UNIVERSITY OF SÃO PAULO
ESCOLA POLITÉCNICA

LUIZ DE BRITO PRADO VIEIRA

Analysis of technologies for recycling the waste generated in concrete production in ready mixed concrete plants

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DEDICATION

To my beloveds Katy, Barbara and Benício

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To my advisers, Antonio Figueiredo and Vanderley John who, sharing their precious knowledge

To Dr. Sérgio Angulo, Vladimir Paulon and Sergio Pacca, for the important advice during the Ph. D. qualification.

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RESUMO

Vieira, LBP. Análise de tecnologias para reaproveitamento de resíduos gerados na produção de concreto em concreteiras [Tese]. São Paulo: Universidade de São Paulo, Escola Politécnica. 2019

O grande volume de resíduos gerados na construção civil é um problema relevante do ponto de vista financeiro e ambiental. Portanto, uma estratégia de eliminação de resíduos na produção do concreto tem grande importância. Esta tese tem por objetivo propor um método de avaliação em campo da eficiência de estratégias de minimização de resíduos gerados na produção de concreto em concreteiras. O estudo experimental foi iniciado pela produção de um inventário sobre os volumes de resíduos gerados na produção do concreto. Foram analisadas as causas e a quantidade de resíduos gerados pela concreteira sob condições reais de operação. O estudo ocorreu por um período de um ano e envolveu 94 plantas. O inventário foi produzido em condições reais de operação e mediu a influência das características do concreto no volume de lastro aderido ao tambor da betoneira. As causas do concreto retornado também foram avaliadas. Verificou-se que o volume total de resíduos produzidos na concreteira equivale a 3,1% do volume total produzido. Além disso, 45% do resíduo produzido é relativo às sobras, sendo a sua principal causa o pedido excessivo (57,9%). O lastro corresponde a 55% do volume total de resíduos gerados, sendo o baixo nível abatimento do concreto o principal fator a causar o incremento deste volume. As três principais estratégias de redução de resíduos utilizadas pelas concreteiras foram avaliadas a viabilidade técnica, financeira e a emissão de CO_2 de cada uma das estratégias estudadas. A metodologia utilizada empregou a avaliação laboratorial seguida do monitoramento e parametrização da produção em escala industrial. Os resultados obtidos permitiram determinar a real capacidade dessas técnicas para reduzir o desperdício e a pegada específica de CO_2 da RMC. Foram analisados três métodos diferentes de reutilização de resíduos: (a) reutilização de concreto no estado fresco usando aditivos estabilizadores de hidratação (HSA); (b) reaproveitamento de concreto fresco pela separação dos agregados da pasta de cimento antes do endurecimento do concreto; (c) reciclagem de concreto endurecido através da produção de agregados reciclados britados. O método de reutilização de concreto com HSA apresenta vantagens claras em relação aos demais analisados do ponto de vista ambiental e financeiro, tornando essa estratégia muito atrativa para a implementação em plantas de RMC. Do ponto de vista técnico esta estratégia tem a vantagem de possibilitar a reutilização do concreto retornado e do lastro simultaneamente. Por outro lado, o uso do HSA demanda um maior investimento do ponto de vista operacional e, em especial, de treinamento de mão de obra. Desta forma, a metodologia de análise conjugando resultados de laboratório e monitoramento das condições de produção se mostrou eficaz na análise de estratégias de mitigação de produção de resíduos em concreteiras.

Palavras-chave: Concreto; Resíduos; Produção Enxuta; Reciclagem Urbana;

ABSTRACT

Vieira, LBP. Analysis of technologies for recycling the waste generated in concrete production in ready mixed concrete plants [Ph. D. Thesis]. São Paulo: Universidade de São Paulo, Escola Politécnica. 2019

The large volume of waste generated in construction is a relevant problem from a financial and environmental point of view. Therefore, a waste elimination strategy in the production of concrete is of great importance. This thesis aims to propose a method of evaluating the efficiency of strategies to minimize residues generated in the ready-mix concrete (RMC) production through laboratory and industrial tests. The experimental study was initiated by the production of an inventory on the volumes of waste generated in the production of RMC under real operating conditions. The causes and the amount of waste generated by the concrete company were analysed. The study took place over a period of one year and involved 94 RMC plants. The inventory was produced under real operational conditions and measured the influence of concrete characteristics on the volume of concrete adhered to the mixer truck drum. The experimental study was performed and measured the influence of concrete characteristics. The causes of returned concrete were also evaluated. It was found that the total volume of waste produced in the concrete corresponds to 3.1% of the total volume produced. In addition, 45% of the waste produced corresponds to leftovers, the main cause of which is excessive ordering (57.9%). Adhered concrete corresponds to 55% of the total volume of waste generated, with the low level of concrete slump being the main factor causing the increase in this volume. The three main waste reduction strategies used by concrete companies were evaluated for the technical, financial feasibility and CO_2 emissions of each of the studied strategies. The methodology used employed laboratory evaluation followed by monitoring and parameterization of production on an industrial scale. The results obtained allowed to determine the real capacity of these techniques to reduce the waste and the specific CO_2 footprint of the RMC. Three different methods of reusing residues were analysed: (a) reusing fresh concrete using hydration stabilizing additives (HSA); (b) reuse of fresh concrete by separating the aggregates from the cement paste before the concrete hardens; (c) recycling of hardened concrete through the production of crushed recycled aggregates. The method of concrete reuse with HSA has clear advantages in relation to the others analysed from the environmental and financial point of view, making this very attractive strategy for implementation in RMC plants. From a technical point of view, this strategy has the advantage of simultaneously allowing the reuse of the returned concrete and the adhered concrete. On the other hand, the use of HSA demands a greater investment from an operational point of view and, in particular, of training of labour. Therefore, the analysis methodology combining laboratory results and monitoring of production conditions proved to be effective in analysing strategies for mitigating waste production in concrete companies

.Keywords: Concrete; Waste; Lean Production; Urban Recycling

Summary

1. INTRODUCTION

According to the publication of the UNEP's International Resource Panel (IRP - UNEP, 2011) between 1905 and 2005, the amount of raw materials extracted from the earth increased from about 7 billion tons to 60 billion tons. This growth was driven by the increase in annual per capita resource consumption (4.6 t/y in 1905 to 8.8 t/y in 2005). Inducers of this demand include population growth, increased global trade, increased biomass consumption, and middle-class growth with changing consumption patterns. According to the publication, if this trend continues, the planet will need to extract 180 billion tons of raw materials annually to meet its demands by 2050

Oikonomou (2005) mentions that environmental protection is a factor directly related to the survival of human beings and, therefore, the protection of natural resources and sustainable development play an important role in the modern requirements for the construction market.

With regard to sustainable development, the immediate implication is the need to produce the largest quantity of assets with the least consumption of natural resources and the least pollution production.

Schandl et al. (2016) say that sustainability implies decoupling economic growth and human well-being negative environmental impacts. The initial goal of decoupling is to achieve economic growth while decreasing the increasing rate of natural resource use and emissions. For Mumovic, & Santamouris (2013), to achieve this decoupling several actions are necessary, among them: improvement of projects, reduction of energy consumption, the replacement of traditional materials with other more eco-efficient, reduction of consumption of virgin raw materials through recycling of waste and increasing the durability of products.

According to John (2010), the construction market currently uses more than half of the raw materials currently extracted worldwide as the result of industrial development, which is dependent on the steady and increasing flow of nonrenewable natural resources. These natural resources are extracted, benefited and, at the end of their life cycle, they will turn into waste joining to the other residues generated during the extraction and beneficiation phases.

Wiedmann, et al. (2015), et al. (2009) say cement-based materials account for about 1/3 of global material consumption and generate almost the same amount of waste during their lifetime. Therefore, it is easy to understand that, due to the large scalem a small increase in resource efficiency has a large effect on mitigation of environmental impact. Consequently, reducing waste generation during concrete production is an important tool to increase the efficiency of this resource.

In many countries, ready-mix concrete (RMC) companies carry out a substantial part of the concrete production. In Brazil, the most recent report from the National Union of Cement Industry (SNIC, 2013) released shows that more than 20% of all Brazilian cement is destined annually for RMC plants, which represents almost 15 million tons. These numbers demonstrate the importance of this market that could not be neglected.

To understand the generation of waste during the production of the RMC plant, it is necessary to keep in mind that a fraction of the concrete load that is transported by the concrete-mixer truck is always returned to the plant. This fact occurs because part of the concrete adheres to the inner surface of the rotating drum and cannot be unloaded on job sites. In addition, eventually, there is a leftover concrete that is returned by the customer for several different reasons. Therefore, a part of the concrete that is produced in these companies ends up being discarded as waste in a "landfill" (Benini, 2005).

Audo et al., (2016) point out that the sending of the RMC concrete production waste to landfills causes financial and environmental costs, since there is the risk of environmental pollution by the leaching of some chemical elements that are in the concrete. Chierrito-arruda er al. (2018) also mentions that landfills are scarce near major urban centers, which increase the cost and pollution associated with transportation between the waste source and the landfill. Consequently, there is a demand to minimize or even eliminate this waste in order to avoid sending it to a "landfill". The greater the amount of waste sent to landfills the greater the environmental risk.

On the other hand, any action to be taken to eliminate or minimize landfill waste should be taken based on the precise information about the volume of waste generated during the operation of the RMC plant. However, it is difficult to determine precisely the volume of waste generated by RMC plants. The study by

Sealey et al. (2001) pointed out that 750 thousand tons of waste were generated annually in the United Kingdom, equivalent to about 2% of all the concrete produced during the period. The study by Iizuka et al. (2012) concludes that in Japan this value was between 1% and 2%. Similar result (1.5%) was obtained by Tam (2008) in Hong Kong. Although the percentage is small, considering the scale of production, it is clear that the generation of residues during RMC production cannot be unappreciated.

There are several management strategies for the treatment of concrete residues. According to Xuan et al. (2018), the choice of the alternative depends on technical aspects, the cost of implementing the process, and even on behavioral and cultural factors. In Brazil, the reuse processes adopted by concrete commonly involve the reuse of fresh concrete in new concrete compositions or the recycling of fresh concrete by mechanical process or the recycling of hardened concrete by crushing. However, there is no accurate information on the amount of waste generated in terms of adhered concrete and leftovers.

