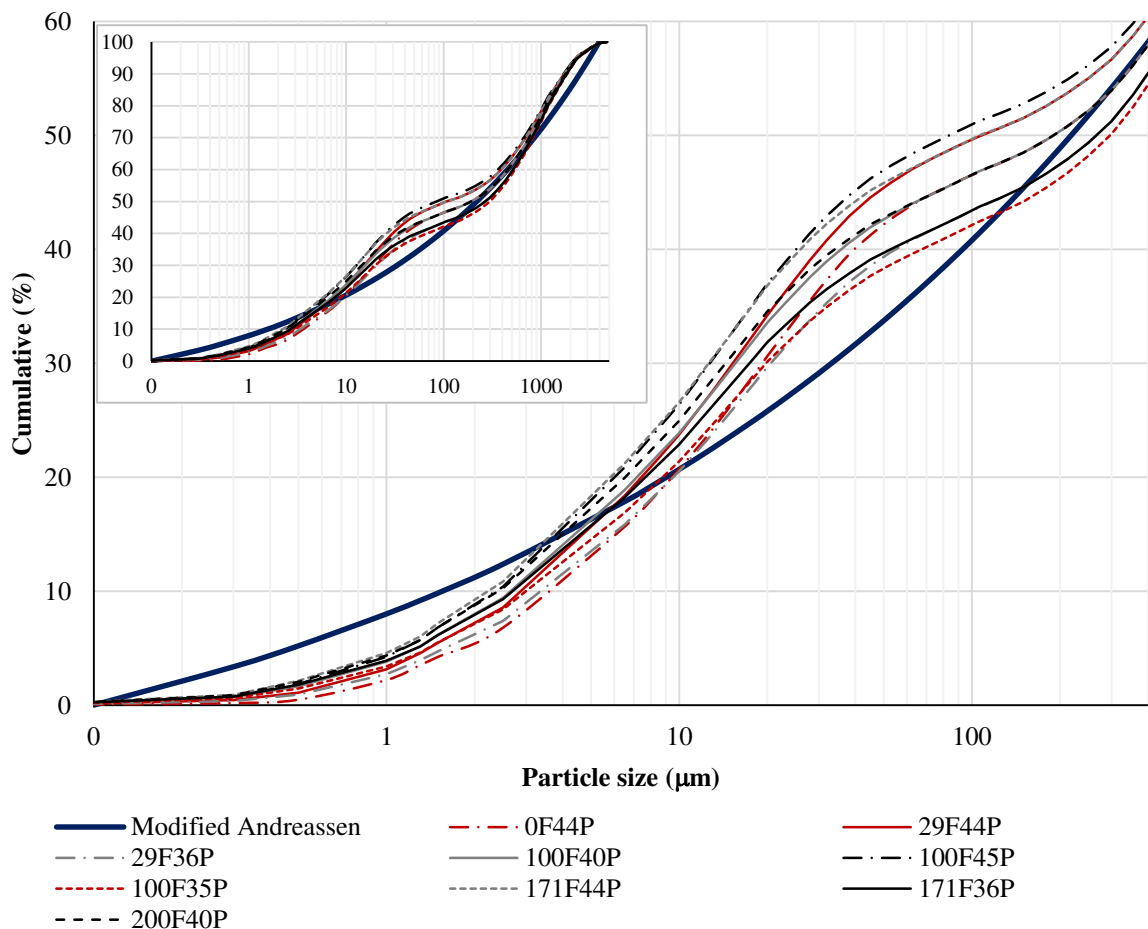


Figure 3.3 – Particle size distribution curves of the dry mixtures compared to the modified Andreassen curve for $q = 0.2$.

The mini-slump test was adapted using a cone with 75 mm of height and diameters of 41 mm and 91 mm. The results were compared with the values of the slump flow test, through the fluidity parameter G_m obtained by Equation 3.2 proposed by Okamura [19], where D_m is the spreading diameter of the microconcrete and D_0 is the inner diameter of the cone base [17,20].

Equação 3.2

$$G_m = \left(\frac{D_m}{D_0} \right)^2 - 1$$

3.2.3 Preparation of concrete and specimens casting

The concretes were prepared using a PHP500 Philco planetary mixer according to the following protocol: (a) half of the dry mix were added to the bowl and homogenized for 3 minutes at low speed; (b) the kneading water containing the total amount of superplasticizer was added to the homogenized dry mixture over the time of 30 seconds with the mixer at slow speed; (c) the mixer was kept at slow speed for additional 60 seconds before being (d) turned off to clean the blades and walls of the bowl, keeping the mixture at rest for 60 seconds; in sequence (e) the mixer was restarted and the mixture was homogenized for an additional time of 60 seconds at medium speed.

The volume of mixed material was set at 1770 ± 10 mL, enough to mold 9 cylindrical test specimens $\text{Ø}5 \times 10$ cm. The specimens were demolded at 1 day of age and kept in water submerged curing.

3.2.4 Rheological tests

Rheological parameters (shear stress, viscosity and spreading) were measured using a FANN 35A rotational viscometer and mini-slump test. For the viscometer test, 3 pastes were made with f/c ratios of 0, 1 and 2, water/powder ratio of 1.56 by volume and 3% superplasticizer (by equivalent cement mass) to adjust the mixture to meet the equipment setup limits. Mini-slump spreading tests were conducted for measuring the microconcrete spread and time to reach a diameter equal to 220 mm.

3.2.5 Concrete characterization program

The mechanical, chemical and physical characterization tests were carried out in the hardened state. Cylindrical specimens ($\text{Ø}5 \times 10$ cm) were used for tensile strength tests by diametral compression and compressive strength (Figure 3.4) according to the methods NBR 7222 [32], NBR 5739 [33] and ASTM C-39 [34]. The ultrasonic pulse velocity (Proceq Pundit Lab, P wave, frequency 54 kHz) was also measured according to NBR 8802 [35] and ASTM C597-16 [36]. For the physical characterization in the hardened state, specific mass and void index tests were carried out according to NBR 9778 [37].

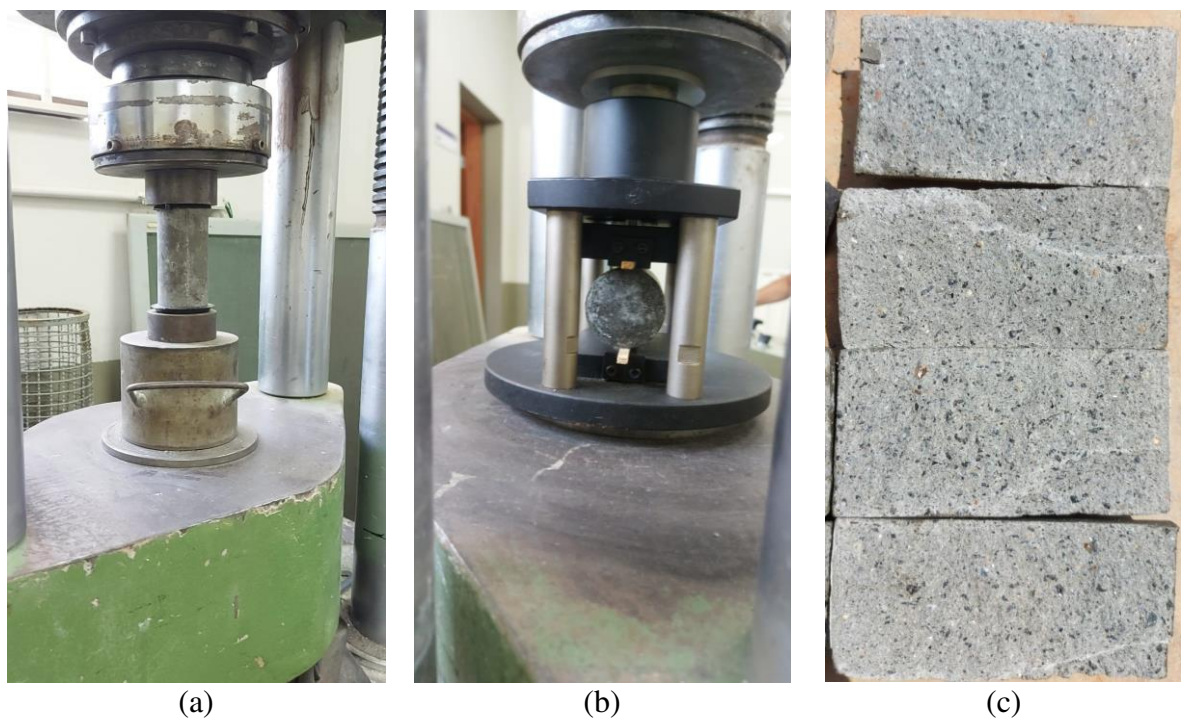


Figure 3.4. Mechanical tests: (a) compressive strength; (b) tension by diametral compression; (c) aspects of some broken specimens after the diametral compression test.

3.2.6 Eco-efficiency performance

The eco-efficiency performance of the concrete matrices was quantified by the binder intensity indicator (bi) proposed by Damineli et al. [38], calculated by Equation 3.3, where the total consumption of binder (b) and the performance achieved in the compressive strength test at 28 days (p) are measured. In this work, only cement was considered as a binder.

Equação 3.3

$$bi = \frac{b}{p}$$

An assessment of the environmental impacts generated in the production of each material used in the microconcrete produced was also carried out, allowing the comparison of these impacts in the mixtures and evaluating the replacement of conventional materials by waste using mechanical strengths as the performance indicator. The life cycle analysis inventory (Table 3.5) and indicators raised and proposed by Souza et al. [39] were used. A global eco-efficiency indicator classified the microconcretes based on the statistical desirability function, attributing values between 0 and 1 (0 – undesirable, 1 – desirable).

Table 3.5 - Results of the life-cycle assessment obtained by Souza et al. [39] (TPE - total primary energy; WC - water consumption; GWP - global warming potential; FAETP - freshwater aquatic ecotoxicity potential; TETP - terrestrial ecotoxicity potential; MAETP - Marine ecotoxicity potential; ODP - Ozone Depletion Potential; EP - Eutrophication Potential; AP - Acidification Potential).

Component	TPE (MJ/kg)	WC (m ³ /kg)	GWP (kg CO ₂ eq./kg)	FAETP (kg 1,4- DB eq./kg)	TETP (kg 1,4- DB eq./kg)	MAETP (kg 1,4- DB eq./kg)	ODP (kg CFC- 11 eq./kg)	EP (kg PO ₄ ³⁻ eq./kg)	AP (kg SO ₂ eq./kgf)
Ordinary Portland Cement (OP)	4.359	3.84E-03	0.883	4.14E-03	1.17E-03	1.94E+01	2.04E-08	2.01E-04	1.54E-03
Fly ash (FA)	0.417	0.00E+00	0.008	1.47E-03	7.90E-05	1.61E+00	2.79E-09	6.84E-06	6.54E-05
Ground granulated blast furnace slag (GGBS)	1.580	2.23E-03	0.177	2.13E-03	1.58E-04	1.11E+01	2.47E-09	1.30E-04	1.76E-03
Sugar cane bagasse ash (SCBA)	0.900	0.00E+00	0.115	8.20E-04	2.02E-04	1.73E+01	5.32E-09	6.70E-05	4.01E-04
Rice husk ash (RHA)	0.540	0.00E+00	0.089	5.70E-04	1.26E-04	1.44E+01	4.65E-09	5.84E-06	6.26E-05
Ornamental rock waste (OSW)	0.003	1.06E-04	0.001	5.17E-06	3.25E-07	5.38E-06	1.26E-10	9.41E-08	3.39E-06
Conventional fine aggregate	0.085	2.20E-06	0.007	5.87E-04	6.31E-06	1.72E+00	1.60E-09	5.84E-06	6.26E-05
Conventional coarse aggregate	0.068	3.44E-05	0.015	2.38E-03	2.09E-05	7.75E+00	1.00E-09	1.41E-05	4.54E-05
Superplasticizer (SP)	24.700	6.04E-03	1.445	2.08E-01	5.13E-03	3.35E+02	9.42E-08	1.46E-03	6.40E-03
Water	0.002	1.00E-03	0.000	5.16E-05	2.03E-06	7.62E-02	1.04E-11	7.48E-08	1.18E-06

The inventory proposed by Souza et al. [39] includes total primary energy (TPE), water consumption (WC), global warming potential (GWP), freshwater aquatic ecotoxicity potential (FAETP), terrestrial ecotoxicity potential (TETP), Marine ecotoxicity potential (MAETP);

Ozone Depletion Potential (ODP), Eutrophication Potential (EP), Acidification Potential (AP), in addition to the primary raw material (PRM) and total recycled material (RM).

The proposed indicators are Energy Negative Impacts Reduction (EIR), Material Impacts Reduction (MIR), Greenhouse Gases Reduction (GGR), Ecotoxicity Potential Reduction (EPR), Acidification, Eutrophication, and Ozone Abatement (AEO), and the composite indicator Eco-Efficiency Potential (EEP). The weighting performance indicator used was the compressive strength. The equations are presented in Table 3.6.

Table 3.6 – Equations for calculating the eco-efficiency indicators.

Indicator	Equation
Energy Negative Impacts Reduction (EIR)	$EIR = \left(\frac{TPE}{fc} \right)$
Material Impacts Reduction (MIR)	$MIR = \frac{1}{3} \cdot \left[\left(\frac{PRM}{fc} \right) + \left(\frac{RM}{fc} \right) + \left(\frac{WC}{fc} \right) \right]$
Greenhouse Gases Reduction (GGR)	$GGR = \left(\frac{GWP}{fc} \right)$
Ecotoxicity Potential Reduction (EPR)	$EPR = \frac{1}{3} \cdot \left[\left(\frac{FAETP}{fc} \right) + \left(\frac{TETP}{fc} \right) + \left(\frac{MAETP}{fc} \right) \right]$
Acidification, Eutrophication, and Ozone Abatement (AEO)	$AEO = \frac{1}{3} \cdot \left[\left(\frac{ODP}{fc} \right) + \left(\frac{EP}{fc} \right) + \left(\frac{AP}{fc} \right) \right]$
Eco-efficiency potential (EEP)	$EEP = \frac{1}{5} \cdot [EIR + GGR + EPR + AEO]$

The mixtures produced were evaluated by comparisons among themselves and among mixtures produced by other authors who used blast furnace slag [40–43], fly ash [42–44], rice husk ash [45–48], sugarcane bagasse ash [49–51], and ornamental stone waste [52] in self-compacting concretes. To compare the mixtures produced with those of other authors, the concretes were classified into strength classes so that they were compared only with similar strengths. Four strength classes were used: C20 for concretes with strengths between 20 and 29 MPa, C30 for concretes with strengths between 30 and 39 MPa, C40 for concretes with strengths between 40 and 49 MPa, and C60 for concretes with strengths between 60 and 69 MPa. The mixture proportions of each concrete are presented in Table 3.7.

Table 3.7 - Constituents and proportioning of the self-compacting concretes (in mass).