According to John (2010), although the construction market uses a lot of waste from other industries, recycling rates are low. There is little or no information available on the efficiency of possible technologies that can be used to recycle concrete waste in RMC plants. Furthermore, the fact that a product contains residues does not ensure that its environmental impact is less than a product composed of virgin materials (John & Glasser, 2016). Therefore, another important point to be analyzed besides the generation of residues resulting from the production of RMC plants is the impact of the reuse of these residues in terms of CO_2 emissions.

1.1. Objectives

The main objective of this thesis is to propose a method of evaluating the efficiency of strategies to minimize waste generated in RMC production through laboratory and industrial tests. In that sense, the following specific objectives are intended:

a) Comparative assessment of the environmental performance of different waste recycling technologies in terms of CO_2 emissions together with the assessment of their ability to minimize the different waste materials generated in the operation of the RMC plants.

b) Development and application of a quantification method for the detailed determination of the waste generated in concrete plants together with their origin.
c) Development of the evaluation process of the main waste recycling techniques within RMC based on their effective implementation in RMC plants and addressing the technological efficiency. For this, were performed: (i) a case study focused on the operational procedures and results obtained in the implementation of the process of reuse of concrete returned with HSA; (ii) an experimental study whose objective is to evaluate the feasibility of using water and reused aggregates as raw material for the production of concrete and; (iii) a survey carried out to evaluate the feasibility of implementing a recycling process of returned concrete that after being crushed is used as a recycled aggregate.

To achieve this goal all methodologies were evaluated on an industrial scale, in concrete production that were effectively delivered and applied on job sites.

1.2. Thesis organization

The thesis is based on the implementation of waste reuse processes in ready mixed concrete plants (Flowchart 1). For this purpose, data surveys were carried out to evaluate the volume and causes of waste generation, laboratory and full-scale tests to evaluate from a technical and operational point of view each of the waste reuse methods and comparative analyzes to evaluate the actual waste reuse and CO_2 mitigation capacity of each technique. .

Initially, an annual inventory was carried out on 94 plants of one of the largest RMC Brazilian companies to determine the amount of concrete leftovers returned to the RMC plant. At the same time as data collection, full scale tests were carried out to determine the amount of concrete adhered inside the mixer drum. As a result of the initial study it was possible to find out the amount of total waste generated in the RMC plants, and the amount of waste that was caused by returned concrete and adhered concrete.

Following the three main methods of waste reuse by RMC plants were analyzed technically and operationally. In this sense, laboratory tests were performed that provided data for the implementation of the scale waste reuse processes, which were tested through the production of concretes that were produced within the normal RMC plant process. In this way, the usual and recycled raw materials were weighed in the plant, mixed and in the ready mix concrete truck that transported the concrete to job sites, where the concrete was applied through concrete pump.

After the evaluation of the reuse methods, the results obtained in the scale tests made it possible to compare the capacity to reduce the amount of waste, based on the feasibility of recycling the adhered concrete and the concrete leftovers used by each technique studied. On the other hand, the impact of the use of the raw material produced by each reuse technique on the compressive strength and the water demand of the concrete made it possible to evaluate the CO_2 emission in different concretes. This makes it possible to calculate the specific CO_2 footprint of concretes of different compressive strength classes, and the comparison between the studied techniques and the concrete produced with the reference material.

The fact that it was possible to establish mix design based on the actual performance of the reused raw materials allows us to evaluate the financial impact of implementing each of the waste reuse methods in RMC plants.

In Chapter 1 presented the motivations that gave rise to the thesis, the objectives of the thesis and the way the information that is part of the thesis were structured.

In Chapter 2, the reasons for concrete wastage at ready mixed concrete plants are analyzed. This chapter is the faithful reproduction of the article written by the author "Waste generation from the production of ready-mixed concrete".

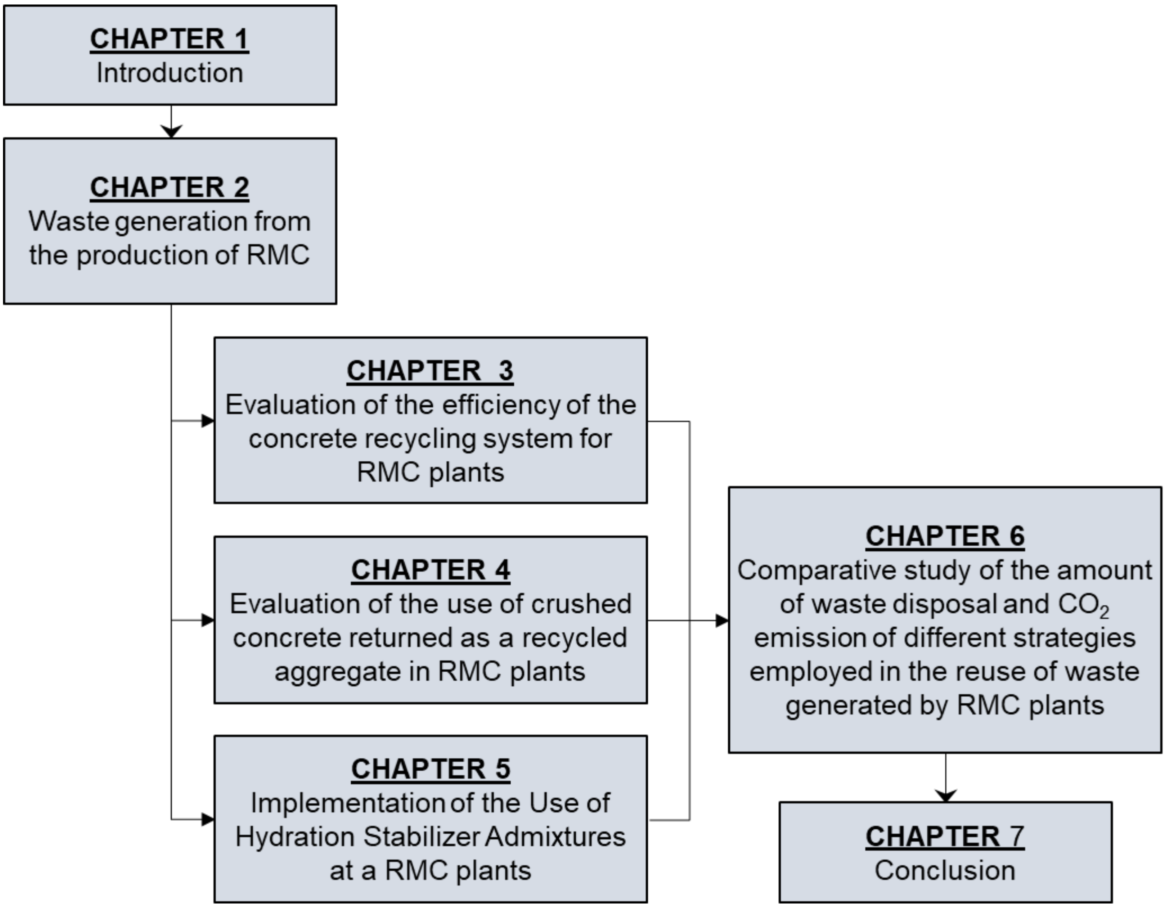
In Chapter 3 the method: to recycle fresh concrete, separating the aggregates and the cement in the mechanical reuse process is analyzed. This chapter is the reproduction of the paper written by the author "Evaluation of the efficiency of the concrete recycling system for ready-mixed concrete plants".

In Chapter 4, the method: Recycling of crushed concrete by turning the returned concrete into recycled aggregates is analyzed. This chapter is the faithful reproduction of the article written by the author "Evaluation of the use of crushed concrete returned as a recycled aggregate in ready-mix concrete plants"

In Chapter 5 the method: reuse of fresh concrete using hydration stabilizing additives is analyzed. This chapter is the faithful reproduction of the article written by the author “Implementation of the Use of Hydration Stabilizer Admixtures at a Ready-Mix Concrete Company".

In Chapter 6, the amount of discarded waste and the CO_2 emissions from the reuse methods evaluated above are analyzed. This chapter is the faithful reproduction of the article written by the author "Comparative study of the amount of waste disposal and CO_2 emission of different strategies employed in the reuse of waste generated by ready mixed concrete plants".

Finally, in chapter 7, the conclusions of the thesis are presented and suggestions for future studies are listed.



Flowchart 1 - Thesis organization

2. WASTE GENERATION FROM THE PRODUCTION OF READY-MIXED CONCRETE

2.1. Introduction

Cement-based materials represent about 1/3 of the global material consumption (Wiedmann, et al., 2015), and over their service lives, they are responsible for nearly the same amount of waste generation. Assuming that concrete is about 40–45% of the global cement consumption, and that aggregates plus water are 7–8 times the cement consumption (Scrivener et al., 2016), the global concrete production in 2017 is about 10^9 t/year (Mineral Commodity Summaries, 2017). Because of the large scale and ubiquity of concrete production, even a small increase in resource-use efficiency has a significant mitigation effect on environmental impact. The reduction of waste generation is one tool to increase resource efficiency. However, except for the end of life, there is little primary information on the amount of waste generated at every stage.

Ready-mixed concrete companies are responsible for a substantial part of concrete production in many countries. Waste is generated in every concrete truckload. A fraction of the concrete load is always returned to the plant, because not all concrete can be unloaded from the rotary drum as it is adhered to the internal surface. Additionally, sometimes there is a returned leftover from client, either because the client ordered more than was actually needed or due to other causes.

In Brazil, according to Correa et al. (2009), the Brazilian Concrete Suppliers Association (ABESC) estimated that in 2009, in the metropolitan region of São Paulo, about 9% of the volume of the concrete produced in the RMC was wasted. This value is significantly higher than the value presented by other researchers in other countries. Obla and Kim (2009) and Lemay et al. (2011) reported that in the USA, the returned concrete is approximately 5% of the total generated volume. The British ready-mixed concrete association (2014) estimates that in the UK, that figure is less than 1%, whereas Sealey (2001) estimated it at 3%. Nielsen and Glavind (2007) indicate that almost 3% of the produced concrete becomes waste in Denmark. According to Kou et al. (2012), about 0.3–0.4% of fresh concrete waste can be produced every day from an RMC plant with a daily production of 1000 m^3 of concrete. Tam and Tam (2007) report that nearly 1.5% of the fresh concrete produced is returned in Hong Kong. Sandrolini and Franzoni (2001) utter that in a 9 m^3 RMC truck, at the end of each delivery, there is around 200 to 400 kg of adhered concrete. Kazaz and Ulubeyli (2016) used Cement Sustainability Initiative (CSI) information (CSI, 2009) generated from available data on concrete recovery in 17 different countries and concluded that the amount of waste produced in a concrete-batching plant corresponds to 0.4–0.5% of the total production, which represents a significant variation. Because none of those studies reported details of the measurement methodology or even the precise fraction corresponding to each cause of waste generation, it is not clear which study is more accurate or which could be specific to other countries.

Xuan et al. (2018) discuss management strategies for treating fresh concrete waste, such as: (i) Recycling in new downgraded products, delivering fresh concrete waste to small pre-cast concrete elements, like paving blocks and wall blocks, or for construction uses, such as backfilling. (ii) Reuse in new batches of concrete mixture with or without chemical additives or admixtures. (iii) Recycling after hardening of fresh concrete waste, transforming the returned concrete by crushing into a recycled concrete aggregate. (iv) Reclaiming by a washing-out process by a mechanical aggregate-reclaiming system to reclaim aggregates and grey water. The difficult point is to determinate which one could be more effective, because this depends on knowledge of the volume and frequency at which waste is generated. The economic viability analysis of these strategies depends on the actual amount of waste produced, which affects the processing infrastructure and its operational costs and logistics.

Previous studies have already evaluated several management strategies. Ferrari et al. (2014) studied the use of superabsorbent polymer and setting accelerator admixtures in the recycling of concrete and concluded that the technique can be used to transform the returned concrete into reusable granular material. Asadollahfardi et al. (2015) carried out experimental and statistical studies to evaluate the use of ready-mixed truck wash water. Vieira and Figueiredo (2016) evaluated, on an industrial scale, the feasibility of using water and aggregates reused by concrete recycling equipment as an input for the production of concrete. Fraile-Garcia (2017) demonstrated that recycled aggregates produced by crushing and sieving the hardened waste concrete are suitable for the production of structural concrete replacing the natural aggregate in up to 50% depending on the waste treatment method. However, the decision about which recycling system will be implemented depends on important information such as the type and amount of waste that will be regularly produced by the industry.

The source of returned concrete is associate to two distinct situations. The first, the adhered concrete, is inherent in the production process, since a certain amount of concrete always remains adhered inside the concrete mixer drum after its total unloading at the job site. The second, the concrete leftovers, is related to the concrete that could have been unloaded in the job site but ended up being returned to RMC. In this last case, there was factors interfering in the process that prevented the total unloading of the concrete truck. In this sense, the leftover concrete can be considered an avoidable waste unlike what happens with the adhered concrete.

The adhered concrete is the fraction of the ready-mix concrete that can only remove by washing (Vieira and Figueiredo, 2016). The adhered concrete cannot remain inside the truck because, in this way, it will harden and compromise the mixing capacity of the mixing drum and the equipment lifespan. Consequently, this material should be removed by washing with water under high pressure at the end of each trip. This leads to a high water consumption in the process as indicated by Mack-Vergara and John (2017). On the other hand, the concrete leftovers can be easily discharged through the normal unloading process and sent to recycling systems or landfills.

There is little data available on the amount of adhered concrete. According to Paolini and Khurana (1998), the amount of adhered concrete is about 300–350 kg when the drum has a capacity of 9 m^3. There is no information on the factors governing the amount of adhered concrete, or even the representativeness of this data. However, it is relevant as a source of waste and waste generation, as identified by Wu et al. (2014).

Some of the trucks will return to the plant with leftover fresh concrete for various reasons, such as order in excess by the user or technical problems, such as surpassed time-to-delivery; non-compliance with workability specification. This specific type of waste is called leftovers and represents a much higher volume of waste per truck than the adhered concrete. The primary data of the publications that deal with this theme are not available. Therefore, the contribution of various waste sources is not clearly understood, making it difficult to prioritize waste-generation-mitigation strategies. Similarly, there are no data on RMC waste generation for developing countries in general, and Brazil in particular.

This research aims to determine the volume of waste generated under the regular operations of RMC plants, detailing the respective causes. In the study the residues from leftover concrete and the concrete adhered inside the concrete mixer drum are analyzed specifically.

This work presents an extensive survey on almost 100 plants of one of the largest RMC in Brazil and allows the discussion of mitigation strategies to enable better decision-making conditions for producers.

Previous studies carried out focusing on the RMC indicated that the residues resulting from the external cleaning activities of the trucks and the dust control of the plant are not representative and, consequently, these topics are not analyzed in this work.

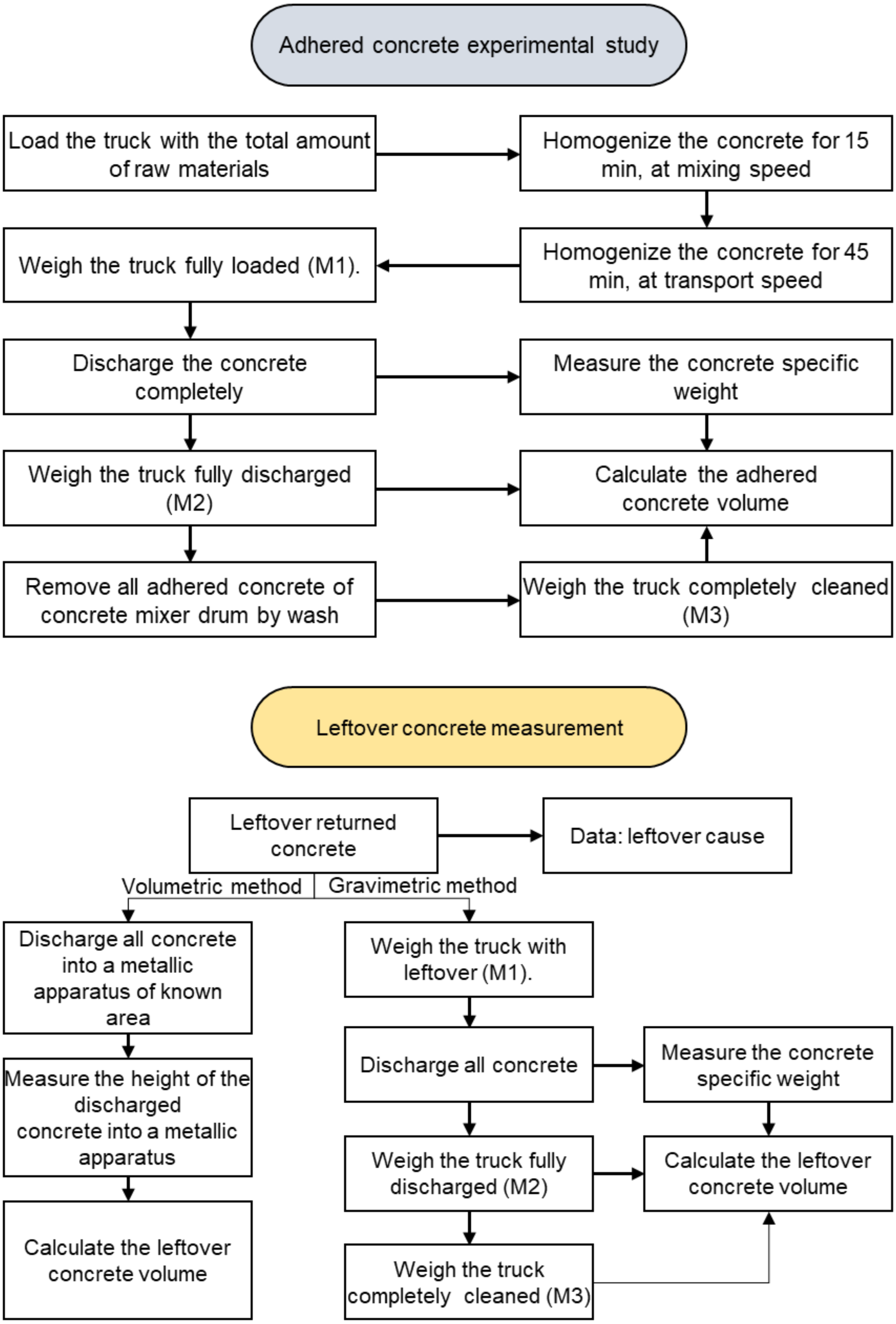
2.2. Methodology

The survey of the volume generated of residues associated with leftovers and their respective causes was carried out in 94 RMC plants from Engemix, one of the major Brazilian companies. These plants are distributed in all geographic regions of Brazil, and the survey was carried out at the same time during one year.

All the analyzed concrete plants had capacities between 35 and 150 m^3/h. The RMC plants were similarly equipped with dry-mix weigh batchers with digital scales, and were composed mainly of cement and aggregate batchers, conveyors, radial stackers, aggregate bins, cement bins, cement silos, batch plant controls, and dust collectors.

Figure 1 shows the summary flowcharts of the macro-activities carried out in the experimental study that measured the amount of concrete adhered and the method used to collect information on the volumes and causes of concrete leftovers.

Figure 1 - Flowcharts of the macro-activities



Source: The author

Because the adhesion of the concrete to the truck's rotary drum mixer is unavoidable and its volume is not usually measured, a parallel experimental study was carried out to quantify the amount of concrete adhered to each drum and to identify the intervening variables. This information allows the postulation of a model to estimate the amount of adhered concrete and dissociate its volume from the total returned concrete measured.

2.2.1. Adhered concrete experimental study

The study focuses on the determination of the adhere concrete for different mixture conditions, resulting in a total of 192 batches. To evaluate the influence of the concrete formulation and characteristics on the volume of adhered concrete, the slump, cement content, and truck load volumes were varied.

- Four level of slump, between 50 and 200 mm (which represents 99% of the concrete produced),
- Four cement contents, varying from 150 to 450 kg/m³ (which represents 99% of the concrete produced),
- Two truck load volumes were used: 4 and 8 m³ (which represents all of the concrete produced),

Twelve batches were produced for each formulation, six with 4 m³ and the other six with 8 m³. Table 1 presents the concrete formulations used in the experiment.