Class	Id	Ref.	PC	Fine aggregate	Coarse aggregate	Water	Admixture (%)	Residue	Addition	fc (MPa)	Slump Flow (mm)	Bi (kg cement/MPa)
C20	171F36P	Author	1.00	0.99	3.24	0.95	2.89%	1.44	0.00	23.48	682	12.80
	171F44P	Author	1.00	0.74	2.41	0.95	2.56%	1.44	0.00	20.66	727	16.46
	200F40P	Author	1.00	0.95	3.09	1.05	3.00%	1.69	0.00	22.31	659	12.98
	20FA	[44]	1.00	1.93	1.82	0.46	0.95%	0.25	0.00	24.80	685	18.03
	0RHA	[45]	1.00	2.35	2.93	0.40	1.70%	0.00	0.00	26.64	740	14.40
	5RHA	[45]	1.00	2.12	2.93	0.40	1.70%	0.12	0.12	20.86	720	18.26
	20SCBA	[49]	1.00	1.75	1.50	0.45	4.00%	0.20	0.00	27.50	680	17.86
	80OSW	[52]	1.00	0.31	2.28	0.58	3.44%	1.24	0.00	26.00	670	16.66
C30	100F35P	Author	1.00	0.78	2.55	0.70	3.30%	0.85	0.00	37.71	659	10.48
	100F40P	Author	1.00	0.63	2.06	0.70	2.00%	0.85	0.00	36.86	659	11.74
	100F45P	Author	1.00	0.52	1.68	0.70	1.85%	0.85	0.00	35.82	682	13.09
	0GGBFS	[40]	1.00	1.00	1.50	0.30	0.00%	0.00	0.00	33.68	0	19.61
	30GGBFS	[40]	1.00	1.43	2.14	0.30	1.57%	0.43	0.00	32.48	560	14.98
	80GGBFS	[41]	1.00	6.35	7.46	2.24	6.25%	4.00	0.00	38.64	700	2.92
	0RHA	[48]	1.00	1.88	1.40	0.44	1.50%	0.00	0.00	33.12	680	15.29
	10RHA	[48]	1.00	1.69	1.40	0.44	1.50%	0.19	0.00	34.72	690	14.74
	0RHA	[46]	1.00	2.20	2.00	0.55	2.00%	0.00	0.00	32.80	740	12.87
	25RHA	[46]	1.00	2.93	2.67	0.73	2.67%	0.33	0.00	33.60	550	9.29
	0SCBA	[50]	1.00	1.66	2.16	0.48	0.52%	0.00	0.00	37.99	740	12.06
	30SCBA	[50]	1.00	2.34	3.09	0.69	1.90%	0.43	0.00	39.81	717	8.10
60ORW	[52]	1.00	0.62	2.28	0.58	2.81%	0.93	0.00	34.40	715	12.69	
C40	29F36P	Author	1.00	0.48	1.55	0.45	2.07%	0.25	0.00	43.32	682	14.53
	29F44P	Author	1.00	0.35	1.15	0.45	1.22%	0.25	0.00	45.34	682	15.71
	40GGBFS	[43]	1.00	2.51	3.93	0.58	0.40%	0.67	0.00	46.80	740	6.23
	40FA	[43]	1.00	2.51	3.93	0.58	0.40%	0.67	0.00	44.40	760	6.44
	0RHA	[47]	1.00	2.36	2.15	0.50	1.25%	0.00	0.61	42.72	740	8.87
	15RHA	[47]	1.00	2.78	2.53	0.59	2.45%	0.18	0.72	40.24	670	7.93
	0SCBA	[51]	1.00	1.91	1.87	0.58	1.80%	0.00	0.29	40.13	671	10.45
	30SCBA	[51]	1.00	2.73	2.67	0.83	2.57%	0.43	0.41	41.88	584	6.96
	0ORW	[52]	1.00	2.50	2.28	0.58	2.11%	0.00	0.00	42.00	700	9.14
40ORW	[52]	1.00	0.93	2.28	0.58	2.11%	0.62	0.00	41.12	695	10.64	
C60	0F44P	Author	1.00	0.32	1.03	0.35	1.00%	0.00	0.00	71.70	614	12.11
	0GGBFS	[42]	1.00	1.58	1.41	0.33	1.60%	0.00	0.00	60.72	690	9.53
	20GGBFS	[42]	1.00	1.97	1.76	0.41	2.00%	0.25	0.00	62.32	700	7.43
	0FA	[42]	1.00	1.58	1.41	0.33	1.60%	0.00	0.00	60.72	690	9.53
	25FA	[42]	1.00	2.15	1.83	0.44	2.14%	0.33	0.00	58.72	740	7.27

3.2.7 Statistical analysis

Response surfaces were drawn to optimize the response variables of mechanical strength (compression and tension), void ratio, ultrasonic pulse velocity and eco-efficiency performance.

A regression equation was found for each response variable, based on Equation 3.4, which estimates the expected values for different proportions powder/total solids and filler/cement ratios, based on the results obtained from the tests. The coefficients of determination (R^2) were found to verify the fit of the regression equations obtained for a significance p-value lower than 0.05. The closer the R^2 value is to 1, the better the fit of the regression equation to the experimental responses.

Equação 3.4

$$y = \beta_0 + \beta_1 a_i + \beta_2 a_i^2 + \beta_3 b_j + \beta_4 b_j^2 + \beta_5 a_i b_j + \varepsilon_{ij}$$

3.3 Results and discussion

3.3.1 Rheological behavior

The viscosity test results on pastes presented in Figure 3.5 show that increasing the cement replacement by filler decreases the plastic viscosity of the mixture.

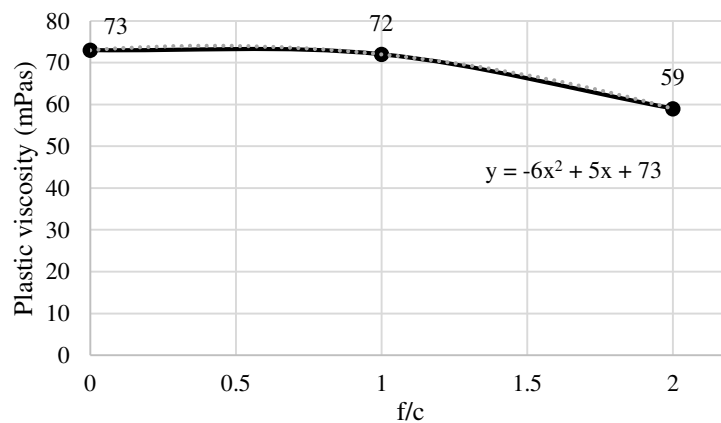


Figure 3.5. Results of the rheological measurements.

The decrease in viscosity in microconcrete with filler caused the occurrence of exudation and segregation with the increase in water consumption. Therefore, to readjust the fluidity and self-compacting characteristics of the mixtures without the need for an increase in water consumption, the superplasticizer dosage was increased. Figure 3.6 shows images of the microconcrete spreading test.

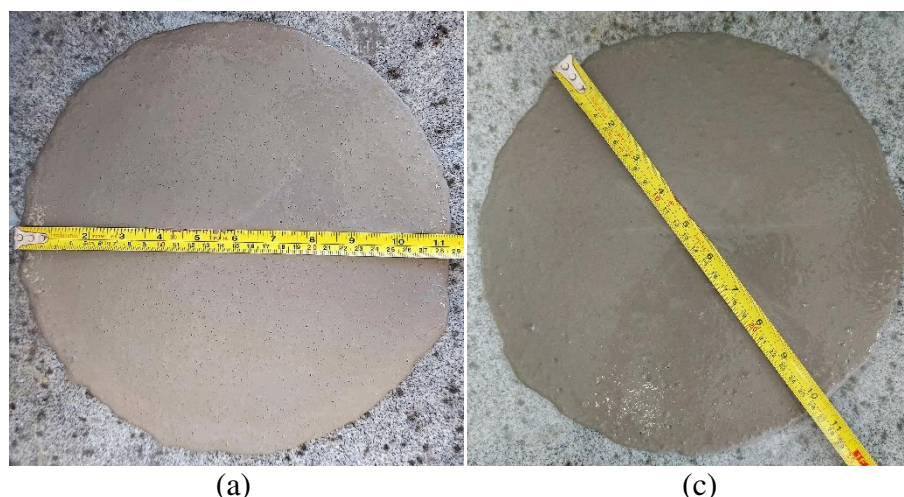


Figure 3.6 – Spreading of the microconcretes (a) 200F40P and (b) 0F44P.

The mini-slump spreading results and the correlation of the results with the slump flow test using the parameter G_m , presented in Table 3.8, show an increase in the workability and fluidity of the mixture when the filler consumption is higher than the cement. Comparing mixes with the same consumption of powder, superplasticizer and water, as in mixes 171F44P, 29F44P and 0F44P, it can be seen that the increase in the filler content increased the spreading and decreased the time to reach 220 mm. These microconcretes with increased filler content proved to be more fluid and less viscous. Therefore, replacing cement with filler does not negatively affect the fluidity of self-compacting concrete when used in large quantities.

Table 3.8 – Microconcretes characteristics in fresh and hardened states.

Trat	Mini-Slump (paste) (mm)	Slump Flow (mm)	T ₂₂₀ (s)	Compressive strength at 28 days (MPa)	Tensile strength in diametrical compression at 28 days (MPa)	Ultrasonic pulse velocity at 28 days (m/s)	Density (kg/m ³)	Void Index (%)	Binder intensity (bi)
200F40P	290	659	4.15	22.31	2.44	4062.20	2.68	26.07	12.98
171F36P	300	682	3.97	23.48	2.39	4015.76	2.73	25.37	12.80
171F44P	320	727	2.6	20.66	2.59	3932.59	2.69	27.95	16.46
100F35P	290	659	5.82	37.71	3.06	4391.09	2.67	23.13	10.48
100F40P	290	659	5.44	36.86	3.70	4376.08	2.68	23.70	11.78
100F45P	300	682	2.75	35.82	3.17	4182.04	2.65	26.03	13.14
29F36P	300	682	5.31	43.32	4.26	4248.30	2.61	19.76	14.53
29F44P	300	682	3.34	45.34	3.67	4063.28	2.62	22.75	15.71
0F44P	270	614	6.5	71.70	6.84	4229.77	2.66	19.64	12.11

3.3.2 Microconcretes performance

The results of compressive strength, tensile strength in diametrical compression and UPV are presented in Table 3.8. Contour and surface plots of compressive strength, tensile strength and UPV are shown in Figure 3.7.

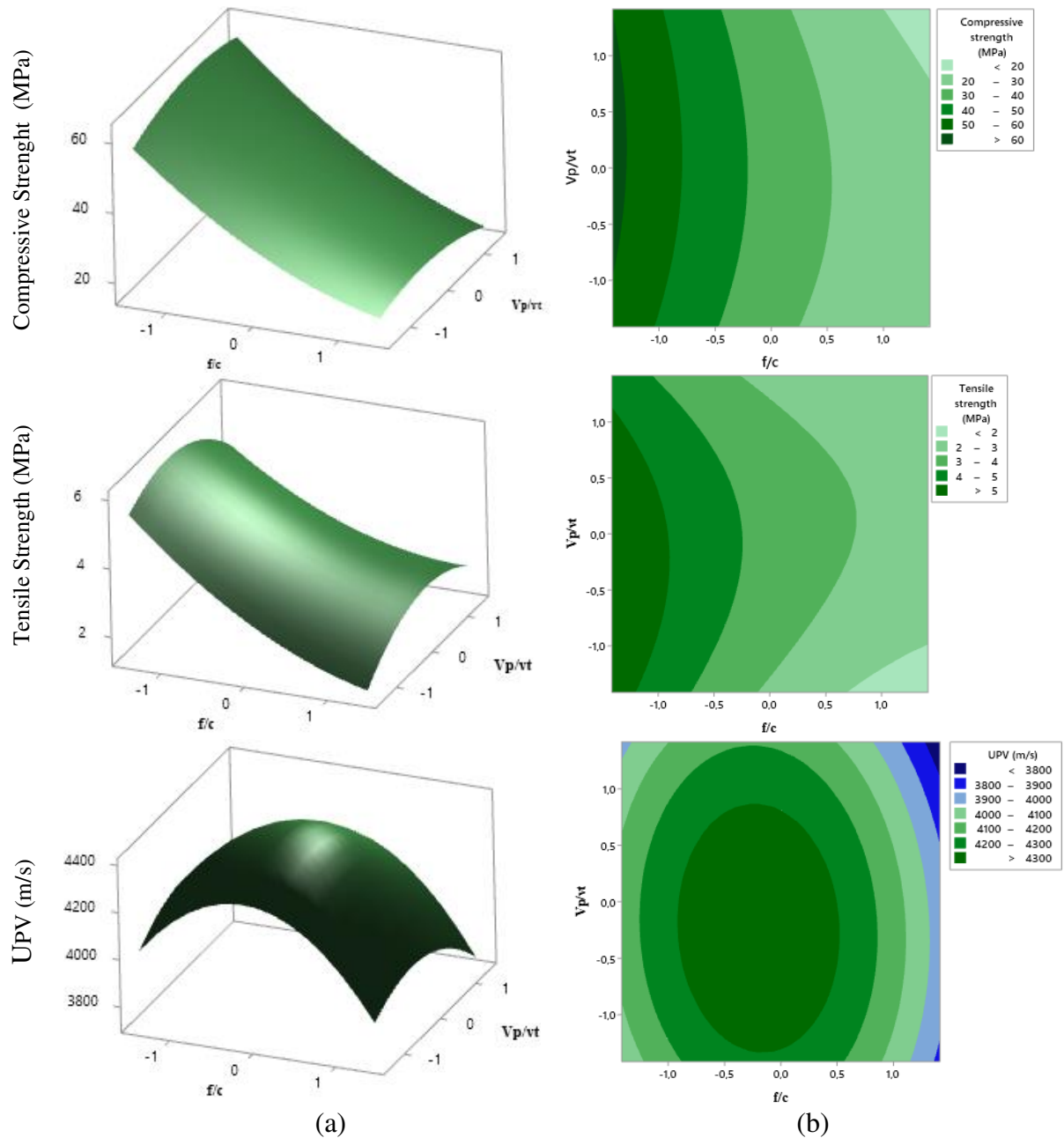


Figure 3.7 – Plots of (a) surface and (b) contour (without adjustments) of results of compressive strength, tensile strength and UPV

The compressive and tensile strengths decrease with increasing filler consumption, given that an inert material partially replaces the cement. However, even at a low proportion of

cement, the concrete with high filler consumption still obtained compressive strength above 20 MPa, considered a structural concrete by the standard NBR 6118:2003 [53].

The analysis of variance showed that the variation of powder and total solids was not significant in the results of compressive strength, tensile strength and UPV. This may be due to the large range of the f/c ratio compared to the small range of the V_p/V_t ratio, reducing the significance of the latter compared to the former. Thus, the variable V_p/V_t was removed from the 3 equations to increase its significance. The coded adjusted equations are presented in Table 3.9, where f/c varies from -1.4 to 1.4 according to the proportions presented in Table 3.1.

Table 3.9 – Coded adjusted regression equations.

Regression equations	ϵ , std.dev.	R^2/R^2_{aj}
$Compressive\ strength\ (MPa) = 33.93 - 14.29\frac{f}{c} + 4.05\left(\frac{f}{c}\right)^2$	5.9924	85.65%/ 84.45%
$Tensile\ strenght\ (MPa) = 3.04 - 1.147\frac{f}{c} + 0.594\left(\frac{f}{c}\right)^2$	0.6894	76.33%/ 74.35%
$UPV\ (MPa) = 4271.9 - 68,2\frac{f}{c} - 121.8\left(\frac{f}{c}\right)^2$	114.669	51.04%/ 46.96%
$Void\ Index\ (\%) = 23.663 + 2.4948\frac{f}{c} + 1.2394\frac{V_p}{V_t} - 0.382\left(\frac{f}{c}\right)^2 + 0.505\left(\frac{V_p}{V_t}\right)^2$	0.4179	98.08%/ 97.73%

It was expected that the increase in the content of aggregates and consequent decrease in powder would negatively affect the mechanical strength. However, the compressive strength results show the opposite when comparing mixtures with similar proportions of cement. Small reductions in powder consumption, keeping the filler/cement ratio fixed, positively affect the mechanical strength of self-compacting concrete. This may be due to small increments in water consumption, as the proportion of water is given about the volume of powder, i.e., the increase in powder consumption consequently increases water consumption, which can negatively affect mechanical strength. This can be observed when comparing the mixtures 100F35P, 100F40P, 100F45P, which have a fixed f/c ratio of 1, and a variation in V_p/V_t of 0.35, 0.40 and 0.45, respectively. The mechanical strength results are lower even though the 100F40P and 100F45P blends have a higher powder consumption compared to 100F35P.

The increase in water consumption in the mixes with the highest amount of powder is reflected in the void ratios of the mixtures, as the increase in V_p/V_t increased the void ratio, as can be seen in the equation presented in Table 3.9 and the graphs of Figure 3.8, adjusted and

withdrawing the non-significant terms. This effect can be observed when comparing the void ratios of mixes with the same f/c content and different V_p/V_t ratios. In this sense, 171F44P (27.95%) had a higher void ratio than 171F36P (25.37%), 29F44P (22.75%) higher than 29F36P (19.76%), and 100F45P (26.03%) higher than 100F40P (23.70%), higher than 100F35P (23.13%). These differences coincide with the differences when compared the PSD curves with the modified Andreassen curve, shown in Figure 3.3, which suggests that mixtures with higher dry packing densities will have lower void ratios. The deviations of the PSD curves to the modified Andreassen curve are shown in Figure 3.9 and compared to the void ratios of the mixtures. Although mixtures with higher powder content present greater adjustments in fine fractions below $6\ \mu\text{m}$, they also present greater deviations to the modified Andreassen curve for fractions between $6\ \mu\text{m}$ and $300\ \mu\text{m}$, and higher void rates, indicating that the adjustment in the proportion of sands is more important than the adjustment in the powder fraction, and higher powder contents decrease the packing of the mixtures, increasing the void index.

The increase in the filler content also strongly influenced the porosity of the mixtures. This may be due to the need for increasing water consumption in the mixes with higher filler contents to maintain workability. However, as the residue is supposed to be inert, part of the water not used in cement hydration remains free, increasing the void ratio of the mixture.