Table 1 – Concrete mixtures by slump class

Slump Class	Cement (kg/m³)	Natural sand (kg/m³)	Artificial sand (kg/m³)	Coarse aggregate (kg/m³)	Superplasticizer (kg/m³)	Water (kg/m³)
S 50	150	537	537	1065	1.05	169
	250	490	490	1068	1.75	169
	350	442	442	1072	2.45	170
	450	394	394	1078	3.15	171
S 100	150	559	559	997	1.05	177
	250	512	512	1000	1.75	177
	350	464	464	1004	2.45	177
	450	417	417	1008	3.15	178
S 160	150	573	573	932	1.05	190
	250	527	527	935	1.75	190
	350	479	479	938	2.45	190
	450	432	432	942	3.15	191
S 220	150	594	594	856	1.05	202
	250	547	547	859	1.75	202
	350	500	500	863	2.45	203
	450	453	453	867	3.15	204

Source: The author

The tests were carried out in a plant located in the city of São Paulo / SP. The raw materials were selected, focusing on the most representative of the plant production because it was impossible to perform a study covering all the cement types available on the Brazilian market. The cement used in test was CP II E 40 (Portland cement blended with up to 34% of blast furnace slag) from Votorantim Cimentos, Santa Helena plant in São Paulo/SP. The admixture used was a G-type superplasticizer according to ASTM C-494 supplied by GCP applied technologies. The fine aggregates used were Quartz fine aggregate (fineness modulus of 1.10), Limestone artificial fine aggregate (fineness modulus of 2.89), and limestone coarse aggregate (maximum size 19 mm and fineness modulus 6.92).

These materials represent about 25% of the production. The RMC plants use a unique type of concrete truck for all plants.

The procedure for estimating the amount of adhered concrete comprehends the following steps:

- The truck mixer drum is loaded with the total amount of raw materials.
- The materials were mixed for 15 min, at mixing speed, between 14 and 16 revolutions of the mixer drums per minute.
- The concrete was continuously mixed for 45 min, at transportation speed, simulating the transport period to the job site, between 1 and 2 revolutions of the mixer drums per minute.
- The fully loaded truck was weighed (M1).
- The truck was fully discharged and weighed again (M2). The concrete slump and specific weight were measured.
- The drum of the truck was completely washed to remove all adhered concrete and then weighed (M3).

After the weighing process, the mass of the adhered concrete, obtained by the difference between M2 and M3, was converted into volume using the concrete specific weight. The volume of the adhered concrete per truck was then obtained and correlated with the most representative parameter of the RMC.

A regression using the least-squares method was performed to correlate the volume of concrete adhered in the truck and the studied variables: slump, cement content, and volume of the loaded concrete. The estimated adhered concrete was calculated by multiplying the average values obtained in the analysis of the production profile of the concrete in the regression equation obtained by the statistical inference by the specific mass of the adhered concrete.

2.2.2. Measurement of leftover concrete

The leftover concrete measurement required a special location installed in all the RMC plants used in the survey. Together with this preparation, an extensive training program was carried out in order to qualify the workers.

Two different methods were used to measure the volume of leftover concrete. In the volumetric method, the concrete was discharged into a metallic apparatus with a defined volume that is used to produce concrete blocks. The leftover concrete from a single truck can fill several units, and one apparatus can receive the leftovers from several trucks. The gravimetric method is used in plants that have truck weight balance, and requires the conversion of the concrete mass into volume using the specific weight. It should be noted that the leftover concrete does not includes the adhered concrete, as discussed in the previous section.

The measurement of the volume of concrete deposited in the metallic apparatus was obtained by multiplying the cross section of the apparatus by the height of the layer of leftover concrete deposited in the apparatus. The height of the layer cast in the apparatus was determined by measuring the internal distance from the bottom of the apparatus to its edge; before and after the layer production, the height measurement was performed at four different points distributed along the perimeter of the cross section of the apparatus.

To calculate the volume of concrete deposited in the apparatus, the average value obtained from the four height measurements was used in order to reduce the error inherent to the measurement procedure. The precision of the measurement was limited by the system created to store the data (0.1 m^3).

The causes of the concrete return were previously classified into 5 groups. These five categories were determined based on the experience of the RMC company in order to cover the totality of events that could force concrete devolution:

- Over order - User returned the concrete
- Load reject - Fresh concrete did not comply with specifications

- Transport time exceeded - Maximum time period for transportation of the concrete was exceeded
- Application time exceeded - The maximum time for concrete application was exceeded
- Equipment failure - Failure of RMC's company equipment (truck or pump)

The boxplot with interquartile constant (c = 1.5) was used to calculate the boxplot quadrants; the resulting upper and lower limits include 99% of the data. The analysis of variance (ANOVA) was used verify the significance of variables (p-value = 0.05).

2.3. Results and discussion

2.3.1. Estimating the adhered concrete volume

Table 2 lists the average results obtained in the experiment to determine the volume of adhered concrete in the truck drum.

Table 2 – Average adhered concrete volume (dm^3) in function of concrete slump and cement consumption

Slump Class	Cement (kg/m^3)	Load 4 m^3 (dm^3)	Load 8 m^3 (dm^3)	Average (dm^3)
S 50	150	161	160	161
	250	170	171	171
	350	178	182	180
	450	189	186	188
S 100	150	133	133	133
	250	145	145	145
	350	152	154	153
	450	161	159	160
S160	150	98	98	98
	250	110	108	109
	350	118	113	116
	450	124	123	124
S 220	150	67	67	67
	250	77	77	77
	350	87	84	86
	450	96	99	98

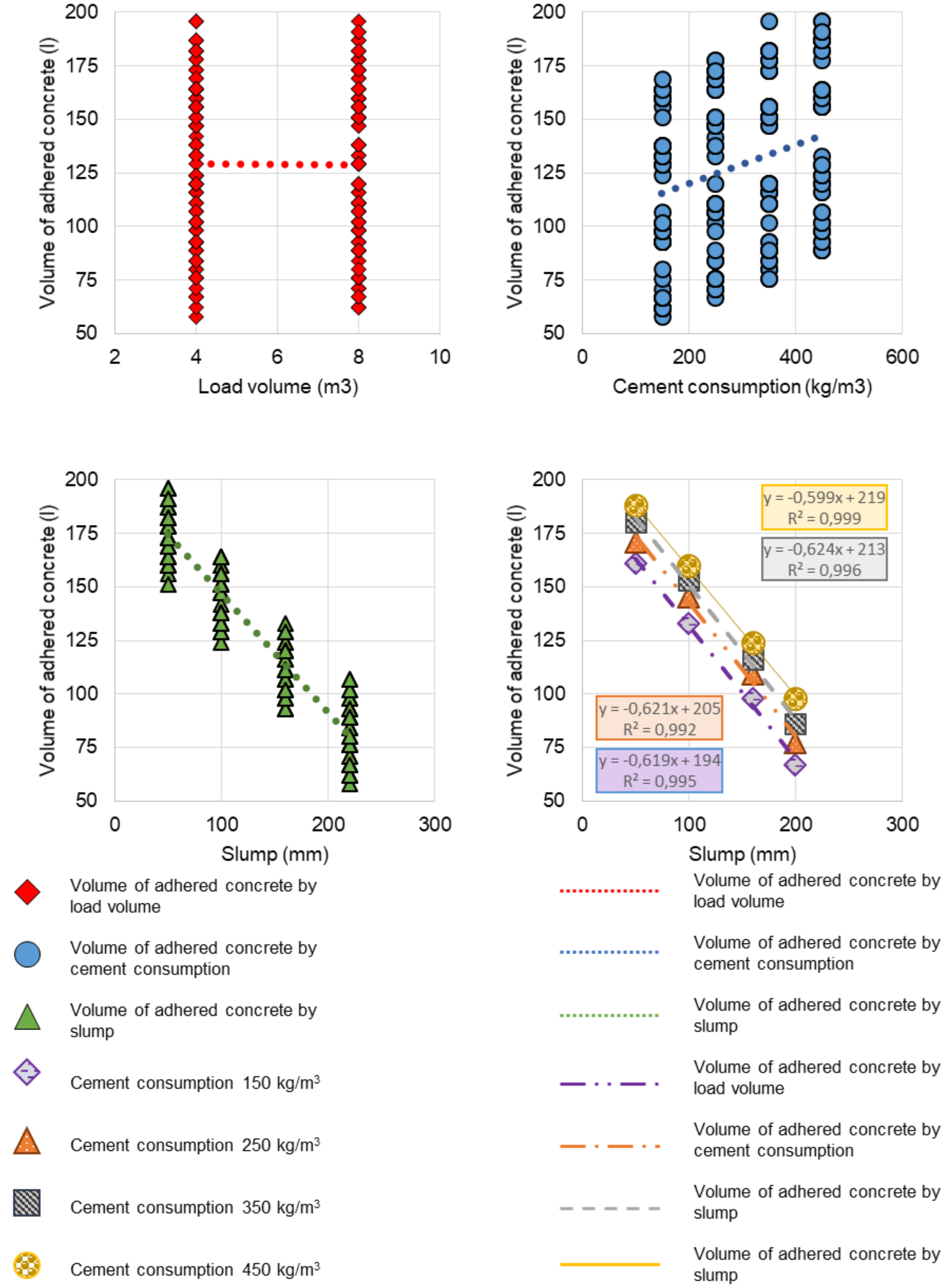
Source: The author

The average result is derived from six individual results. The amount of adhered concrete varied from 67 dm^3 (slump 220 mm and 150 kg/m^3 of cement) up to 189 dm^3 (slump 50 mm and 450 kg/m^3 of cement). These values, when converted to mass, vary between 160 kg and 470 kg. The amplitude of variation of these values is very close to the range of variation found by Sandrolini and Franzoni (2001). However, it is important to emphasize that is important to determine how the characteristics of the concrete influence the variation of the volume of adhered concrete.

The loaded volume in the drum does not present any influence on the amount of concrete adhered to the internal surface. This finding could be justified by the fact that the adhered material is dependent on the contact of the concrete with the internal drum surface. Even when a lower load is used (4 m^3), it is guaranteed that the entire surface will be in contact with the loaded concrete, at least when the concrete is discharged. Because the loaded volume is not relevant, the smaller is the concrete load, the higher the percentage of concrete wasted due to adhesion. In this sense, smaller loads are inherently less efficient. In consequence, parameterization of the adhered concrete through the percentage of concrete produced is not the most accurate procedure. Because only one type of truck is used in the experiment, it is important to remember that further experiments are required to confirm the influxes of different sizes or geometries of truck drums. The slump appears to be the most influencing parameter to define the volume of adhered concrete. This fact is associated with the higher level of yielding stress of the material (Roussel, 2016) that provides conditions to build up a thicker layer of adhered concrete. The adhered volume is also affected by the cement content due to the increase in the material cohesion with the increase of the fine material content. However, the cement content presents a lower influence on the volume of the adhered concrete.