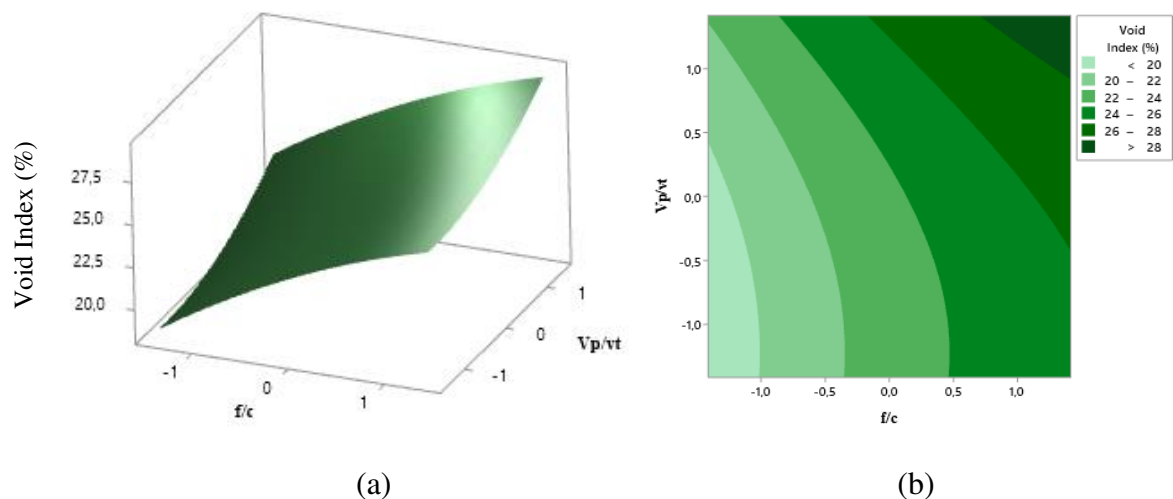


Figure 3.8 – Adjusted graphs of (a) surface and (b) contour for void index.

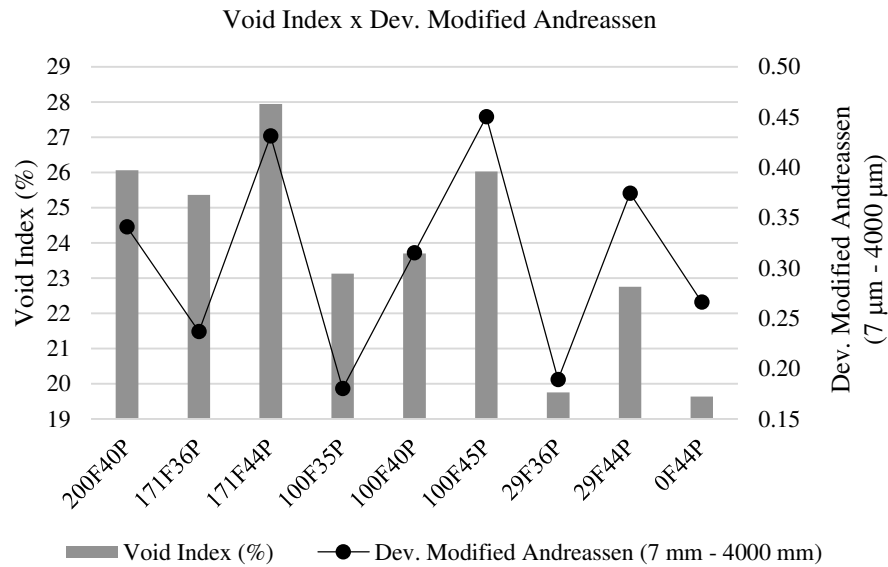


Figure 3.9 – Measured voids indices vs. deviations of the PSD curves to the modified Andreassen curve.

3.3.3 Eco-efficiency performance

3.3.3.1 Performance of the studied mixtures

The environmental impacts weighted by the mechanical performances of the produced microconcretes are presented in Table 3.10. The result of the comparisons of the mixtures through the individual and composite indicators performed through the statistical desirability tool is presented in Table 3.11. The results of the EEP indicator are shown in Figure 3.10 in comparison to the mechanical strengths of the mixtures.

Mixtures with the same f/c present lower EEP results when V_p/V_t is higher due to a similar strength between the mixes and increased cement consumption. Therefore, the packing density of the mixtures was a factor of great impact on the performance of the mixtures by controlling the void index and, consequently, the compressive strength, making small increments of powder negative for the eco-efficiency of the microconcrete, since it reduced the packing density.

The 0F44P mixture showed the best eco-efficiency performance, reaching the average strength of the other mixes, with low cement and high filler consumption. Despite the high consumption of cement in the mixes with a low proportion of filler, the mechanical strength

compensates the impact in terms of mechanical efficiency, showing that the comparison of mixes with a wide range of strengths may not be a good way of evaluating the eco-efficiency of mixes with high replacements of cement by inert waste at the same basis.

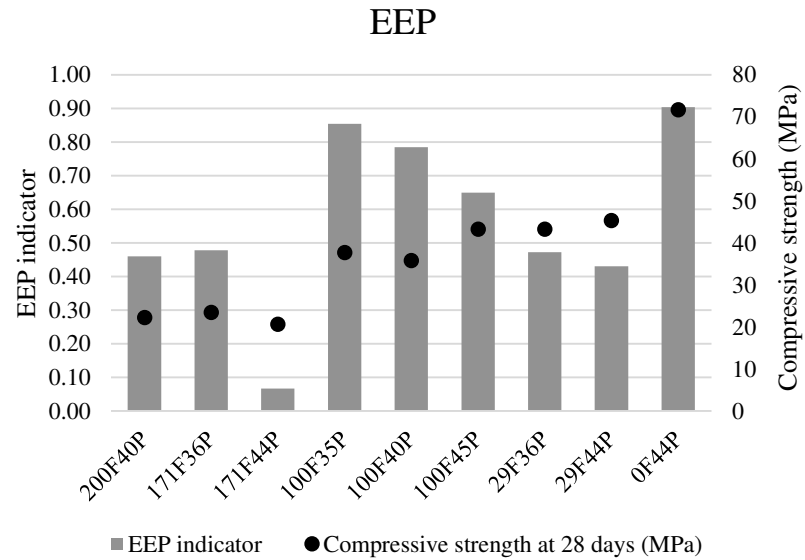


Figure 3.9 – EEP indicators for the produced microconcretes.

Table 3.10 - Ratios between the environmental impacts of each concrete mixture and their compressive strengths.

Identification	TPE/f _c	PRM/f _c	RM/f _c	WC/f _c	GWP/f _c	FAETP/f _c	TETP/f _c	MAETP/f _c	ODP/f _c	EP/f _c	AP/f _c
	MJ/(m ³ .MPa)	kg/(m ³ .MPa)	kg/(m ³ .MPa)	kg H ₂ O/(m ³ .MPa)	kg CO ₂ eq/(m ³ .MPa)	kg 1.4-DB/(m ³ .MPa)	kg 1.4-DB/(m ³ .MPa)	kg 1.4-DB/(m ³ .MPa)	kg 1.4-DB/(m ³ .MPa)	kg (PO ₄) ⁻³ /(m ³ .MPa)	kg (SO ₂)/(m ³ .MPa)
200F40P	68.04	79.44	21.97	69.50	12.75	2.38E-01	1.81E-02	7.16E+02	3.65E-07	3.82E-03	2.51E-02
171F36P	66.88	79.46	18.48	66.84	12.58	2.37E-01	1.78E-02	7.17E+02	3.61E-07	3.78E-03	2.48E-02
171F44P	83.33	84.28	23.76	85.10	15.85	2.58E-01	2.23E-02	7.90E+02	4.38E-07	4.56E-03	3.06E-02
100F35P	54.72	52.70	8.80	51.10	10.16	1.83E-01	1.46E-02	5.37E+02	2.86E-07	3.02E-03	1.99E-02
100F40P	57.46	51.80	9.93	56.56	11.14	1.60E-01	1.55E-02	5.08E+02	2.99E-07	3.09E-03	2.12E-02
100F45P	63.09	51.21	11.07	62.76	12.30	1.61E-01	1.71E-02	5.18E+02	3.24E-07	3.34E-03	2.31E-02
29F36P	69.69	50.11	3.55	64.41	13.48	1.78E-01	1.88E-02	5.62E+02	3.54E-07	3.67E-03	2.54E-02
29F44P	71.69	46.14	3.85	68.79	14.31	1.50E-01	1.96E-02	5.14E+02	3.63E-07	3.69E-03	2.63E-02
0F44P	54.25	32.28	0.00	51.07	10.92	1.06E-01	1.49E-02	3.74E+02	2.73E-07	2.77E-03	1.99E-02

Table 3.11 - Values of individual desirability and values of environmental indicators of each concrete.

Identification	Individual desirability											Composite indicators					
	TPE	PRM	RM	WC	GWP	FAETP	TETP	MAETP	ODP	EP	AP	EIR	MIR	GGR	EPR	AEO	EEP
200F40P	0.53	0.09	0.92	0.46	0.54	0.13	0.54	0.18	0.44	0.41	0.51	0.53	0.49	0.54	0.28	0.46	0.46
171F36P	0.57	0.09	0.78	0.54	0.57	0.14	0.58	0.18	0.47	0.44	0.54	0.57	0.47	0.57	0.30	0.48	0.48
171F44P	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.07
100F35P	0.98	0.61	0.37	1.00	1.00	0.49	1.00	0.61	0.93	0.86	1.00	0.98	0.66	1.00	0.70	0.93	0.85
100F40P	0.89	0.62	0.42	0.84	0.83	0.65	0.88	0.68	0.84	0.82	0.88	0.89	0.63	0.83	0.73	0.85	0.79
100F45P	0.70	0.64	0.47	0.66	0.62	0.64	0.68	0.65	0.69	0.68	0.70	0.70	0.59	0.62	0.66	0.69	0.65
29F36P	0.47	0.66	0.15	0.61	0.42	0.52	0.45	0.55	0.51	0.50	0.49	0.47	0.47	0.42	0.51	0.50	0.47
29F44P	0.40	0.73	0.16	0.48	0.27	0.71	0.36	0.66	0.46	0.49	0.41	0.40	0.46	0.27	0.58	0.45	0.43
0F44P	1.00	1.00	0.00	1.00	0.87	1.00	0.96	1.00	1.00	1.00	1.00	1.00	0.67	0.87	0.99	1.00	0.90

3.3.3.2 Comparison of the mixtures with works of other authors

To compare the mixes produced with other traits of similar strength, mixtures of authors who incorporated residues in self-compacting concrete were used. The mixtures, the results of environmental impacts and the sustainability indicators for the strength classes C20, C30, C40 and C60 are presented in Tables A.3.1, A.3.2, A.3.3, A.3.4, 4.3.5, respectively, in the appendix.

The EEP indicators, separated by strength classes and presented in Figure 3.11, show that mixtures with f/c ratios above 1 become advantageous for low strength classes due to the high content of residue incorporated in the matrix and reduction of environmental impacts associated with the cement production. Compared to traits with the same strengths from other authors, mixtures with high residue incorporation are better even with lower strengths, as shown in Figures 3.11 a and b.

However, even the high mechanical strength of the mixes with low substitutions cannot compensate for the high environmental impact of cement, as shown in Figures 3.11 c and d, e.g., the mixes 29F36P and 0F44P, that had EEP greater than 200F40P and 171F36P (Figure 3.10), presented low eco-efficiency when compared to other mixtures of similar strengths.

Therefore, the high replacement of cement by filler is highly advantageous to the eco-efficiency of concretes that need low mechanical strength, and the mixes with f/c ratios above 1 and V_p/V_t below 0.4 have excellent performance for concrete structures requiring low strengths.

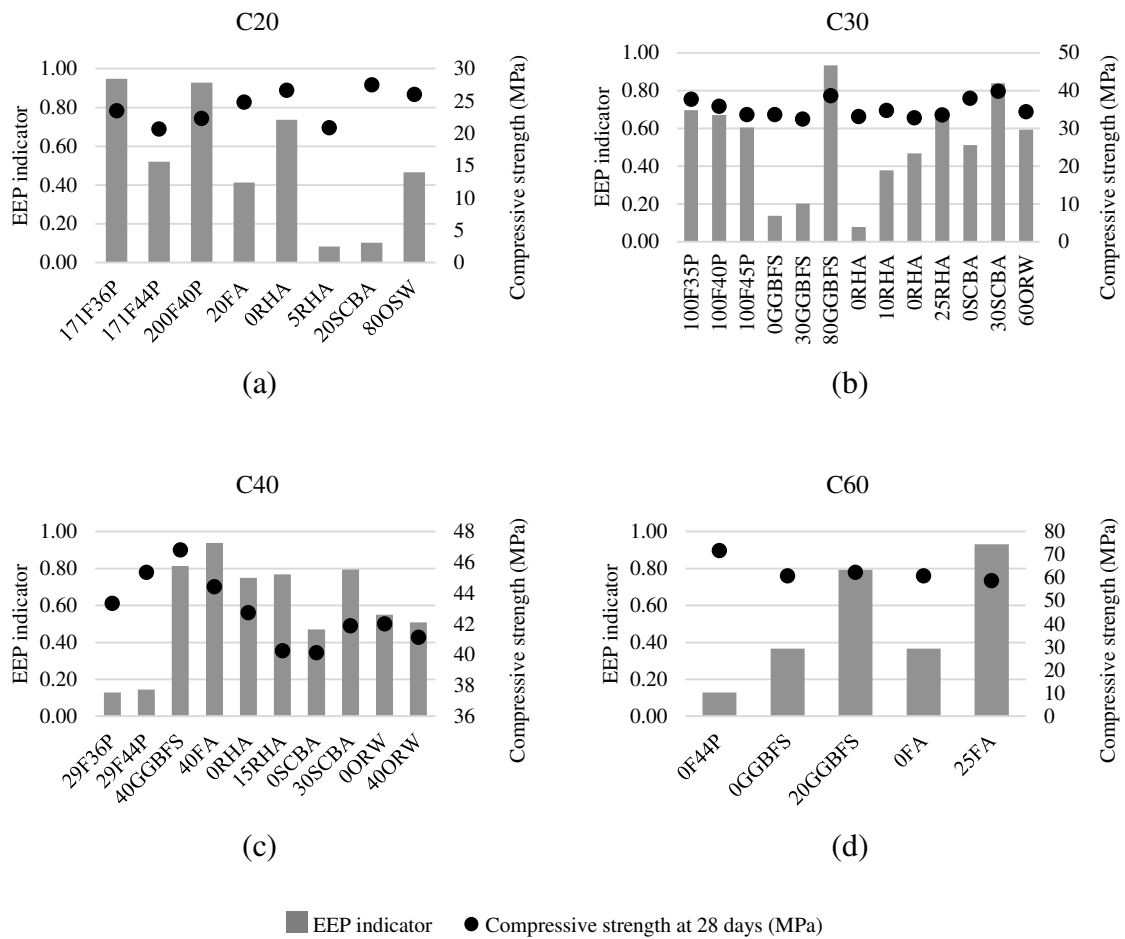


Figure 3.10 –EEP indicator for the SCCs of different strength classes with the incorporation of residues.

3.4 Conclusion

The present work studies ied high incorporation of ornamental rock waste as a filler to replace cement consumption (f/c) and the variation of powder volume (V_p/V_t) in self-compacting microconcrete.

The results showed that the increase in powder consumption in the microconcretes reduced the packing density of the particles, increasing the void index, and consequently, decreasing the mechanical strength. However, the mixtures incorporating ornamental stone residues proved to be effective in reducing cement consumption and increasing eco-efficiency. The inert residue has a good filler function, filling the voids and replacing cement. Despite increasing the porosity of the mixture and decreasing the mechanical strength, the mixtures with filler/cement ratios above 1 reach the minimum mechanical strength for being classified as

structural concrete, and, when compared to SCCs from other authors with the same strength classes, they proved to be more eco-efficient, demonstrating that microconcretes with high rates of cement replacement by waste filler can be feasible and more sustainable.

Acknowledgment

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance code 001. The authors also acknowledge the support provided by the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG), and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). Thanks are also due to the Brazilian Research Groups SIcon-CNPq/UFV and RECICLOS-CNPq/UFOP.