In order to illustrate the observed general behavior, the graph presented in Figure 2 shows the correlations between the individual results of the volume of adhered concrete and the all variables studied (2a, 2b and 2c). The mean values of the adhered concrete volume are correlated with the slump level for each cement consumption. The high level of the coefficient of determination obtained for these correlations demonstrates their high level of representability (2d).

Figure 2 - Correlation between the volume of adhered concrete and the (a) load volume, (b) cement consumption, (c) slump level and (d) the average value of the volume of adhered concrete and the slump level for each cement consumption.



Source: The author

The ANOVA test was used to provide a better overall analysis, and proves that the consumption and slump have a statistically significant ($p<0.001$) influence on the volumes of adhered concrete, reinforcing the greater importance of the slump. On the other hand, the truck load again did not present any statistically significant influence ($p=0.556$) on the adhered volume.

Equation 1, obtained by a linear least-square multiple regression, describes the effect of cement consumption and concrete slump on adhered concrete, with a determination coefficient of 0.98. Residues are homogeneously distributed (Figure 3).

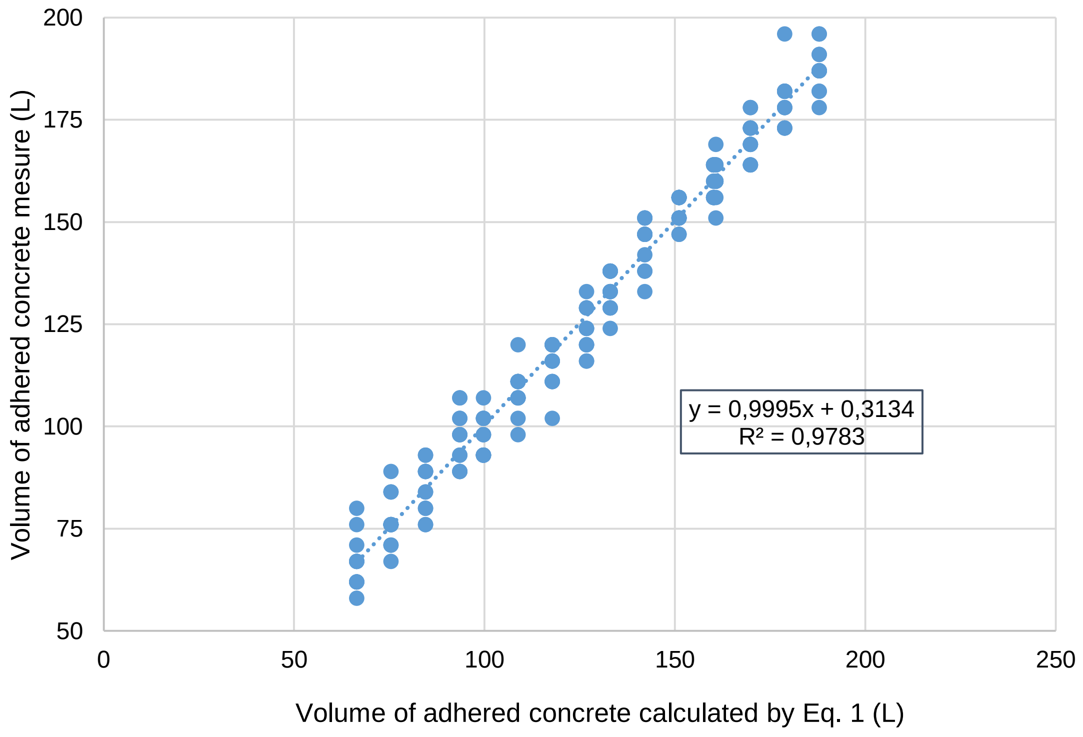
$$A = 175 + 0.0903 \times C - 0.555 \times S \qquad \text{(Eq. 1)}$$

A: Volume adhered concrete (dm^3)

C: Cement consumption (kg/m^3)

S: Concrete slump (mm)

Figure 3 - Adhered concrete: correlation of measured and theoretical volume (Eq. 1)



Source: The author

Considering that the concrete specification is the client's decision, it is difficult to minimize the adhered concrete in dry-batch plants without innovation in the equipment, particularly on the rotary drum mixer design. However, this study is limited to the dry batch type, and it is possible that, in the case for wet batch or even in the case of half-wet batch plants, the amount of adhered concrete waste will be different and hopefully smaller.

2.3.2. Inventory of the returned concrete waste

Nearly 5 million cubic meters in almost 770 thousand trips were produced in the 94 RMC plants in the period from January 1 to December 31, 2011. Table 3 shows the volume and number of trips that returned with only adhered concrete or concrete leftovers for each slump level. The volume of total adhered concrete is the result of the calculation of the cement consumption average of the respective slump class versus the total trips produced of each slump class in each RMC plant. The total volume of concrete returned is the sum of the inferred total volume of adhered concrete by Eq. 1 and the measured volume of leftover concrete.

Table 3 - Total ready-mixed concrete waste

Concrete slump class		S 50	S 100	S 160	S 220	Total
Adhered concrete	Trips (un)	1.292	371.451	219.678	35.217	627.638
	Total (m^3)	218	53.378	24.689	3.135	81.420
Leftover concrete	Trips (un)	80	19.809	16.415	3.587	39.891
	Total (m^3)	131	33.432	27.908	6.016	67.487
Total trips (un)		1.372	391.26	236.093	38.804	667.529
Total returned concrete (m^3)		349	86.810	52.597	9.151	148.907
Total concrete produced (m^3)		10.198	2.907.544	1.670.674	256.743	4.845.158

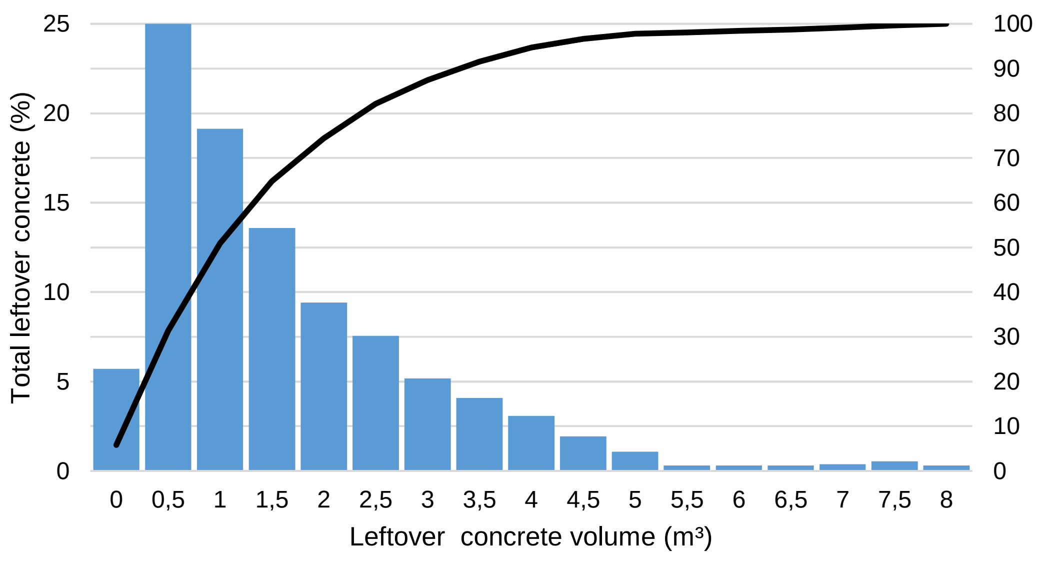
Source: The author

The fraction of the concrete adhered (1.7% of the concrete produced) is similar to the volume of leftovers concrete (1.4% of the concrete produced). Although it is possible to reduce the volume of leftovers, the volume of concrete adhered will vary according to the number of deliveries made by RMC trucks, as it is inherent to the technology.

The causes that most affected the volume of concrete leftovers are the over order (0.81% of the concrete produced) and application time exceeded (0.53% of the concrete produced). The causes: equipment failure, load rejection and transport time exceeded together accounted for 0.06% of the concrete produced.

Figure 4 resumes the contribution of each leftover volume class to the total returned concrete. The average volume of leftover concrete per truck mixer was relatively low, presenting an average value of 1.69 m^3 with a standard deviation of 1.46 m^3. It is interesting to observe that only 5% of the trucks return with leftover concrete (but always with adhered concrete) and about 25% of the concrete returned comes with a load between 0 m^3 and 0.5 m^3 (plus the adhered concrete); 50% of the trips with leftover concrete contained less than 1.2 m^3 with only 10% with loads above 3 m^3.

Figure 4 – Distribution of the percentage of the leftover as a function of the truck load volume.



Source: The author

Table 4 resumes the contribution of each cause for the leftover concrete. The results show that the main causes of returning concrete loads are (a) over order, representing almost 58% of the leftover volume, and (b) maximum application time being exceeded, 38%. Both causes are related to factors that are not under the RMC's direct control. Other causes represent the remaining 4% of the leftover concrete.

Table 4 – Relative frequency of volume and travel of leftover concrete by its causes

Causes of concrete leftover	Leftover concrete			
	Trips		Volume	
	(un)	(%)	(m^3)	(%)
No concrete leftover	628,588	94.03%	4,783,095	98.61%
Over order	26,476	3.96%	39,096	0.81%
Transport time	62	0.01%	383	0.01%
Application time exceeded	12,719	1.90%	25,640	0.53%
Load reject	252	0.04%	758	0.02%
Equipment failure	382	0.06%	1,610	0.03%
Total	668,479	100%	4,850,582	100%

Source: The author

The results of the ANOVA variance analysis show that the geographical region of the plant is not statistically significant ($p = 0,892$) in, and therefore does not influence, the percentage of returned concrete.

There is a large difference among the means ($\bar{x}$) and standard deviation (σ) and medians (μ) of the volumes of leftover concrete as a function of the different causes . Because each of these causes is influenced by different factors is important to emphasize the following aspects:

- Application time exceeded ($\bar{x}$=2.0 | σ=1.8 | μ=1.4) – According to the Brazilian standard, the placement of concrete must start at least 30 min after the concrete mixer truck arrives at the job site and should be completed in less than 150 min, counted from the first addition of water. Construction teams not being ready, concrete planning failure, and breaking of equipment used in the launching and densification of concrete induce this type of cause.
- Over order ($\bar{x}$=1,5 | σ=1.1 | μ=1.2) – The difference between the volume of concrete requested and the volume required for concreting is caused by possible discrepancies between the volume requested, the volume required, and the fact that the Brazilian standard establishes that commercialization of concrete must occur in multiples of 0.5 m^3.
- Equipment failure ($\bar{x}$=4.2 | σ=2.7 | μ=4.7) – Failure or breakdown of equipment that belongs to the RMC company. This tends to occur at the beginning or end of the concrete discharge. It may be possible that during

the concreting, the equipment is forced to the limit that could result in a break. This is caused by failure to maintain equipment, poorly dimensioned equipment for the service, low quality of equipment, or concrete quality problems.

- Transport time exceeded ($\bar{x}$=5.9 | σ=1.3 | μ=6.0) – The Brazilian standard establishes a time limit for the transportation of concrete (90 min); whenever this limit is exceeded, the truck is prevented from being unloaded at the work site and is returned fully loaded. This cause is influenced by logistic failures, like route-planning errors or unforeseen traffic jams.
- Load rejected ($\bar{x}$=3.0 | σ=2.6 | μ=1.8) - The load was rejected by the client and the truck must be returned without discharge, typically due to non-conformities with the specified slump or to other requirements such as strength class, cement type, or content.

Over order and excessive transport time represent more than 95% of the actual return of the leftover concrete volume. Although significantly lower, other causes that are also responsible for the leftover concrete need to be considered. This consideration is important when the RMC plant establishes a strategy to minimize the generation of production waste. As an example, when the leftover is due to transport time, although not very significant in general terms for a plant that produces 400 m^3 of concrete daily, the arrival of a large volume of concrete back to the RMC plant will affect the daily conditions of routine work.

The training of the workers can also reduce equipment maintenance problems, failures in logistical planning, clumsiness in the concrete mix design, and inability to judge the most suitable solutions for construction. Some cases that have been pointed out in the survey of concrete leftovers illustrate important situations. As an example, sometimes the job site team is too small to deal with possible occurences, resulting in a delay in the concrete-casting operation. Over order may be a result of uncertainty about the required concrete volume, because the return of an eventual excess order is cheaper than ordering an additional truck with the minimum volume of 3 m^3.

2.3.3. Environmental impact and options

The volume of wasted concrete causes environmental (increase in material demand and waste generation) and financial impacts, which need to be mitigated. Data from the SNIC (2015) indicate that, approximately 11 million tons of cement are destined for Brazilian RMC plants per year. Assuming that concrete contains 11% cement on average, it is possible to estimate that the average concrete production in Brazil is approximately 35 million cubic meters per year. Adopting the values found in this study for all RMC companies in Brazil, it is possible to estimate that the volume of waste generated annually is approximately 1.05 million cubic meters, which could not be neglected. In that sense, the establishment of effective strategies to reduce the generation and treatment of waste in RMC plants is essential.

Because the slump is a demand of the client and cement consumption is usually a function of concrete strength established in the design phase, it is very difficult for RMC companies to minimize the adhered concrete waste volume. The only option is to create an infrastructure to recycle leftovers in the range of 1% to 2% of the volume of the concrete produced on a daily basis. As the removal of the adhered concrete takes place whenever the truck returns to the plant, the use of setting-retarder admixtures tends to be preferred, as it is simple, quick, and easy to apply.

Approximately 50% of trips with leftover concrete contain less than 1.2 m^3. This indicates that any type of solution to handle this source of waste should be able to manage a large number of leftover trucks with low volumes of concrete. Some measures can be taken to reduce the volume of leftover concrete, such as better planning for placing the concrete on the job site. Another specific problem in Brazil is the standard regulations that prohibit selling concrete volumes with fractions less than 0.5 m^3. The adequacy of technical standards to allow commercialization of RMC in fractions of 0.1 m^3 could be useful to reduce leftovers. On the other hand, this adjustment may increase the volume of leftovers, since there may be more planning errors that lead to the need to order complementary concrete loading for the RMC. Therefore, the reuse or recycling processes should be simpler and easier to perform.

Currently, because of the amount of waste generated in concrete production, studies are carried out in search of solutions that can be used in RMC plants, such as:

- Adding hydration-stabilizing admixtures in order to extend the concrete service life for reuse;
- Using fresh concrete recyclers, which allow the recovery of aggregates and water;
- Recycling the leftover concrete after hardening by crushing and transforming it into recycled aggregates.

Processes that affect the productivity of the RMC plant, and hence will negatively influence their financial result, tend to be avoided. Therefore, the use of low-capacity or complex recyclers/crushers is not considered a feasible alternative.

2.4. Conclusions

According to this study, about 55% of the volume of concrete returned to the RMC plant is due to the adhered concrete and occurs continuously. The removal of adhered concrete from the drum of the concrete mixer is only possible by washing it, which implies in a large amount of water consumed in the process. The parameterization proposed in this study, correlating the volume of adhered concrete with the level of slump and cement consumption, can be used as a valuable tool to guarantee the efficiency of the process.

A significant reduction of the amount of residues associate to leftover concrete generated in the production of the RMC is possible through procedures that aim at reducing the quantity of material returned. Improvements in delivery logistics can reduce waste associated with the application time exceeded and the implementation of commercial practices such as charging for over-ordered volume to job sites would possibly reduce part of the 95% of the waste that is generated from of concrete leftovers. In this sense, the surveys carried out in this study can be used as reference for similar concrete production situations in order to validate waste management strategies.

3. EVALUATION OF CONCRETE RECYCLING SYSTEM EFFICIENCY FOR READY-MIX CONCRETE PLANTS

3.1. Introduction

Waste is constantly generated during the process of manufacturing ready-mix concrete. It is difficult to precisely determine the waste volume, but it is estimated that it can reach very high values. As an example, Sealey et al. (2001) showed that the volume of waste generated annually by ready-mix–concrete plants in the UK reached 750,000 tons at the time.

The quantity of fresh concrete that became waste in the construction industry in Europe is estimated at the range of 1 to 4.0 % of the total concrete produced, while in Brazil 9% of the volume of ready-mixed concrete goes to waste (Correia et al.,2009). In Japan and Hong Kong, about 1–2 wt% (Iizuka et al.,2012) and 1.5wt% (Tam,2008) of the total produced concrete goes to waste, respectively. This shows that the problem cannot be neglected.

There is always a portion of concrete that is returned to the plant owing to various reasons (e.g., material adhered inside the barrel of the concrete mixer truck and leftovers from different sources), thereby generating waste. In other words, part of the concrete that is produced and sent to the clients is discarded as waste in a “landfill”. However, there are costs involved in this process, both financially and environmentally (Benini, 2005); because there is also the risk of pollution the environment by leaching their arsenic and chromium contents (Audo et al., 2016). Thus, there is a need for minimizing or even eliminating this waste in order to avoid sending it to a “landfill”.

An alternative for solving this problem is the use of fresh concrete recyclers in concrete plants. This technological alternative aims to reuse the constituents of concrete that is returned to ready-mix-concrete plants (Tartuce, 2006) in order to reduce the volume of material destined for a “landfill”. The reuse of the recycled materials originated from recyclers in concrete plants may affect negatively the mechanical properties of concrete (Tartuce, 2006) and its workability (Correia et al., 2009). Those negative impacts could be overcome, but this process could imply in raising unitary cost for concrete.

The potential use of equipment for fresh concrete recycling, which allows the recovery of aggregates and water, could be attractive because previous studies have demonstrated that there are economic benefits in addition to environmental benefits. The reduction of total costs is related to residue transportation to the landfill together with a reduction of the demand for aggregates and water for regular concrete production (Rezende et al., 1996). This reduction of complementary costs could compensate the increase in the unitary cost of concrete if this cost rise is restricted. In that sense, studies focusing the reduction of the negative influence of the recycled materials in industrial concrete production are necessary.

Xian (2016) studied the reuse of dewatered slurry concrete waste for the production of new concrete mixtures adopting the accelerated carbonation technique and concluded that the variation in water to solid ratio of the collected fresh on dewatered slurry concrete waste affected significantly the compression strength of concrete. An alternative to that problem is presented by Audo et al. (2016) that had applied sludge from ready-mixed concrete plants as a substitute for limestone fillers in mortars where it could lead to an increase in compressive strength depending on the mix design.

The technological impact of the reuse of recycled concrete aggregates in the production of new concrete has already been previously studied. Montgomery (1998) has demonstrate that the use of recycled aggregates impacts negatively on slump and on concrete compressive strength. Tam and Tam (2009) concluded that it is essential to carefully assess some properties of recycled aggregate including particle density, porosity and absorption, particle shape, strength and toughness, and chloride and sulphate contents.

More recently, Sheen et al. (2013) assessed the use of aggregates recycled from construction and demolition waste in concrete plants and found a reduction of up to 25% in compressive strength. This reduction in strength was associated to the higher porosity of recycled concrete, which may be less intense in the case of the recovered aggregate obtained in ready-miexed concrete plants due to its lower porosity.

Recommended practices have already been published, focusing on the use of recycled water in the production of concrete (CCAA, 2007). These recommendations are an excellent reference guide for the use of water but do not address the water processing that occurs inside the plant itself. This process demands substantial care, to avoid that the input does not reduce the compressive strength or the setting time of the concrete as noted by Asadollahfardi et al. (2015), who demonstrated that the use of wash water for production in concrete trucks has important technological impacts that must be well parameterized. As an example, the use of admixtures in concrete production should be carefully analysed in order to avoid technical problems (Chatveera and Lertwattanaruk, 2009), who proved that the use of slurry reduces the compressive strengths of concretes mixed with sludge water are in the range of 85–94% of normal concrete. Thus, industrial conditions demand a comprehensive study to ensure the robustness of this technology.

However, fewer studies were found addressing the use of recycled aggregates obtained from concrete returned to the plant. Correia et al. (2009) gave an important contribution through a laboratorial study using fresh concrete waste collected at a concrete dosing central. Nevertheless, the studies focusing the use of recycled fresh waste in real conditions of production are scarce. Further, no works were observed relating to analysis of the simultaneous utilization of reused water and aggregates obtained from recycling equipment. Therefore, the technical impact of the recycled material utilization process in the concrete industry deserves to be further studied.

There are different types of aggregate recycling equipment available for separating the materials in fresh concrete. However, there are no studies addressing the effectiveness of these devices. Furthermore, the separation systems may differ in the resultant characteristics for the recycled materials (i.e., aggregates, water, and slurry). Thus, it is necessary to assess the efficiency of these processes on an industrial scale. Therefore, this experimental study aims to evaluate the feasibility of the utilization of reused water and aggregates as an input for concrete production at an industrial scale.