References

- [1] ABIROCHAS, Balanço das Exportações e Importações Brasileiras de Rochas Ornamentais em 2019, ABIROCHAS. 55 (2020).
- [2] M.K. Degen, G.L. Vieira, L. Calmon, J.G. Uliana, R.S. Bastos, Concretos produzidos com resíduos provenientes do beneficiamento de rochas ornamentais como substituto parcial de cimento, An. Do 55o Congr. Bras. Concreto CBC2013. (2013) 1–12.
- [3] P. Danish, G. Mohan Ganesh, Study on influence of Metakaolin and waste marble powder on self-compacting concrete – A state of the art review, Mater. Today Proc. (2020). <https://doi.org/10.1016/j.matpr.2020.11.629>.
- [4] European Parliament and Council, Directive (EU) No 851/2018 - Waste, (2018).
- [5] Brasil, Plano Nacional de Resíduos Sólidos (Lei no 12.305/2010), Bras. Diário Of. Da União. (2011).
- [6] M.A. Rodrigues, J.A.M. Filho, Fabricação de concreto autoadensável com utilização de resíduos de marmorarias como adição mineral, Rev. Eletrônica Eng. Civ. 14 (2017) 50–71.
- [7] E. Bacarji, R.D. Toledo Filho, E.A.B. Koenders, E.P. Figueiredo, J.L.M.P. Lopes, Sustainability perspective of marble and granite residues as concrete fillers, Constr. Build. Mater. 45 (2013) 1–10. <https://doi.org/10.1016/j.conbuildmat.2013.03.032>.
- [8] P.K. Mehta, P.J.M. Monteiro, Concreto: Propriedades e materiais, IBRACON. (2014).

- [9] S. Çankaya, B. Pekey, A comparative life cycle assessment for sustainable cement production in Turkey, *J. Environ. Manage.* 249 (2019). <https://doi.org/10.1016/j.jenvman.2019.109362>.
- [10] J. Lehne, F. Preston, Making concrete change - Innovation in low-carbon cement and concrete, 2018.
- [11] R.M. Andrew, Global CO₂ emissions from cement production, 1928-2018, *Earth Syst. Sci. Data.* 11 (2019) 1675–1710. <https://doi.org/10.5194/essd-11-1675-2019>.
- [12] E. Worrell, L. Price, N. Martin, C. Hendriks, L.O. Meida, Carbon dioxide emissions from the global cement industry, *Annu. Rev. Energy Environ.* 26 (2001) 303–329. <https://doi.org/10.1146/annurev.energy.26.1.303>.
- [13] D.C. Reis, P.C.R.A. Abrão, T. Sui, V.M. John, Influence of cement strength class on environmental impact of concrete, *Resour. Conserv. Recycl.* 163 (2020) 105075. <https://doi.org/10.1016/j.resconrec.2020.105075>.
- [14] Z.S. Ali, M. Hosseinpoor, A. Yahia, New aggregate grading models for low-binder self-consolidating and semi-self-consolidating concrete (Eco-SCC and Eco-semi-SCC), *Constr. Build. Mater.* 265 (2020). <https://doi.org/10.1016/j.conbuildmat.2020.120314>.
- [15] N. Gupta, R. Siddique, R. Belarbi, Sustainable and Greener Self-Compacting Concrete incorporating Industrial By-Products: A Review, *J. Clean. Prod.* 284 (2020). <https://doi.org/10.1016/j.jclepro.2020.124803>.
- [16] P.C.C. GOMES, Optimization and Characterization of High-Strength Self- Compacting Concrete, *Universitat Politècnica de Catalunya*, 2002.
- [17] P.C.C. GOMES, A.R. Barros, Métodos de dosagem de concreto autoadensável, PINI, São Paulo, 2009.
- [18] A.M. Neville, *Propriedades do Concreto*, 5. ed, Bookman, Porto Alegre, 2016.
- [19] H. Okamura, M. Ouchi, Self-Compacting Concrete, *J. Adv. Concr. Technol.* 1 (2003) 5–15.
- [20] EFNARC, The European Guidelines for Self-Compacting Concrete, *Eur. Guidel. Self Compact. Concr.* (2005) 63. <http://www.efnarc.org/pdf/SCCGuidelinesMay2005.pdf>.
- [21] E.M. Lisbôa, Obtenção do concreto auto-adensável utilizando resíduo do beneficiamento do mármore e granito e estudo de propriedades mecânicas, *Dissertação (Mestrado)*, Universidade Federal de Alagoas, 2004. http://www.repositorio.ufal.br/bitstream/riufal/377/1/EdvaldoMonteiroLisboa_Capa_Cap2.pdf.

- [22] B.C. Xavier, Comparação do concreto autoadensável com adição de resíduo de beneficiamento de mármore e granito com o concreto autoadensável convencional, Dissertação (mestrado), Universidade Estadual de Campinas, 2019.
- [23] F. Cavalcante, M.D.S. Silva, L. Brasileiro, Utilização de resíduos de rochas ornamentais em concreto autoadensável, (2019) 0–13.
- [24] M.S. Savadkoohi, M. Reisi, Environmental protection based sustainable development by utilization of granite waste in Reactive Powder Concrete, *J. Clean. Prod.* 266 (2020) 1–12. <https://doi.org/10.1016/j.jclepro.2020.121973>.
- [25] J.M. Franco de Carvalho, T.V. de Melo, W.C. Fontes, J.O. dos S. Batista, G.J. Brigolini, R.A.F. Peixoto, More eco-efficient concrete: An approach on optimization in the production and use of waste-based supplementary cementing materials, *Constr. Build. Mater.* 206 (2019) 397–409. <https://doi.org/10.1016/j.conbuildmat.2019.02.054>.
- [26] A. Lozano-lunar, I. Dubchenko, S. Bashynskiy, A. Rodero, J.M. Fernández, J.R. Jiménez, Performance of self-compacting mortars with granite sludge as aggregate, *Constr. Build. Mater.* 251 (2020) 118998. <https://doi.org/10.1016/j.conbuildmat.2020.118998>.
- [27] J.E. Funk, D.R. Dinger, Particle size control for high-solids castable refractories, *Am. Ceram. Soc. Bull.* (1994).
- [28] R. Sarkar, Particle size distribution for refractory castables: A review, *InterCeram Int. Ceram. Rev.* 65 (2016) 82–86. <https://doi.org/10.1007/bf03401156>.
- [29] R. Vanderlei, Análise experimental do concreto de pós reativos: dosagem e propriedades mecânicas, 2004.
- [30] A.L. de Castro, V.C. Pandolfelli, Revisão: conceitos de dispersão e empacotamento de partículas para a produção de concretos especiais aplicados na construção civil, *Cerâmica.* 55 (2009) 18–32. <https://doi.org/10.1590/s0366-69132009000100003>.
- [31] F.T. Ramal Jr, R.G. Pileggi, J.B. Gallo, V.C. Pandolfelli, A curva de distribuição granulométrica e sua influência na reologia de concretos refratários, *Cerâmica.* 48 (2002) 212–216. <https://doi.org/10.1590/s0366-69132002000400008>.
- [32] ABNT, NBR 7222: Concreto e argamassa — Determinação da resistência à tração por compressão diametral de corpos de prova cilíndricos, Assoc. Bras. Normas Técnicas - Rio Janeiro. (2011).
- [33] ABNT, NBR 5739: Concreto - Ensaio de compressão de corpos de prova cilíndricos, Assoc. Bras. Normas Técnicas. (2018).
- [34] ASTM, C39/C39M: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, *Annu. B. ASTM Stand.* (2010) 1–7. <https://doi.org/10.1520/C0039>.

- [35] ABNT, NBR 8802: Concreto endurecido — Determinação da velocidade de propagação de onda ultrassônica, Associação Brasileira de Normas Técnicas - ABNT, 2019.
- [36] ASTM, C597 - 16 Standard Test Method for Pulse Velocity Through Concrete, Am. Soc. Test. Mater. - ASTM. (2016) 4. <https://doi.org/10.1520/C0597-16.2>.
- [37] ABNT, NBR 9778: Argamassa e concreto endurecidos -Determinação da absorção de água, índice de vazios e massa específica, Assoc. Bras. Normas Técnicas. (2011).
- [38] B.L. Damireli, F.M. Kemeid, P.S. Aguiar, V.M. John, Measuring the eco-efficiency of cement use, *Cem. Concr. Compos.* 32 (2010) 555–562. <https://doi.org/10.1016/j.cemconcomp.2010.07.009>.
- [39] A. Miranda de Souza, G.E. Soares de Lima, G.H. Nalon, M.M. Salgado Lopes, A. Luís de Oliveira Júnior, G.J. Rodrigues Lopes, M. José de Andrade Olivier, L.G. Pedroti, J.C. Lopes Ribeiro, J.M. Franco de Carvalho, Application of the desirability function for the development of new composite eco-efficiency indicators for concrete, *J. Build. Eng.* (2021) 102374. <https://doi.org/10.1016/j.jobbe.2021.102374>.
- [40] O.M. Ofuyatan, A.G. Adeniyi, D. Ijie, J.O. Ighalo, J. Oluwafemi, Development of high-performance self compacting concrete using eggshell powder and blast furnace slag as partial cement replacement, *Constr. Build. Mater.* 256 (2020) 119403. <https://doi.org/10.1016/j.conbuildmat.2020.119403>.
- [41] P. Dinakar, K.P. Sathy, U.C. Sahoo, Design of self-compacting concrete with ground granulated blast furnace slag, *Mater. Des.* 43 (2013) 161–169. <https://doi.org/10.1016/j.matdes.2012.06.049>.
- [42] M. Uysal, M. Sumer, Performance of self-compacting concrete containing different mineral admixtures, *Constr. Build. Mater.* 25 (2011) 4112–4120. <https://doi.org/10.1016/j.conbuildmat.2011.04.032>.
- [43] H. Zhao, W. Sun, X. Wu, B. Gao, The properties of the self-compacting concrete with fly ash and ground granulated blast furnace slag mineral admixtures, *J. Clean. Prod.* 95 (2015) 66–74. <https://doi.org/10.1016/j.jclepro.2015.02.050>.
- [44] A. Jain, R. Gupta, S. Chaudhary, Sustainable development of self-compacting concrete by using granite waste and fly ash, *Constr. Build. Mater.* 262 (2020). <https://doi.org/10.1016/j.conbuildmat.2020.120516>.
- [45] M. Hamza Hasnain, U. Javed, A. Ali, M. Saeed Zafar, Eco-friendly utilization of rice husk ash and bagasse ash blend as partial sand replacement in self-compacting concrete, *Constr. Build. Mater.* 273 (2021) 121753. <https://doi.org/10.1016/j.conbuildmat.2020.121753>.
- [46] V. Kannan, K. Ganesan, Chloride and chemical resistance of self compacting concrete containing rice husk ash and metakaolin, *Constr. Build. Mater.* 51 (2014) 225–234. <https://doi.org/10.1016/j.conbuildmat.2013.10.050>.

- [47] E. Molaei Raisi, J. Vaseghi Amiri, M.R. Davoodi, Mechanical performance of self-compacting concrete incorporating rice husk ash, *Constr. Build. Mater.* 177 (2018) 148–157. <https://doi.org/10.1016/j.conbuildmat.2018.05.053>.
- [48] A.S. Gill, R. Siddique, Strength and micro-structural properties of self-compacting concrete containing metakaolin and rice husk ash, *Constr. Build. Mater.* 157 (2017) 51–64. <https://doi.org/10.1016/j.conbuildmat.2017.09.088>.
- [49] T. Akram, S.A. Memon, H. Obaid, Production of low cost self compacting concrete using bagasse ash, *Constr. Build. Mater.* 23 (2009) 703–712. <https://doi.org/10.1016/j.conbuildmat.2008.02.012>.
- [50] L.C. Larissa, M.A. Marcos, M. V. Maria, N. S. L. de Souza, E.C. de Farias, Effect of high temperatures on self-compacting concrete with high levels of sugarcane bagasse ash and metakaolin, *Constr. Build. Mater.* 248 (2020) 118715. <https://doi.org/10.1016/j.conbuildmat.2020.118715>.
- [51] D.H. Le, Y.N. Sheen, M.N.T. Lam, Fresh and hardened properties of self-compacting concrete with sugarcane bagasse ash–slag blended cement, *Constr. Build. Mater.* 185 (2018) 138–147. <https://doi.org/10.1016/j.conbuildmat.2018.07.029>.
- [52] T. Uygunođlu, I.B. Topđu, A.G. Çelik, Use of waste marble and recycled aggregates in self-compacting concrete for environmental sustainability, *J. Clean. Prod.* 84 (2014) 691–700. <https://doi.org/10.1016/j.jclepro.2014.06.019>.
- [53] ABNT, NBR 6118: Projeto de estruturas de concreto — Procedimento, Assoc. Bras. Normas Técnicas. (2014).

APPENDIX

Table A.3.1 - Ratio between the environmental impacts of each concrete mixture and its compressive strength.

Identification	Reference	TPE/f _c	PRM/f _c	RM/f _c	WC/f _c	GWP/f _c	FAETP/f _c	TETP/f _c	MAETP/f _c	ODP/f _c	EP/f _c	AP/f _c
		MJ/(m ³ .MPa)	kg/(m ³ .MPa)	kg/(m ³ .MPa)	kg H ₂ O /(m ³ .MPa)	kg CO ₂ eq /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg 1.4-DB /(m ³ .MPa)	kg (PO ₄) ⁻³ /(m ³ .MPa)	kg (SO ₂) /(m ³ .MPa)
171F36P	Autor	66.88	79.46	18.48	66.84	12.58	2.37E-01	1.78E-02	7.17E+02	3.61E-07	3.78E-03	2.48E-02
171F44P	Autor	83.33	84.28	23.76	85.10	15.85	2.58E-01	2.23E-02	7.90E+02	4.38E-07	4.56E-03	3.06E-02
200F40P	Autor	68.04	79.44	21.97	69.50	12.75	2.38E-01	1.81E-02	7.16E+02	3.65E-07	3.82E-03	2.51E-02
20FA	[44]	87.09	94.22	4.51	79.73	16.97	2.16E-01	2.33E-02	7.30E+02	4.86E-07	4.58E-03	3.28E-02
0RHA	[45]	72.31	96.50	0.00	63.99	13.97	2.31E-01	1.92E-02	7.48E+02	4.14E-07	4.05E-03	2.78E-02
5RHA	[45]	94.40	118.04	4.30	81.12	18.12	2.94E-01	2.50E-02	1.01E+03	5.39E-07	5.37E-03	3.65E-02
20SCBA	[49]	100.41	84.66	3.57	81.84	17.86	3.08E-01	2.61E-02	9.10E+02	5.28E-07	5.44E-03	3.67E-02
80OSW	[52]	87.25	69.92	20.60	80.47	16.17	2.82E-01	2.33E-02	8.19E+02	4.43E-07	4.76E-03	3.14E-02
100F35P	Author	54.72	52.70	8.80	51.10	10.16	1.83E-01	1.46E-02	5.37E+02	2.86E-07	3.02E-03	1.99E-02
100F40P	Author	57.46	51.80	9.93	56.56	11.14	1.60E-01	1.55E-02	5.08E+02	2.99E-07	3.09E-03	2.12E-02
100F45P	Author	63.09	51.21	11.07	62.76	12.30	1.61E-01	1.71E-02	5.18E+02	3.24E-07	3.34E-03	2.31E-02
0GGBFS	[40]	86.11	74.53	0.00	82.15	17.92	1.63E-01	2.37E-02	6.43E+02	4.62E-07	4.48E-03	3.27E-02
30GGBFS	[40]	82.94	73.23	6.42	79.41	15.36	2.14E-01	2.06E-02	7.27E+02	4.11E-07	4.78E-03	3.87E-02
80GGBFS	[41]	38.25	49.90	11.67	46.63	5.38	1.38E-01	6.78E-03	4.48E+02	1.57E-07	2.79E-03	2.84E-02
0RHA	[48]	91.78	73.00	0.00	71.95	15.43	3.30E-01	2.34E-02	8.33E+02	4.70E-07	4.94E-03	3.24E-02
10RHA	[48]	72.43	66.90	2.76	65.11	14.08	1.73E-01	1.93E-02	6.03E+02	3.95E-07	3.88E-03	2.75E-02
0RHA	[46]	63.00	74.17	0.00	58.53	12.25	1.72E-01	1.68E-02	5.63E+02	3.52E-07	3.40E-03	2.40E-02
25RHA	[46]	49.32	68.33	3.10	44.49	9.34	1.54E-01	1.29E-02	5.27E+02	2.90E-07	2.82E-03	1.93E-02
0SCBA	[50]	62.13	64.29	0.00	54.94	11.67	1.91E-01	1.64E-02	5.79E+02	3.35E-07	3.38E-03	2.31E-02
30SCBA	[50]	41.52	57.67	3.48	37.77	8.14	1.16E-01	1.10E-02	4.59E+02	2.43E-07	2.39E-03	1.64E-02
60ORW	[52]	61.99	57.01	11.77	59.74	12.07	1.77E-01	1.68E-02	5.66E+02	3.25E-07	3.36E-03	2.29E-02
29F36P	Author	69.69	50.11	3.55	64.41	13.48	1.78E-01	1.88E-02	5.62E+02	3.54E-07	3.67E-03	2.54E-02
29F44P	Author	71.69	46.14	3.85	68.79	14.31	1.50E-01	1.96E-02	5.14E+02	3.63E-07	3.69E-03	2.63E-02
40GGBFS	[43]	37.60	50.08	4.15	38.47	6.84	1.18E-01	8.95E-03	4.10E+02	1.94E-07	2.34E-03	1.95E-02
40FA	[43]	32.57	51.71	4.29	29.51	6.27	1.08E-01	8.64E-03	3.65E+02	1.97E-07	1.82E-03	1.25E-02
0RHA	[47]	42.68	53.40	5.42	39.38	8.42	1.03E-01	1.12E-02	3.69E+02	2.48E-07	2.25E-03	1.65E-02
15RHA	[47]	41.29	54.81	7.10	36.42	7.83	1.17E-01	1.06E-02	4.01E+02	2.44E-07	2.25E-03	1.61E-02
0SCBA	[51]	52.84	56.15	2.99	47.97	9.97	1.45E-01	1.40E-02	4.57E+02	2.91E-07	2.79E-03	1.96E-02
30SCBA	[51]	40.42	50.44	5.82	34.21	7.20	1.28E-01	1.04E-02	4.29E+02	2.32E-07	2.26E-03	1.53E-02
0ORW	[52]	46.52	58.27	0.00	42.26	8.84	1.41E-01	1.23E-02	4.43E+02	2.62E-07	2.55E-03	1.77E-02
40ORW	[52]	52.75	51.08	6.58	49.84	10.17	1.54E-01	1.42E-02	4.87E+02	2.79E-07	2.87E-03	1.95E-02

0F44P	Author	54.25	32.28	0.00	51.07	10.92	1.06E-01	1.49E-02	3.74E+02	2.73E-07	2.77E-03	1.99E-02
0GGBFS	[42]	46.01	41.36	0.00	41.11	8.95	1.12E-01	1.23E-02	3.67E+02	2.47E-07	2.42E-03	1.72E-02
20GGBFS	[42]	39.97	38.36	1.86	37.25	7.42	1.06E-01	1.01E-02	3.42E+02	2.07E-07	2.23E-03	1.72E-02
0FA	[42]	46.01	41.36	0.00	41.11	8.95	1.12E-01	1.23E-02	3.67E+02	2.47E-07	2.42E-03	1.72E-02
25FA	[42]	37.63	39.55	2.43	32.52	6.98	1.07E-01	9.88E-03	3.27E+02	2.08E-07	1.99E-03	1.39E-02

Table A.3.2 - Values of individual desirability and values of environmental indicators of each concrete in C20.