3.2. System implementation

In order to check the efficiency of the reuse of fresh concrete by mechanical processes, a ready-mix–concrete producer installed two different sets of equipment in São Paulo city: a drum-type recycler and a rotary sieve-type recycler located in concrete plants situated in the west and south sides of the city, respectively. The size and production capacity of both plants are very similar. Moreover, the plants use exactly the same raw materials and service the same consumer profile, which results in very similar production conditions. The plants also have decantation boxes of similar dimensions, which are used for washing the waste and the concrete returned in concrete mixing trucks.

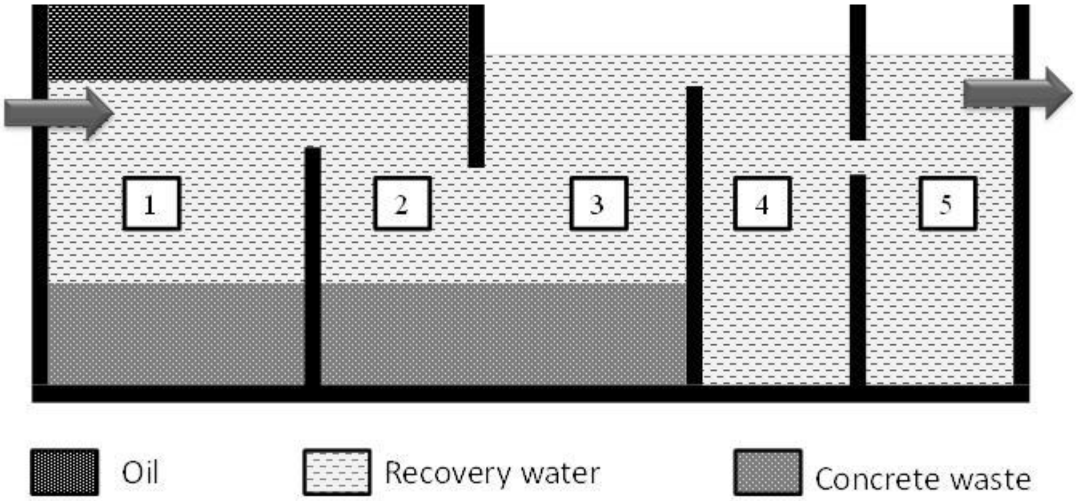
The installation process of the recyclers was defined and supervised by the equipment suppliers. All suggestions proposed by the equipment suppliers concerning plant layout adjustments were accepted and implemented as a way of ensuring that the equipment would operate under nearly ideal conditions

In order to avoid errors during the operation of the recyclers that would interfere in the results of the study, the operation of the recyclers in each plant was performed by a single RMC employee, who was previously trained by the equipment suppliers. With the exception of concretes with some kind of addition in their composition (e.g. fibres, pigments, silica fume), all concrete residue returned to the plant was recycled.

Both plants had their own decanters (i.e., settling boxes), which served to reduce the solid content. In addition to the decanters, segregate oils and other elements immiscible in water were the only ways of treating the concrete slurry. In order to reduce the content of particles dispersed in the reclaimed water, the basic design of a waste settling box is a tank assembly that reduces the effluent speed, so it allows gravity to separate waste from solid waste and oils. The settling boxes dimensions are calculated according to the size and production volume of each plant. These calculations also consider aspects related to the cleaning process of the boxes when they are in operation.

The installed settling boxes contain five compartments, which are connected and are set according to the role that each one plays; Figure 5 shows a schematic cross section of a standard settling box. The first compartment (1), which is the reception box, regulates the flow and receives water from the plant system. All concrete slurry that comes from the recyclers is also discharged in this box. The second compartment (2) is the oil containment box, which retains all the oil that enters the system. The third compartment (3) is the residue containment box: in which, the water and solid waste are separated by decanting and the solids are retained. The fourth compartment (4) is called the security box, which retains any material that has escaped from the first three boxes, safeguarding that only water reaches the last compartment (5), which stores the reclaimed water.

Figure 5 - Standard decanter system—schematic cross section.



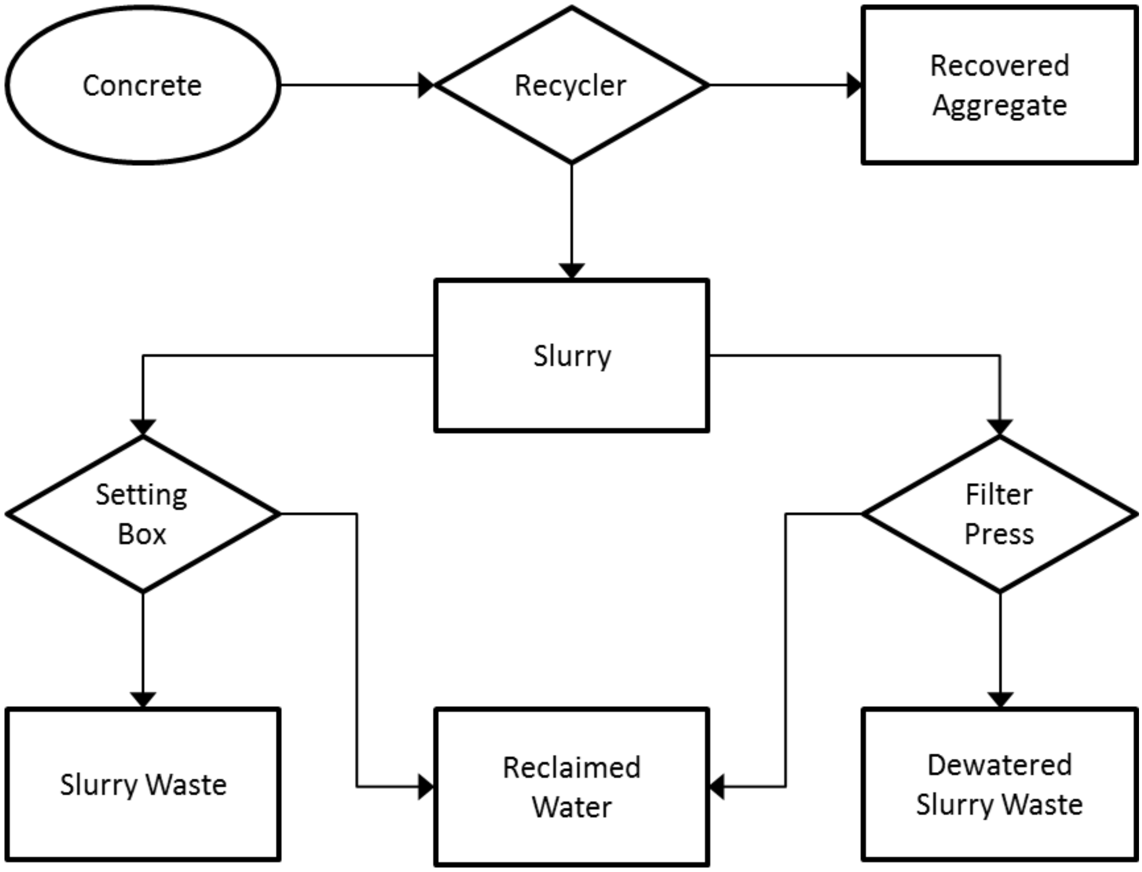
Source: The author

The recyclers were installed in both plants such that it was possible for each truck to discharge its concrete residue without disturbing the movement of other vehicles. It was also built as a temporary storage bay in the recycler output of solids. Therefore, it was possible to separate the recycled aggregate of others and avoid the contamination of raw materials. In addition, the recycler output of grey slurry was introduced directly into the decanter.

After the installation of the recyclers, all recovered aggregates generated daily were collected and sent to the “drying bay”, where the water content was reduced by natural drying. Recycled aggregates stay in this bay for approximately day; after which, aggregates were homogenized and placed in the “output bay”. This bay was named as such because it holds the recovered aggregates before they are sent to concrete production or disposal. During the first month of operation of the recyclers, the output bay was empty and all the recycled aggregate was sent for disposal in “landfills” at the end of each production day. This procedure was intended to ensure that no material build-up occurred on the courtyard of the ready-mix–concrete plant during the period in which the recycled aggregate was being evaluated in the laboratory for future application.

In the recycling process of fresh concrete with mechanical equipment, aggregates are separated from the concrete by washing with water under pressure in rotating drums, creating what is commonly called recovered aggregate and slurry. In both cases, the concrete slurry was sent to a settling box in order to separate the phases with a higher concentration of solids (concrete slurry or grey sludge) from the reclaimed water. This process is schematically shown in Figure 6. Thus, the use of mechanical recyclers will generate demand for allocation of three products: recovered aggregate, reclaimed water and slurry. The first two can be reintroduced to the production process and reused as a recycled material; only the slurry would be disposed in “landfills”.

Figure 6 - Mechanical recyclers - flowchart

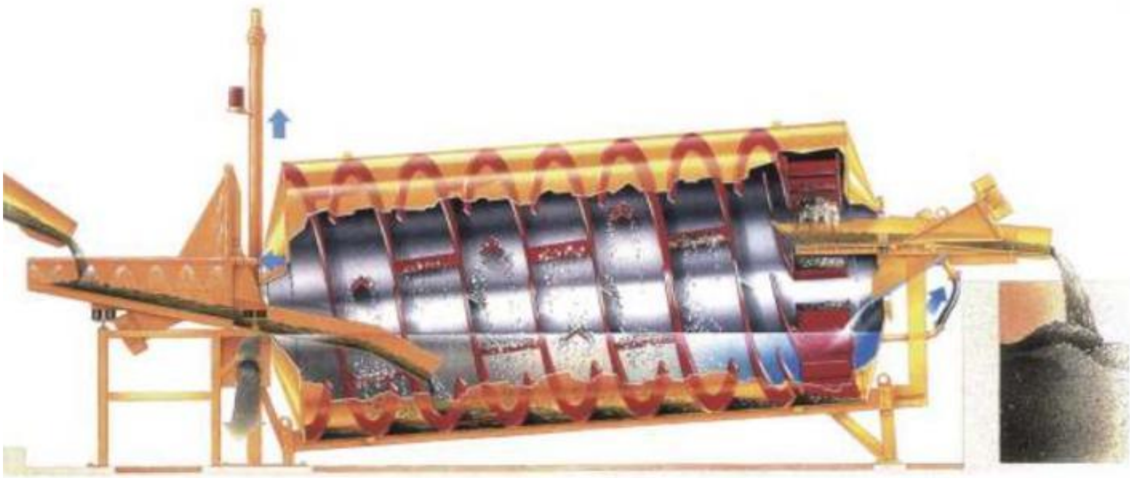


Source: The author

It is important to have in mind some relevant aspects for the successful reuse of aggregates. From the concrete producer's point of view, it is important to guarantee that the recovered aggregate has great homogeneity. The homogeneity of the material will facilitate the management of the production of material, with a lower demand for intervention to adjust the quality of the mixture. In that sense, it is important to check the aggregate characteristics that could affect the concrete behaviour. Considering that the recycled aggregate is related to the source—the aggregate that was originally used in the production of concrete—it can be assumed that some aspects linked to its petrographic characteristics remain unchanged. However, it is known that the recycling process will affect the particle size distribution of the recycled aggregate (Tam and Tam, 2009). As there will be a mix between coarse and fine aggregates, the recovered aggregate will possess a particle size distribution that results from the combination of the coarse and fine aggregates of the original compositions. Thus, it is essential to check how this occurs. In particular, if recycling changes the fine material content of the aggregate, it can cause changes in the concrete mix (Troxell et al., 1968).