Identification	Reference	Individual desirability										Composite indicators							
		TPE	PRM	RM	WC	GWP	FAETP	TETP	MAETP	ODP	EP	AP	EIR	MIR	GGR	EPR	AEO	EEP	
171F36P	Autor	1.00	0.80	0.78	0.87	1.00	0.77	1.00	1.00	1.00	1.00	1.00	1.00	0.81	1.00	0.92	1.00	0.95	
171F44P	Autor	0.51	0.70	1.00	0.00	0.41	0.54	0.45	0.75	0.57	0.53	0.51	0.51	0.57	0.41	0.58	0.53	0.52	
200F40P	Autor	0.97	0.80	0.92	0.74	0.97	0.76	0.96	1.00	0.98	0.97	0.97	0.97	0.82	0.97	0.91	0.97	0.93	
20FA	[44]	0.40	0.50	0.19	0.25	0.21	1.00	0.34	0.95	0.30	0.52	0.32	0.40	0.31	0.21	0.76	0.38	0.41	
0RHA	[45]	0.84	0.45	0.00	1.00	0.75	0.83	0.83	0.89	0.70	0.84	0.75	0.84	0.48	0.75	0.85	0.76	0.74	
5RHA	[45]	0.18	0.00	0.18	0.19	0.00	0.15	0.12	0.00	0.00	0.04	0.01	0.18	0.12	0.00	0.09	0.02	0.08	
20SCBA	[49]	0.00	0.69	0.15	0.15	0.05	0.00	0.00	0.34	0.06	0.00	0.00	0.00	0.33	0.05	0.11	0.02	0.10	
80OSW	[52]	0.39	1.00	0.87	0.22	0.35	0.28	0.34	0.65	0.54	0.41	0.44	0.39	0.70	0.35	0.42	0.46	0.47	

Table A.3.3 - Values of individual desirability and values of environmental indicators of each concrete in C30.

Identification	Reference	Individual desirability										Composite indicators							
		TPE	PRM	RM	WC	GWP	FAETP	TETP	MAETP	ODP	EP	AP	EIR	MIR	GGR	EPR	AEO	EEP	
100F35P	Author	0.69	0.89	0.75	0.70	0.62	0.69	0.54	0.77	0.59	0.75	0.84	0.69	0.78	0.62	0.67	0.73	0.70	
100F40P	Author	0.64	0.92	0.84	0.58	0.54	0.80	0.48	0.85	0.54	0.72	0.79	0.64	0.78	0.54	0.71	0.69	0.67	
100F45P	Author	0.54	0.95	0.94	0.44	0.45	0.79	0.39	0.82	0.46	0.63	0.70	0.54	0.77	0.45	0.67	0.60	0.60	
0GGBFS	[40]	0.11	0.00	0.00	0.00	0.00	0.78	0.00	0.49	0.03	0.18	0.27	0.11	0.00	0.00	0.42	0.16	0.14	
30GGBFS	[40]	0.17	0.05	0.55	0.06	0.20	0.54	0.18	0.27	0.19	0.06	0.00	0.17	0.22	0.20	0.33	0.08	0.20	
80GGBFS	[41]	1.00	1.00	0.99	0.80	1.00	0.90	1.00	1.00	1.00	0.84	0.46	1.00	0.93	1.00	0.97	0.77	0.93	
0RHA	[48]	0.00	0.06	0.00	0.23	0.20	0.00	0.02	0.00	0.00	0.00	0.28	0.00	0.10	0.20	0.01	0.09	0.08	
10RHA	[48]	0.36	0.31	0.23	0.38	0.31	0.74	0.26	0.60	0.24	0.42	0.50	0.36	0.31	0.31	0.53	0.39	0.38	
0RHA	[46]	0.54	0.01	0.00	0.53	0.45	0.74	0.41	0.70	0.38	0.60	0.66	0.54	0.18	0.45	0.62	0.55	0.47	
25RHA	[46]	0.79	0.25	0.26	0.85	0.68	0.82	0.64	0.80	0.57	0.83	0.87	0.79	0.45	0.68	0.75	0.76	0.69	
0SCBA	[50]	0.55	0.42	0.00	0.61	0.50	0.65	0.43	0.66	0.43	0.61	0.70	0.55	0.34	0.50	0.58	0.58	0.51	
30SCBA	[50]	0.94	0.68	0.30	1.00	0.78	1.00	0.75	0.97	0.72	1.00	1.00	0.94	0.66	0.78	0.91	0.91	0.84	
60ORW	[52]	0.56	0.71	1.00	0.51	0.47	0.72	0.41	0.70	0.46	0.62	0.71	0.56	0.74	0.47	0.61	0.60	0.59	

Table A.3.4 - Values of individual desirability and values of environmental indicators of each concrete in C40.

Identification	Reference	Individual desirability									Composite indicators							
		TPE	PRM	RM	WC	GWP	FAETP	TETP	MAETP	ODP	EP	AP	EIR	MIR	GGR	EPR	AEO	EEP
29F36P	Author	0.05	0.67	0.50	0.11	0.10	0.00	0.07	0.00	0.05	0.01	0.06	0.05	0.43	0.10	0.02	0.04	0.13
29F44P	Author	0.00	1.00	0.54	0.00	0.00	0.38	0.00	0.24	0.00	0.00	0.00	0.00	0.51	0.00	0.21	0.00	0.14
40GGBFS	[43]	0.87	0.68	0.58	0.77	0.93	0.80	0.97	0.77	1.00	0.72	0.49	0.87	0.68	0.93	0.85	0.74	0.81
40FA	[43]	1.00	0.54	0.60	1.00	1.00	0.93	1.00	1.00	0.98	1.00	1.00	1.00	0.71	1.00	0.98	0.99	0.94
0RHA	[47]	0.74	0.40	0.76	0.75	0.73	1.00	0.77	0.98	0.68	0.77	0.71	0.74	0.64	0.73	0.92	0.72	0.75
15RHA	[47]	0.78	0.29	1.00	0.82	0.81	0.82	0.82	0.82	0.70	0.77	0.74	0.78	0.70	0.81	0.82	0.74	0.77
0SCBA	[51]	0.48	0.17	0.42	0.53	0.54	0.44	0.51	0.53	0.42	0.48	0.48	0.48	0.38	0.54	0.50	0.46	0.47
30SCBA	[51]	0.80	0.65	0.82	0.88	0.88	0.67	0.84	0.68	0.78	0.77	0.80	0.80	0.78	0.88	0.73	0.78	0.79
0ORW	[52]	0.64	0.00	0.00	0.68	0.68	0.50	0.67	0.60	0.60	0.61	0.63	0.64	0.23	0.68	0.59	0.61	0.55
40ORW	[52]	0.48	0.59	0.93	0.48	0.52	0.32	0.49	0.38	0.49	0.44	0.49	0.48	0.67	0.52	0.40	0.47	0.51

Table A.3.5 - Values of individual desirability and values of environmental indicators of each concrete in C60.

Identification	Reference	Individual desirability									Composite indicators							
		TPE	PRM	RM	WC	GWP	FAETP	TETP	MAETP	ODP	EP	AP	EIR	MIR	GGR	EPR	AEO	EEP
0F44P	Author	0.00	1.00	0.00	0.00	0.00	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.31	0.00	0.13
0GGBFS	[42]	0.50	0.00	0.00	0.54	0.50	0.00	0.51	0.15	0.40	0.45	0.45	0.50	0.18	0.50	0.22	0.44	0.37
20GGBFS	[42]	0.86	0.33	0.76	0.74	0.89	1.00	0.95	0.69	1.00	0.70	0.46	0.86	0.61	0.89	0.88	0.72	0.79
0FA	[42]	0.50	0.00	0.00	0.54	0.50	0.00	0.51	0.15	0.40	0.45	0.45	0.50	0.18	0.50	0.22	0.44	0.37
25FA	[42]	1.00	0.20	1.00	1.00	1.00	0.80	1.00	1.00	0.98	1.00	1.00	1.00	0.73	1.00	0.93	0.99	0.93

CHAPTER 4 - Influence of filler/cement and lightweight aggregate /conventional aggregate ratios in the design of lightweight aggregate self-compacting concrete mixtures containing waste from the ornamental stone industry

Abstract

The present work aimed to study the rheological, physical, mechanical, and eco-efficiency behavior of self-compacting microconcretes with replacement of conventional aggregates by lightweight aggregates from expanded polystyrene (LWA) waste, and replacement of cement binder by filler from ornamental stone waste (OSW). The dosage was performed using the particle packing methodology, and the mixtures were prepared following a second-order composite project. Fresh and hardened tests were performed and analyzed by response surfaces. Mixtures with high LWA incorporations showed signs of segregation, and the two residues reduced the mechanical strength of the microconcretes. However, the results showed that LWA can reduce the density of microconcrete, and OSW increases workability and decreases matrix viscosity, which can serve to control segregation by reducing the water consumption required in the mixtures without loss of water in fluidity.

Keywords: Lightweight aggregate self-compacting microconcrete. Ornamental stone waste. Expanded polystyrene waste. Lightweight aggregates.

4.1 Introduction

To reduce the weight of concrete elements and obtain more fluid mixtures, lightweight aggregates self-compacting concrete (LWASCC) have been studied for structural and sealing purposes in slender pieces with high reinforcement rates. [1–3]. Many research involving lightweight aggregates (LWA), natural or artificial, are carried out to understand the behavior of these aggregates in the cement matrix, reducing the density of the concrete from 2400 kg/m³ to values below 2000 kg/m³ [4–9].

The reduction of the specific mass maintaining the mechanical strength permits to reduce the weight of structural elements, reducing the loads transferred to the foundation, and saving costs for using lighter equipment for lifting the pieces. [2,3,10,11]. In addition to driving the growth of sustainable building construction, soundproof and thermally insulating green buildings, using low-density and low-cost materials [2].

However, the low density of LWA leads to a reduction in the mechanical strength of LWASCC making it necessary a large volume of cement to ensure structural strength, which implies the low environmental efficiency of these concretes due to the high energy expenditure in the production of cement, which accounts for around 7% of global emissions of carbon dioxide (CO₂) in the atmosphere [1,12–20].

Problems with segregation and exudation can occur in the production of self-compacting concrete containing LWA due to the low density that favors the float of the aggregates, absorption of the mixing water and, consequently the admixtures, making it difficult to spread and self-consolidate the mixture, resulting in loss of mechanical strength [1,3,5–7]. The problem of segregation can be overcome by dosing the concrete so that it has adequate cohesion and consistency and a paste with higher yield strength, which can be achieved by controlling the water/cement factor, fine aggregate content, the addition of minerals, and incorporation of viscosity-modifying admixtures [1,3,6].

The use of filler can also become a viable alternative in low-density self-compacting concretes to increase the cohesion of the mixture and prevent the segregation and flotation of light aggregates. [3,12,21–24]. A material prone to being used as a filler is ornamental stone

waste (OSW), which has a fine granulometry. This material is produced in high volumes annually and can be absorbed in civil construction. [25–27].

The studies found in the literature only relate the use of OSW to lightweight concrete, as Zafar et al. [28], who studied the use of granite residue in autoclaved concrete as a substitute for sand and observed a low pozzolanic action but an increase in the packing density of the mixtures, in concrete density, in mechanical strength, strong acid resistance, and a decrease in porosity and absorption. Alyousef et al. [29] studied the replacement of sand by marble residue in lightweight concrete floor blocks containing expanded perlite and verified an increase in concrete density and strength and the possibility of being used as insulation blocks.

However, few studies incorporate OSW into lightweight aggregate self-compacting microconcrete (without coarse aggregate). So, this study aimed to investigate the effects of partial replacement of cement by ornamental stone waste on lightweight aggregate self-compacting microconcrete's physical and mechanical behavior using expanded polystyrene residue as aggregate and reducing cement consumption, contributing to the production of a more sustainable material.

4.2 Experimental

4.2.1 Materials

To manufacture lightweight aggregate self-compacting microconcretes (LWASCM), expanded polystyrene waste was used as lightweight aggregate (LWA). Ornamental stone waste (OSW) provided by a manufacturer in Cachoeiro de Itapemirim, Espírito Santo State, Brazil, was used as a filler. A high early strength Portland cement (PC) CPV-ARI was used as a binder. Two conventional aggregates were used: natural quartz river sand (R-Sand) and manufactured gneiss sand (M-Sand) from the region of Viçosa, Minas Gerais State, Brazil. A commercial superplasticizer was used as a water reducer based on polycarboxylate ether (PCE).

Tables 4.1-4.3 present the physical properties of cement and OSW, the chemical properties of OSW, and the physical properties of aggregates, respectively. Figure 4.1 shows the granulometric distribution of the materials, and Figure 4.2 shows the image of the LWA.

Table 4.1 – Physical properties of the PC and OSW.

Material	Specific density (g/cm³)	Specific surface area (Blaine) (cm²/g)
PC	3.15	2135.81
OSW	2.60	2996.11
M-sand	2.86	-
R-sand	2.63	-
Superplasticizer	1.09	-

Table 4.2 – Chemical composition of the OSW.

Compound	OSW
SiO ₂ content. %	74.5
CO ₂ content. %	8.1
Al ₂ O ₃ content. %	5.3
CaO content. %	5.0
MgO content. %	3.5
Na ₂ O content. %	1.7
K ₂ O content. %	1.0
Fe ₂ O ₃ content. %	0.6
TiO ₂ content. %	0.1
Other oxides. %	0.1

Table 4.3 – Physical properties of the M-Sand, R-Sand and LWA.

Material	Bulk density (g/cm³)
M-Sand	1.556
R-Sand	1.428
LWA	5.213E-03

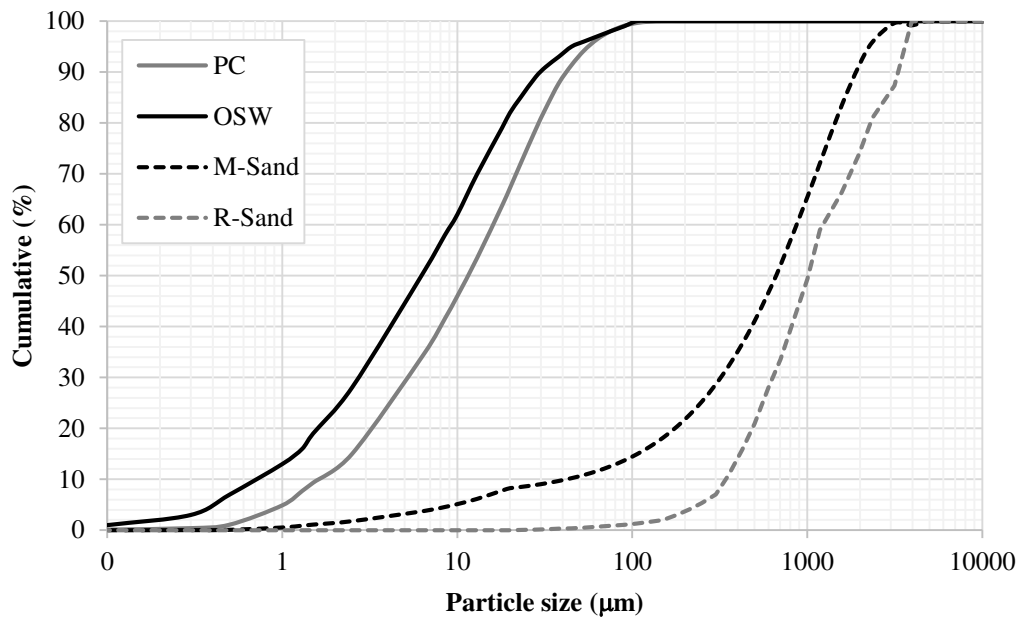


Figure 4.1 – Granulometric curves of materials.



Figure 4.2 – Lightweight aggregates.

4.2.2 Experimental design

The LWASCM were designed to fit all materials used to a granulometric curve similar to the modified Andreassen packing curve [30]. The modified Andreassen packing curve is obtained using Equation 4.1. where $CPFT$ is the accumulated percentage of particles with a diameter smaller than D (by volume); D is the particle size; D_L is the diameter of the largest particle; D_S is the diameter of the smallest particle; and q is the distribution coefficient (q -value).

Equation 4.1

$$CPTF (\%) = 100 \left(\frac{D^q - D_S^q}{D_L^q - D_S^q} \right)$$

The powder and aggregates content was obtained by fitting the modified Andreassen curve so that the powder, fine and coarse aggregates met the limits suggested by EFNARC [22]. For this, the distribution coefficient should be between 0.20 and 0.23; then, 0.2 was used to better fit the curve and provide a higher content of fines to increase the mixture's viscosity, maintain workability, and reduce the tendency to segregation of lightweight aggregates [31–34].

With the data obtained from the modified Andreassen curve adjustment, a proportion of sands of 1:3 (R-Sand/M-Sand) was established, and a proportion of the powder volume to total solid volume ratio (V_p/V_t) of 35 %. Once the dosage limits were established, filler/cement (f/c) volume ratios were defined between 0 and 200%, and light aggregates/conventional aggregates (V_{LWA}/V_{CA}) between 0% and 60%. For the calculations of V_{LWA}/V_{CA} , bulk density was used as converting parameter due to the small density of the residue and the difficulty of measuring its specific mass.

The mixtures proportions were defined following a second-order composite project (as illustrated in Figure 4.3 and presented in Table 4.4). The proportions of the mixtures by volume of dry materials of the LWASCM and the mass consumptions are presented in Table 4.5. The water/powder ratio was adjusted to a spread of 270 mm (± 10 mm) in the mini-slump test to obtain mixtures that showed no exudation and segregation. The superplasticizer content was set at 1% of the mass of the total powder content. The superplasticizer was added and accounted into the mixing water.

The mini-slump test was adapted using a cone with diameters of 41 mm and 91 mm and 75 mm of height for a spreading diameter of 220 mm, and the results were compared through the fluidity parameter G_m obtained by Equation 4.2 proposed by Okamura [23], where D_m is the spreading diameter, and D_0 is the inner diameter of the base of the cone [21,22].

Equation 4.2

$$G_m = \left(\frac{D_m}{D_0}\right)^2 - 1$$

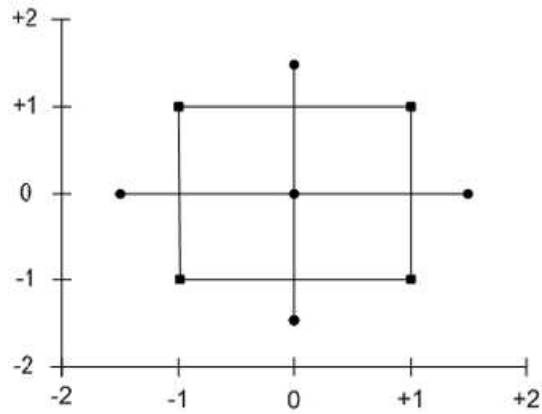


Figure 4.3 - second-order composite

Table 4.4 - Levels of variables used in LWASCC.

Proportions	-1,4142	-1	0	1	1.4142
Filler/cement (f/c)	0	0.29	1	1.71	2
Lightweight aggregates/ Convencional aggregates (V_{LWA}/V_{CA})	0	0.0879	0.3	0.512	0.6

Table 4.5 - Mixtures of LWASCM (PC - Portland Cement; OSW - ornamental stone waste; M-Sand - artificial sand; R-Sand - river sand; LWA - lightweight aggregate; W- water; SP - superplasticizer).

Trat	f/c	V _{LWA} / V _{CA}	PC (%)	OSW (%)	M- Sand (%)	R- Sand (%)	LWA (%)	PC (kg/m ³)	OSW (kg/m ³)	M-Sand (kg/m ³)	R-Sand (kg/m ³)	LWA (kg/m ³)	W (kg/m ³)	SP (kg/m ³)
100F0LWA	0	-1,4142	20	20	45	15	0	462.41	391.27	953.61	291.76	0.00	258.95	9.25
170F9LWA	1	-1	14.78	25.22	41.05	13.68	5.27	335.42	484.51	854.02	261.29	0.37	272.41	9.08
29F9LWA	-1	-1	30.94	9.06	41.05	13.68	5.27	671.83	166.50	816.93	249.94	0.35	304.01	8.69
0F30LWA	-1,4142	0	40	0	31.5	10.5	18	832.44	0.00	600.84	183.83	1.15	332.98	8.32
100F30LWA	0	0	20	20	31.5	10.5	18	449.93	380.71	649.51	198.72	1.24	278.96	9.00
200F30LWA	1,4142	0	13.33	26.67	31.5	10.5	18	317.07	536.59	686.57	210.06	1.31	237.80	9.51
170F51LWA	1	1	14.78	25.22	21.95	7.32	30.73	338.50	488.95	460.97	141.03	2.16	265.74	9.16
29F51LWA	-1	1	30.94	9.06	21.95	7.32	30.73	666.04	165.06	433.18	132.53	2.03	310.00	8.61
100F60LWA	0	1,4142	20	20	18	6	36	462.41	391.27	381.44	116.70	2.56	258.95	9.25

4.2.3 Concrete production and specimens casting

The LWASCM were prepared using a Philco PHP500 planetary mixer according to the following protocol: (a) the dry mix was homogenized; (b) the initial kneading water containing all the superplasticizer was added to the homogenized dry mixture, with the mixer at slow speed, over 30 seconds; (c) the mixer was kept at slow speed for additional 60 seconds before being (d) turned off to clean the blades and bowl walls, keeping the mixture at rest for 60 seconds; in sequence (e) the mixer was restarted and the mixture was homogenized for an additional time of 60 seconds at medium speed.

The volume of mixed material was 1770 ± 10 ml, enough to mold 9 cylindrical test specimens measuring $\varnothing 5\times 10$ cm. The specimens were demolded at 1 day of age and kept submerged in lime-saturated water for curing.

4.2.4 Concrete characterization tests

In the fresh state, the spreading and tendency to segregation and exudation were analyzed using the mini-slump test, with the viscosity being measured through the time (T_{220}) that the mixture takes to reach a spread with a diameter equal to 220 mm. The pastes with f/c ratios of 0, 1 and 2, water/power ratio of 1.5 and superplasticizer content of 3% were tested using a FANN 35A rotational viscometer to compare the viscosities at different filler consumptions.

The mechanical, chemical and physical characterization tests were carried out in the hardened state. The tensile strength test by diametrical compression and compressive strength test in cylindrical specimens (5x10 cm) were carried out following the methods NBR 7222 [35], NBR 5739 [36] and ASTM C-39 [37]. The dynamic modulus of elasticity and setting time of the LWASCM were also determined by measuring the ultrasonic pulse velocity (Proceq Pundit Lab, P wave, frequency 54 kHz) according to the NBR 8802 [38] and ASTM C597-16 [39].

For the physical characterization in the hardened state, specific density and void index tests were carried out following the method NBR 9778 [40].

4.2.5 Eco-efficiency performance

The eco-efficiency performance of the LWASCM matrix was determined by the binder intensity (bi) proposed by Damineli et al. [41], calculated by Equation 4.3, where the total consumption of binder (b) and the performance achieved in the compressive strength test at 28 days (p) are the input parameters.

Equation 4.3

$$bi = \frac{b}{p}$$

4.2.6 Statistical analysis

To optimize the experimental design, response surfaces were drawn for compressive strength, tensile strength, void ratio, density, ultrasonic pulse velocity, water volume, and binder intensity. A regression equation was found for each test performed that estimates the expected values for different proportions of f/c and V_{LWA}/V_{CA} ratios, based on the results obtained from the tests. The equation model is shown in Equation 4.4. To verify the fit of the regression equations obtained, the coefficients of determination (R^2) were found for a significance p -value lower than 0.05. The closer the R^2 value to 1, the better the fit.

Equation 4.4

$$y = \beta_0 + \beta_1 a_i + \beta_2 a_i^2 + \beta_3 b_j + \beta_4 b_j^2 + \beta_5 a_i b_j + \varepsilon_{ij}$$

4.3 Results

4.3.1 Fresh state properties

According to the plastic viscosity tests presented in Table 4.6, the increase in the OSW content leads to a decrease in the viscosity of the paste. Therefore, mixtures with higher contents of OSW must have a lower water/powder ratio to maintain workability without loss of viscosity or tendency to segregation. The spreading of the produced mixtures that reached the range of 260 to 280 mm presented in Figure 4.4 show that the mixtures did not show signs of segregation

during the test, having the LWA spread throughout the microconcrete. However, new segregation tests are necessary to confirm the results, as further discussed.

Table 4.6 – Viscosity test results.

f/c	0	1	2
Plastic viscosity (mPa·s)	73	72	59

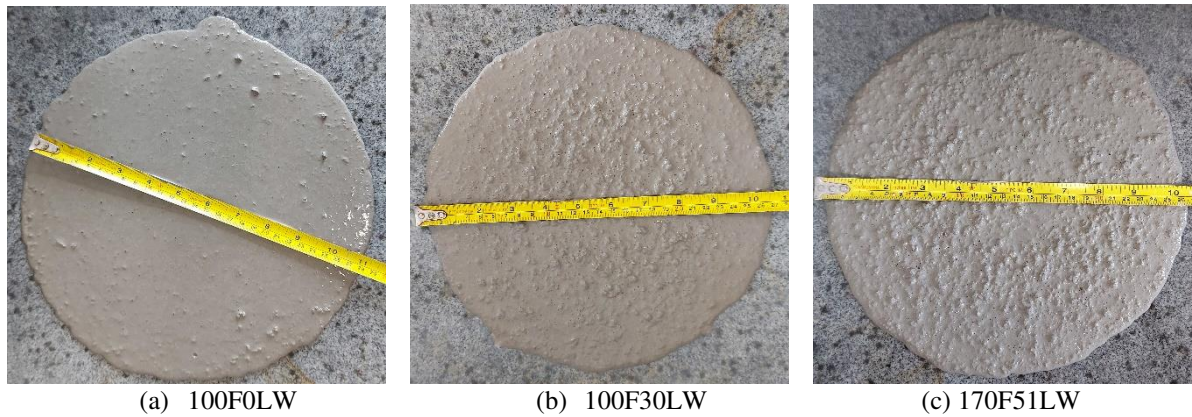


Figure 4.4 – Mini slump spreading of LWASCM: (a) 100F0LW; (b) 100F30LW; (c) 170F51LW.

The water to powder volume ratio (V_w/V_p) of each mixture, mini-slump spreading, mini-slump correlation with slump flow, and T_{220} are presented in Table 4.7. The coded regression equation of the water consumption and contour graphs are shown in Table 4.8 and Figure 4.5, respectively.

Table 4.7 – Test results.

Trat	Vw/ Vp	Mini-Slump (mm)	Correlation Slump Flow (mm)	T ₂₂₀ (s)	Compressive strength at 28 days (MPa)	Tensile strength in diametrical compression at 28 days (MPa)	Ultrasonic pulse velocity at 28 days (m/s)	Density (g/cm ³)	Void Index (%)	Binder intensity indicator (bi)
100F0LWA	0.874	280	636	3.91	41.42	4.21	3855.84	2.66	21.87	11.16
170F9LWA	0.936	275	625	3.12	16.72	2.85	3545.41	2.51	24.34	20.06
29F9LWA	1.092	265	602	5.13	37.53	4.35	3846.98	2.46	20.34	17.90
0F30LWA	1.248	265	602	2.10	17.45	4.03	3676.72	2.36	19.52	47.70
100F30LWA	0.967	270	614	2.98	17.06	2.95	3524.47	2.38	22.68	26.37
200F30LWA	0.780	280	636	3.00	7.18	1.97	3286.38	2.35	21.58	44.15
170F51LWA	0.905	270	614	4.22	12.39	2.18	3419.69	2.21	23.24	27.31
29F51LWA	1.123	273	620	2.23	9.30	2.92	3416.92	2.24	23.61	71.60
100F60LWA	0.874	260	591	5.34	12.39	2.18	3419.69	2.21	23.24	37.31

Table 4.8 – Coded regression equations of the results.

Regression equations	ε, std.dev.	R ² /R ² aj
$\frac{V_w}{V_p} = 0,9247 - 0,0827 \frac{f}{c} - 0,0468 \frac{V_{LWA}}{V_{CA}} + 0,0596 \left(\frac{f}{c}\right)^2$	0.1057	51.15%/ 44.78%
$f_c (MPa) = 11,035 - 4,590 \frac{f}{c} - 9,761 \frac{V_{LWA}}{V_{CA}} + 7,567 \left(\frac{V_{LWA}}{V_{CA}}\right)^2 + 4,854 \frac{V_{LWA}}{V_{CA}} \cdot \frac{f}{c}$	1.7273	98.35%/ 98.05%
$Tensile\ strength\ (MPa) = 2,8926 - 0,7064 \frac{f}{c} - 0,6867 \frac{V_{LWA}}{V_{CA}} + 0,1185 \left(\frac{V_{LWA}}{V_{CA}}\right)^2$	0.1752	97.08%/ 96.70%
$UPV (MPa) = 3473,7 - 128,1 \frac{f}{c} - 168,3 \frac{V_{LWA}}{V_{CA}} + 68,1 \left(\frac{V_{LWA}}{V_{CA}}\right)^2$	92.7483	85.22%/ 83.30%
$Density\ (kg/m^3) = 2,41886 - 0,005 \frac{f}{c} - 0,15614 \frac{V_{LWA}}{V_{CA}} - 0,04032 \left(\frac{f}{c}\right)^2 + 0,01019 \left(\frac{V_{LWA}}{V_{CA}}\right)^2$	0.0086	99.74%/ 99.69%
$Void\ Index\ (\%) = 24,722 + 0,674 \frac{f}{c} + 0,369 \frac{V_{LWA}}{V_{CA}} - 1,825 \left(\frac{f}{c}\right)^2 - 0,822 \left(\frac{V_{LWA}}{V_{CA}}\right)^2 - 1,377 \frac{V_{LWA}}{V_{CA}} \cdot \frac{f}{c}$	0.6228	89.26%/ 86.71%
$BI = 46,98 - 3,99 \frac{f}{c} + 14,31 \frac{V_{LWA}}{V_{CA}} - 10,44 \left(\frac{V_{LWA}}{V_{CA}}\right)^2 - 7,81 \frac{V_{LWA}}{V_{CA}} \cdot \frac{f}{c}$	6.9461	87.78%/ 85.56%

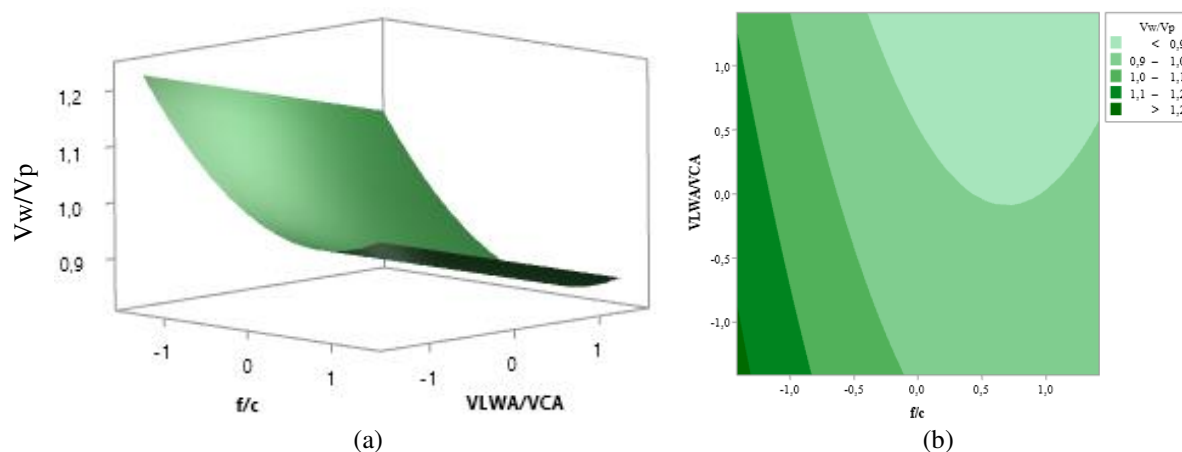


Figure 4.5 – Plots of coded (a) surface and (b) contour of the water to powder volume ratio (V_w/V_p).

The V_w/V_p results show that the increase in the powder content considerably reduced the water consumption necessary for the mixture to reach the fixed spread, which is the most significant variable and agrees with the results obtained in the plastic viscosity measurements. The increase in the content of lightweight aggregates also decreased water consumption, which may be due to the smooth particles of LWA, which also is a water-repellent material, increasing the fluidity of the mixture. However, in the preliminary tests, higher levels of water consumption for mixtures with high LWA content led to segregation and flotation of the aggregates. To achieve cohesive and stable mixtures, lower water consumption is necessary. In this sense, the spreading can be controlled by increasing the superplasticizer dosage and OSW filler content.

4.3.2 Hardened state properties

The results of compressive strength and tensile strength in diametral compression and their regression equations, presented in Tables 4.7 and 4.8, respectively, show that the equations were well adjusted and reflect the results.

Compressive strength is mainly governed by the term V_w/V_p , demonstrating that this is the most significant factor, and the higher its value, the lower the mechanical strength. The tensile strength in diametral compression has both factors as predominant, being reduced both by the increase in the consumption of LWA and by the replacement of cement by filler. This difference in the significance of the terms in the two mechanical strength tests can be explained

by Figure 4.6, which shows the images of the broken specimens in the tensile strength test in the diametrical compression.

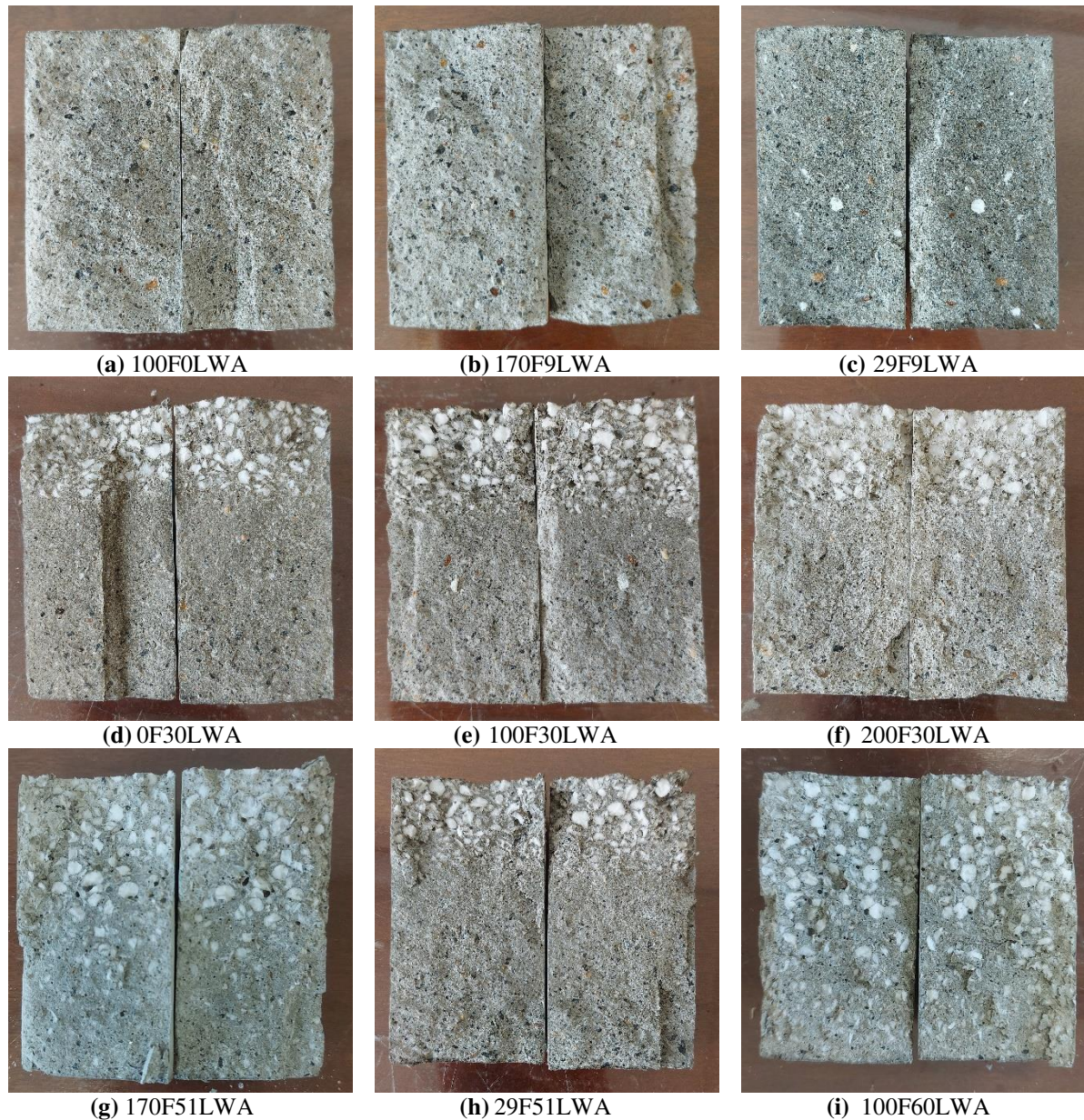


Figure 4.6 – Images of the broken specimens in the tensile strength test in diametral compression.

It can be seen from Figure 4.6 that the higher the content of LWA, the greater the segregation of the aggregates, making it easy to visually observe the difference in the concentration of LWA at the top of the specimen. Images a, b and c of Figure 4.6 are the only ones that do not show segregation and are from the mixtures 100F0LWA, 170F5LWA and 29F9LWA with a low proportion of LWA, which, when analyzed in their mechanical strength

results, present the highest strengths, falling only due to the low consumption of cement in the 170FOLWA mixture.

On the other hand, the images d, e, f, g, h, and i of Figure 4.6, for having higher levels of LWA, showed strong segregation and fluctuation of LWA, which was not observed during the mini-slump test, and occurring only during the casting of the mixtures in the specimen molds. The high concentration of LWA on top of the specimens created a lightweight layer of low paste concentration and, consequently, low mechanical strength, causing the specimens' collapse in such layers (Figure 4.7). On the other hand, despite the high consumption of lightweight aggregates, the segregation was less intense in mixtures with higher concentrations of OSW filler, as in images g and i of Figure 4.6, showing that the filler can function as a stabilizing material in LWASCM.



Figure 4.7 – specimen ruptured in the compressive strength test.

The tensile strength test in diametral compression is performed by applying a force along with the specimen height. Therefore, part of the force is also applied to the compact layers with lower concentrations of LWA, leading to higher mechanical strengths even showing signs of segregation, i.e., while the LWA-rich layer governed the results in the compressive strength test, making the term V_{LWA}/V_{CA} having greater significance, in the tensile strength test by diametrical compression, the LWA-poor layers governed, making both V_{LWA}/V_{CA} and f/c significant. The surface and contour plots of Figure 4.8 illustrate the drop in the mechanical strength of the mixtures according to the increase in OSW and LWA.

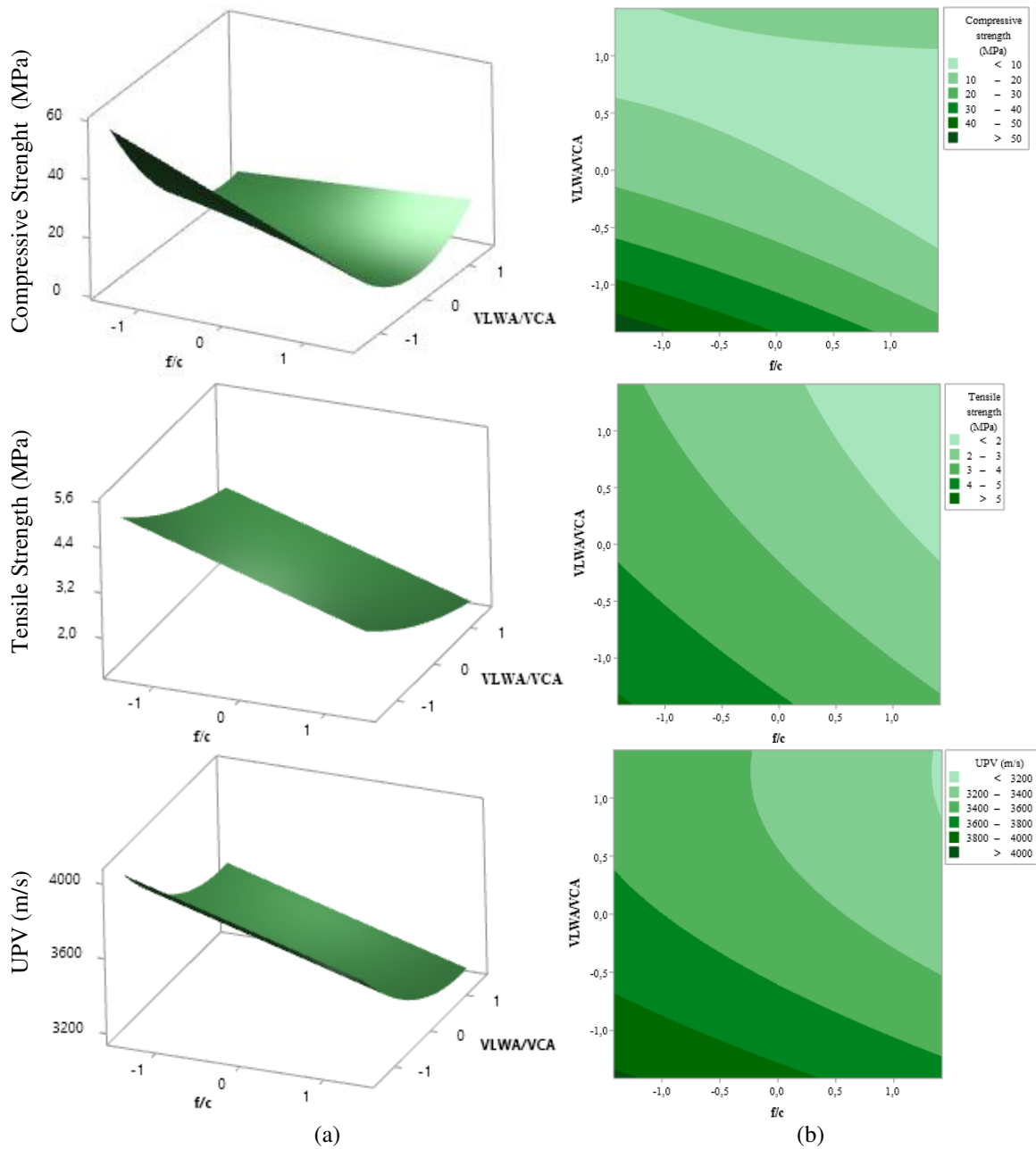


Figure 4.8 – Plots of (a) surface and (b) contour of compressive strength, tensile strength and UPV.

The ultrasonic pulse velocity results are similar to the tensile strength in diametrical compression due to the two distinct layers. However, for UPV, the consumption of LWA is more important in the results, decreasing the speeds with the increase of LWA.

Despite the segregation, lack of stability of the matrix to avoid the flotation of the aggregates and the consequent high drop in mechanical strength, the incorporation of LWA managed to reduce the density of the microconcretes. According to Table 4.7, the mixture with

the highest content of LWA (100F60LWA) managed to reach 2.21 g/cm^3 , a density 17% lower than that of the mix 100F0LWA. Even if the lowest density found does not yet configure a lightweight microconcrete, the decrease in the density led to lighter concrete elements.

The density regression equation was adjusted, with R^2 close to 1, and with V_{LWA}/V_{CA} with greater significance, demonstrating that the incorporation of LWA has a direct connection with the drop in the density of the mixtures, which can also be observed in Figure 4.8.

The void ratio in mixtures with V_{LWA}/V_{CA} ratios up to 0.09 increased with increasing filler content, making the regression equation having the f/c term with greater significance. However, in mixtures with replacements of conventional aggregates by LWA above 30%, the segregation of LWA may have interfered with the readings, causing LWASCM with similar proportions of LWA to have similar void ratios, regardless of the concentration of f/c .

Figure 4.9 shows a convex surface, in which proportions f/c up to 1 and V_{LWA}/V_{CA} from up to 0.3 increase the void ratio, and mixtures with proportions of these two variables above these values have lower void ratios. This result may be linked to the difference in the water consumption of the mixtures. Despite the increase in f/c , increasing the void ratio, the spreading increased, requiring a lower V_w/V_p , which reduces the voids left by the water. The 100F60LWA mixture, despite having the maximum concentration of LWA, presented the lightweight aggregates less concentrated at the top and better distributed along with the specimen height, i.e., the mixture was more cohesive and less prone to segregation, which may be due to a reduction in water consumption and an increase in the filler content.

Therefore, although the results demonstrate that the increase of f/c and V_{LWA}/V_{CA} decreases mechanical strength and density and increases the void ratio of lightweight microconcretes, the segregation that occurred did not allow the results to demonstrate the real mechanical potential of these microconcretes.

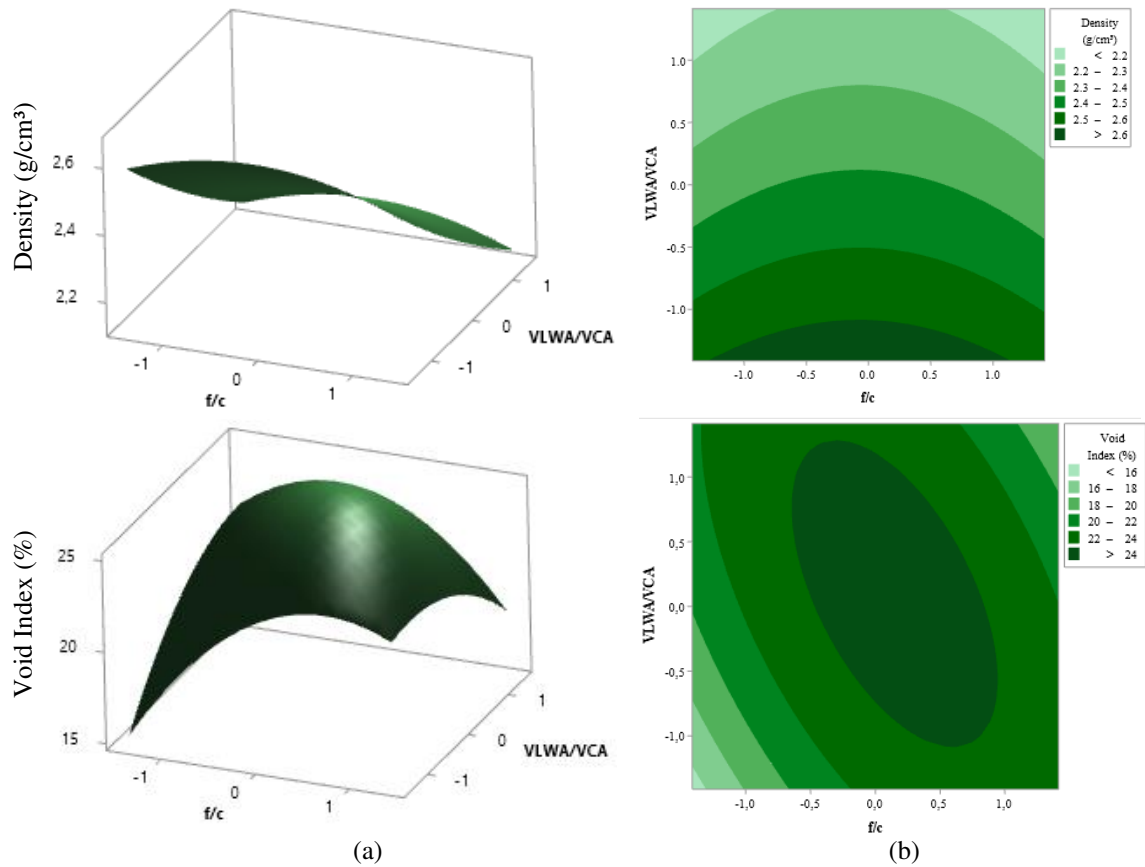


Figure 4.9 – Adjusted graphs of (a) surface and (b) contour for density and void index.

4.3.3 Eco-efficiency performance

Figure 4.10 shows the results of the sustainability indicator Binder Intensity (BI). Although the increase in the filler content decreases the BI in mixtures with LWA and increases eco-efficiency through the high incorporation of waste and reduction of cement, the LWA is significant and considerably increases the BI indicator, decreasing eco-efficiency.

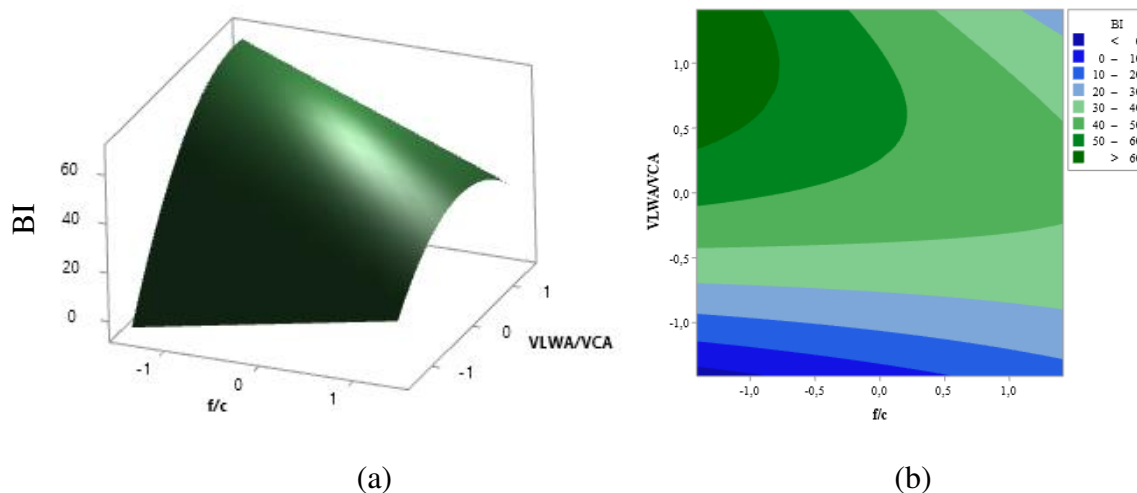


Figure 4.10 – Adjusted graphs of (a) surface and (b) contour for Binder Intensity (BI).

The results were expected since the indicator only considers cement consumption and mechanical strength, i.e., mixtures with lower cement consumption and high strengths have better eco-efficiency performances according to this indicator. Therefore, this indicator does not consider the waste incorporation, causing inert waste incorporated into concrete to have a lower eco-efficiency impact.

As lightweight concretes generally have lower mechanical strengths due to the lightweight aggregates' low density and mechanical performance, it was expected that mixtures with LWA would have higher BI. However, the high result of the BI indicator (above 20) indicates that the segregation of LWA and the consequent drop in mechanical strength diverged the results, causing the mixtures that did not segregate to present an increase in BI with the increase of filler. In contrast, the segregated mixtures had lower BI for lower cement consumption as they had similar mechanical strength, and the increase in the f/c ratio increased eco-efficiency.

Therefore, matrix stabilization and segregation resistance must be effective for a more consistent evaluation. For the eco-efficiency performances of LWASCM with inert waste, other sustainability indicators that consider incorporation of waste must be used to compare the mixtures produced.

4.4 Conclusion

The present work studied the production of lightweight self-compacting microconcrete with the partial replacement of cement by ornamental stone waste as a filler and the partial replacement of conventional aggregates by expanded polystyrene lightweight aggregates by up to 60%. The mixtures with V_{LWA}/V_{CA} above 0.3 showed that it is difficult to maintain the resistance of segregation during the molding of the specimens, which can cause the drop of mechanical strength and void ratio, and generate results with experimental errors.

However, despite the fluctuation of the aggregates, it can be seen that the increase in the content of f/c and the increase in the content of V_{LWA}/V_{CA} lead to a decrease in the consumption of water necessary to leave the mixture fluid, and consequently, increase the spreading and fluidity. The increase in V_{LWA}/V_{CA} also decreases the density of the mixtures, making the microconcretes lighter. With these results, more assertive studies can be carried out for the stabilization of mixtures with lightweight aggregates, reducing the spreading range to reduce water consumption and try to retain segregation, or reducing water consumption, increasing the superplasticizer content and adding additions that increase the shear stress of the mixtures.

Acknowledgment

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance code 001. The authors also acknowledge the support provided by the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG), and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). Thanks are also due to the Brazilian Research Groups SICon-CNPq/UFV and RECICLOS-CNPq/UFOP.

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

References

- [1] B. Vakhshouri, S. Nejadi, Mix design of light-weight self-compacting concrete, Case Stud. Constr. Mater. 4 (2016) 1–14. <https://doi.org/10.1016/j.cscm.2015.10.002>.
- [2] A.S. Souza, C.M. de Carvalho, Low density self compacting concrete: for application in pre-fabricated panels, InterScientia. 5 (2017) 75–91.

- [3] J.A. Rossignolo, *Concreto leve estrutural: produção, propriedades, microestrutura e aplicações*, PINI, São Paulo, 2009.
- [4] S. Yang, X. Yue, X. Liu, Y. Tong, Properties of self-compacting lightweight concrete containing recycled plastic particles, *Constr. Build. Mater.* 84 (2015) 444–453. <https://doi.org/10.1016/j.conbuildmat.2015.03.038>.
- [5] D.S. Law Yim Wan, F. Aslani, G. Ma, Lightweight Self-Compacting Concrete Incorporating Perlite, Scoria, and Polystyrene Aggregates, *J. Mater. Civ. Eng.* 30 (2018) 04018178. [https://doi.org/10.1061/\(asce\)mt.1943-5533.0002350](https://doi.org/10.1061/(asce)mt.1943-5533.0002350).
- [6] M.M. Ranjbar, S.Y. Mousavi, Strength and durability assessment of self-compacted lightweight concrete containing expanded polystyrene, *Mater. Struct. Constr.* 48 (2015) 1001–1011. <https://doi.org/10.1617/s11527-013-0210-6>.
- [7] R. Madandoust, M.M. Ranjbar, S. Yasin Mousavi, An investigation on the fresh properties of self-compacted lightweight concrete containing expanded polystyrene, *Constr. Build. Mater.* 25 (2011) 3721–3731. <https://doi.org/10.1016/j.conbuildmat.2011.04.018>.
- [8] N.N. Hilal, M.F. Sahab, T.K. Mohammed Ali, Fresh and hardened properties of lightweight self-compacting concrete containing walnut shells as coarse aggregate, *J. King Saud Univ. - Eng. Sci.* 33 (2021) 364–372. <https://doi.org/10.1016/j.jksues.2020.01.002>.
- [9] A.F. Angelin, R.C. Cecche Lintz, W.R. Osório, L.A. Gachet, Evaluation of efficiency factor of a self-compacting lightweight concrete with rubber and expanded clay contents, *Constr. Build. Mater.* 257 (2020) 119573. <https://doi.org/10.1016/j.conbuildmat.2020.119573>.
- [10] J. Li, Y. Chen, C. Wan, A mix-design method for lightweight aggregate self-compacting concrete based on packing and mortar film thickness theories, *Constr. Build. Mater.* 157 (2017) 621–634. <https://doi.org/10.1016/j.conbuildmat.2017.09.141>.
- [11] G.E. Abdelaziz, A study on the performance of lightweight self-consolidated concrete, *Mag. Concr. Res.* 62 (2010) 39–49. <https://doi.org/10.1680/macrc.2008.62.1.39>.
- [12] P. Mehta, P. Monteiro, *Concrete: Microstructure, Properties, and Materials*, 4th ed., McGraw Hill Education, New York, 2013.
- [13] S. Çankaya, B. Pekey, A comparative life cycle assessment for sustainable cement production in Turkey, *J. Environ. Manage.* 249 (2019). <https://doi.org/10.1016/j.jenvman.2019.109362>.
- [14] J. Lehne, F. Preston, *Making concrete change - Innovation in low-carbon cement and concrete*, 2018.
- [15] R.M. Andrew, Global CO₂ emissions from cement production, 1928-2018, *Earth Syst. Sci. Data.* 11 (2019) 1675–1710. <https://doi.org/10.5194/essd-11-1675-2019>.

- [16] E. Worrell, L. Price, N. Martin, C. Hendriks, L.O. Meida, Carbon dioxide emissions from the global cement industry, *Annu. Rev. Energy Environ.* 26 (2001) 303–329. <https://doi.org/10.1146/annurev.energy.26.1.303>.
- [17] D.C. Reis, P.C.R.A. Abrão, T. Sui, V.M. John, Influence of cement strength class on environmental impact of concrete, *Resour. Conserv. Recycl.* 163 (2020) 105075. <https://doi.org/10.1016/j.resconrec.2020.105075>.
- [18] Z.S. Ali, M. Hosseinpour, A. Yahia, New aggregate grading models for low-binder self-consolidating and semi-self-consolidating concrete (Eco-SCC and Eco-semi-SCC), *Constr. Build. Mater.* 265 (2020). <https://doi.org/10.1016/j.conbuildmat.2020.120314>.
- [19] N. Gupta, R. Siddique, R. Belarbi, Sustainable and Greener Self-Compacting Concrete incorporating Industrial By-Products: A Review, *J. Clean. Prod.* 284 (2020). <https://doi.org/10.1016/j.jclepro.2020.124803>.
- [20] P.C.C. GOMES, Optimization and Characterization of High-Strength Self-Compacting Concrete, *Universitat Politècnica de Catalunya*, 2002.
- [21] P.C.C. GOMES, A.R. Barros, Métodos de dosagem de concreto autoadensável, PINI, São Paulo, 2009.
- [22] EFNARC, The European Guidelines for Self-Compacting Concrete, *Eur. Guidel. Self Compact. Concr.* (2005) 63. <http://www.efnarc.org/pdf/SCCGuidelinesMay2005.pdf>.
- [23] H. Okamura, M. Ouchi, Self-Compacting Concrete, *J. Adv. Concr. Technol.* 1 (2003) 5–15.
- [24] A.M. Neville, *Properties of concrete*, Pearson, 2012.
- [25] ABIROCHAS, Balanço das Exportações e Importações Brasileiras de Rochas Ornamentais em 2019, *ABIROCHAS.* 55 (2020).
- [26] E. Bacarji, R.D. Toledo Filho, E.A.B. Koenders, E.P. Figueiredo, J.L.M.P. Lopes, Sustainability perspective of marble and granite residues as concrete fillers, *Constr. Build. Mater.* 45 (2013) 1–10. <https://doi.org/10.1016/j.conbuildmat.2013.03.032>.
- [27] M.A. Rodrigues, J.A.M. Filho, Fabricação de concreto autoadensável com utilização de resíduos de marmorarias como adição mineral, *Rev. Eletrônica Eng. Civ.* 14 (2017) 50–71.
- [28] M.S. Zafar, U. Javed, R.A. Khushnood, A. Nawaz, T. Zafar, Sustainable incorporation of waste granite dust as partial replacement of sand in autoclave aerated concrete, *Constr. Build. Mater.* 250 (2020). <https://doi.org/10.1016/j.conbuildmat.2020.118878>.
- [29] R. Alyousef, O. Benjeddou, C. Soussi, M.A. Khadimallah, M. Jedidi, Experimental Study of New Insulation Lightweight Concrete Block Floor Based on Perlite Aggregate,

Natural Sand, and Sand Obtained from Marble Waste, *Adv. Mater. Sci. Eng.* 2019 (2019). <https://doi.org/10.1155/2019/8160461>.

[30] J.E. Funk, D.R. Dinger, Particle size control for high-solids castable refractories, *Am. Ceram. Soc. Bull.* (1994).

[31] R. Sarkar, Particle size distribution for refractory castables: A review, *InterCeram Int. Ceram. Rev.* 65 (2016) 82–86. <https://doi.org/10.1007/bf03401156>.

[32] R. Vanderlei, *Análise experimental do concreto de pós reativos: dosagem e propriedades mecânicas*, 2004.

[33] A.L. de Castro, V.C. Pandolfelli, Revisão: conceitos de dispersão e empacotamento de partículas para a produção de concretos especiais aplicados na construção civil, *Cerâmica*. 55 (2009) 18–32. <https://doi.org/10.1590/s0366-69132009000100003>.

[34] F.T. Ramal Jr, R.G. Pileggi, J.B. Gallo, V.C. Pandolfelli, A curva de distribuição granulométrica e sua influência na reologia de concretos refratários, *Cerâmica*. 48 (2002) 212–216. <https://doi.org/10.1590/s0366-69132002000400008>.

[35] ABNT, NBR 7222: Concreto e argamassa — Determinação da resistência à tração por compressão diametral de corpos de prova cilíndricos, *Assoc. Bras. Normas Técnicas - Rio Janeiro*. (2011).

[36] ABNT, NBR 5739: Concreto - Ensaio de compressão de corpos de prova cilíndricos, *Assoc. Bras. Normas Técnicas*. (2018).

[37] ASTM, C39/C39M: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, *Annu. B. ASTM Stand.* (2010) 1–7. <https://doi.org/10.1520/C0039>.

[38] ABNT, NBR 8802: Concreto endurecido — Determinação da velocidade de propagação de onda ultrassônica, *Associação Brasileira de Normas Técnicas - ABNT*, 2019.

[39] ASTM, C597 - 16 Standard Test Method for Pulse Velocity Through Concrete, *Am. Soc. Test. Mater. - ASTM*. (2016) 4. <https://doi.org/10.1520/C0597-16.2>.

[40] ABNT, NBR 9778: Argamassa e concreto endurecidos -Determinação da absorção de água, índice de vazios e massa específica, *Assoc. Bras. Normas Técnicas*. (2011).

[41] B.L. Damineli, F.M. Kemeid, P.S. Aguiar, V.M. John, Measuring the eco-efficiency of cement use, *Cem. Concr. Compos.* 32 (2010) 555–562. <https://doi.org/10.1016/j.cemconcomp.2010.07.009>.

CHAPTER 5 - General conclusion

Abstract

This work aimed to study the behavior in the fresh and hardened state and the eco-efficiency of self-compacting microconcretes and lightweight self-compacting microconcretes incorporating ornamental stone waste filler and expanded polystyrene waste fine aggregates. This chapter presents a general conclusion and recommendations for future work.

5.1 General conclusions

Self-compacting microconcrete (SCC) with high incorporation of ornamental stone waste such as filler (OSW) and lightweight aggregate self-compacting microconcrete (LWASCM) with OSW and lightweight aggregates of expanded polystyrene waste (LWA) was produced. The SCCs had variations in the content of filler/cement (f/c) and volume of powder/total volume (V_p/V_t). The LWASCMs had variations in the content of f/c and volume of lightweight aggregates/total aggregates (V_{LWA}/V_{CA}).

The results showed that the powder/cement variation was not significant within the limit of workability suitable for the SCCs. However, higher volumes of powder reduced the packing density, which increased the void content. Therefore, denser packed mixtures proved to be more effective, even with low cement consumption.

The variation of V_{LWA}/V_{CA} provided a decrease in the density of microconcretes. However, due to segregation, the mechanical strength results were not consistent.

The OSW proved to be a promising filler to partially replace cement, reducing its consumption, decreasing the viscosity and increasing the workability of mixtures at high concentrations. Cement replacements by up to 66.67% decreased the mechanical compressive strength by up to 68.88%, which was expected since the residue is a crystalline and inert material. However, despite the drop in strength, the SCCs with high OSW incorporations showed excellent eco-efficiency performances compared to SCCs with similar strengths, proving that replacing cement with OSW is an effective route to increase sustainability.

5.2 Proposals for future works

After completing the work, new areas of study emerge to be explored. Some proposals for future work are presented:

- Carry out new studies on strategies for improving packing density in eco-efficient SCCs, in order to increase waste consumption and improve performance.
- Expand the studies for other waste, comparing the results with different materials.

- To study the addition of new materials and blends, including pozzolanic additions, to evaluate the interaction of other residues in self-compacting microconcretes containing ornamental stone residues.
- Carry out durability tests and evaluate the characteristics of self-compacting microconcretes with the incorporation of ornamental stone waste as a structural recovery material.
- Stabilize lightweight self-compacting microconcretes, control segregation and perform new analyses in addition to studying thermal and acoustic performance and behavior in a fire situation.
- Carry out eco-efficiency evaluation considering structural elements, with reinforcement rates to assess the set's sustainability in different concrete strength classes.