The drum-type recycler, which is shown in Figure 7, uses spirals that rotate in the opposite direction of the flow, inducing the segregation of water from the solids in fresh concrete. In this type of recycling process, the slurry is drained through the bottom side of the recycler to cylindrical tanks where particles of cement and fine aggregates are maintained in suspension by means of stirrers.

Figure 7 - Drum type recycler

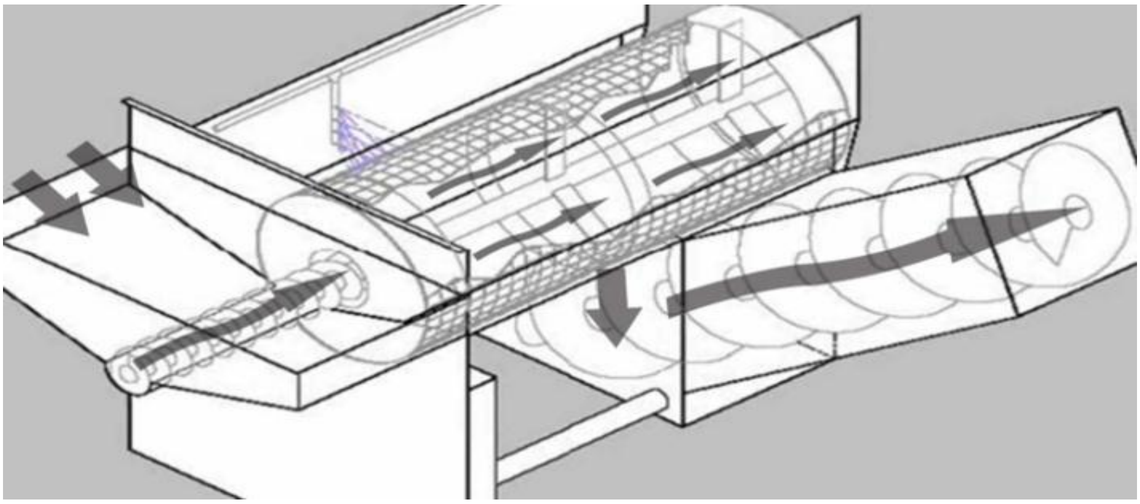


Source: Schwing Stetter (2019)

The aggregates can also be separated into fractions in these recyclers if some equipment with a sieve is also installed. However, this was not the case in the present study. Thus, the resulting actual aggregate was a combination of fine and coarse aggregates.

In contrast, the rotary sieve-type recycler (Figure 8) washes and separates the residue, which flows down in the rotary sieve, into coarse aggregate and mortar that is carried by a rotatable screw. Thus, it initially separates coarse fractions from the aggregates mixture, and the water is subsequently recovered from the fine aggregates. Both aggregate fractions (fine and coarse aggregates) can be dumped into separate bays, allowing for their future reuse in specific proportions in the manufacturing of new concrete.

Figure 8 - Rotary sieve-type recycle



Source: Schwing Stetter (2005)

The use of reclaimed water in concrete production could be an interesting alternative. However, this procedure must be performed very carefully in order to not harm the concrete quality. The effect of reclaimed water in the concrete is related to the content of solids and salts—as chlorides and sulphates—as well as its pH. The solids content could be correlated to the density of the reclaimed water (Low et al., 2007). When the amount of fine particles in the reclaimed water is higher than the defined limits, its use entails a negative effect on the effectiveness of water-reducing agents such as plasticizers and other admixtures (Chatveera and Lertwattanaruk, 2009). Thus, the reclaimed water should have density less than 1.03 g/cm^3 (Lobo and Mullings, 2003).

The volume of water generated during truck washing and concrete recycling is much greater than the volume of water ordinarily used for concrete production in the plant. Thus, it is important to emphasize that it is highly convenient for ready-mix producers to limit the generated volume of reclaimed water to a level that does not exceed the water consumption capacity of the plant. This avoids the need to create reservoirs for water storage or the achievement of specific and more complex treatments for its disposal into public collection services.

3.3. Experimental evaluation methodology

The decision to install the two recyclers in two plants included the premise of an experimental evaluation to verify their effectiveness. Therefore, a methodology was established to evaluate the applicability of such equipment considering the technical impacts that are described below.

3.3.1. Preliminary laboratory tests

Prior to the actual implementation of concrete production with the recycled materials, laboratory studies were performed to characterize each material, and mix-design studies were conducted to verify the impact of their use in the concrete mixes.

All data obtained in the tests for the recovered aggregates, slurry and water were compared with values obtained for aggregates and water ordinarily used in the plants. The samples used in the tests were collected and prepared in accordance with procedures established by Brazilian standards. The ready-mix–concrete producer used the concept of “total aggregate” according to NBR 7211. This Brazilian standard defines “total aggregate” as the resulting aggregate obtained from the mixture of coarse and fine aggregates. This concept allows for adjustments of the size distribution curve as a function of the different aggregate proportions. Thus, the same concept was adopted for the analysis of recycled aggregates.

The laboratory tests were performed on aggregate samples taken from the “output bay”. Twenty samples were tested every day for each original and recovered aggregate. The sample collection followed the recommendations from the Brazilian Standard NM 26 “Aggregates—Sampling”. The recovered aggregate has been characterized through the determination of specific density (NBR NM 53) and the particle size distribution (NBR NM 248).

During the 20 days, slurry samples were also collected directly from the recycler-settling box. The reclaimed water obtained at the output of the fifth decanter box was also sampled with the same frequency. The sampling of the slurry was done randomly and occurred during one aleatory recycling procedure performed in the plant. The sampling of the reclaimed water was always performed at the beginning of the workday. Samples of slurry and reclaimed water were analysed, adopting assays for determining the specific density and pH (NBR 15900). The head of the plant also collected reference water on a daily basis at the beginning of the working period to perform its characterization.

The effects of the recovered aggregate in the concrete mix design studies were evaluated by adopting a slump of 100 mm and characteristic strength classes varying from 20 MPa to 40 MPa (concrete classes C20, C25, C30, C35, and C40). The mix-design procedure adopted by the company is described in detail by Monteiro et al. (1993). In this regard, the compressive strength results were evaluated through a mix-design procedure where the original aggregates were replaced by recovered aggregates.

3.3.2. Tests on production conditions

All the aggregates commonly used in the production of concrete were sampled and tested daily. The study included 200 samples of each of the aggregates used in concrete production for which the specific density, particle size distribution, fineness modulus, and weight percentage of material passing through a 0.150 mm opening sieve were assessed. It should be noted that the number of samples was the same for conventional aggregates as it was for each of the aggregates obtained from the two analysed sets of equipment. The sampling of the three types of aggregates occurred during the same period for both plants. In the previous laboratory tests, the relative variation of the particle size distribution of the aggregates was also analysed for both cases. Samples of recovered water were collected daily to check the variability in terms of specific gravity and pH. The same number of samples (200) used for the aggregates was used for water characterization.

In order to analyse the impact of recycled materials on concrete quality, concrete mixtures were manufactured, and samples were tested for compressive strength and workability over a year. In consequence, approximately 1,000 cubic meters of concrete, which was made from reclaimed aggregate and reclaimed water and distributed in 145 mixer trucks, was tested.

When evaluating workability, focusing on the so-called monopoint tests is too limited to verify the behaviour of the material (Kuder et al., 2007). Therefore, the analysis was complemented by monitoring the field applications of pumpable concrete with recycled aggregate. The pumpability of concrete is defined as the ability of the material to be pumped without segregation or a significant increase in the pump pressure (Crepas, 1997). The pumpability is associated with the rheology of the material, and it is influenced by particle size, shape, texture, and factors inherent to all equipment used for pumping (Kishore, 1992). Naturally, the pressure and the optimal pumping speed are directly related to the type and model of the equipment (Crepas, 1997). Thus, to evaluate the effect of the recovered aggregates, all field tests were performed on concrete that was pumped over 28 meters by similar pumps. During the concrete pumping process, the pressure of the pump was recorded and compared with the historical pattern used by the company. In that sense, the concrete producer expects that the adequate pressure for pumping concrete should not exceed 180 Bar in their equipment.

The concrete truck driver and the pumping operators had no knowledge if the concrete was being produced with recovered or regular aggregates. Moreover, the loading procedure was done alternately with recycled and natural aggregates in order to prevent any result induction.

The field tests were focused on concrete whose specification requires a slump level of 100 mm and strength class C25. However, in order to avoid risks of non-compliance with the delivered concrete, the company decided to dispatch concrete from a higher class (C30) to the job sites. That decision was due to there being no prior knowledge about the variability of the concrete produced with recovered aggregates in the industry.

There were 31 different concrete applications with concrete with recovered aggregates and reclaimed water. Of which, 17 applications were made with aggregates from the drum-type recycler, and 14 were made with aggregates from the rotary sieve-type recycler.

For the 31 concrete applications, 275 concrete mixing trucks were delivered. Of which, 145 trucks were loaded with the usual aggregates of the ready-mix–

concrete plant, and 130 trucks were charged with concrete with recovered aggregate and reclaimed water. Of the latter group of trucks, 70 used aggregates from the drum-type recycler, and 60 used aggregates from the rotary sieve-type recycler. To reduce the possibility that specific operation problems could influence the performance of the material under evaluation, the production of concrete and shipment of concrete mixing trucks with regular and recovered aggregates and reclaimed water were done interchangeably.

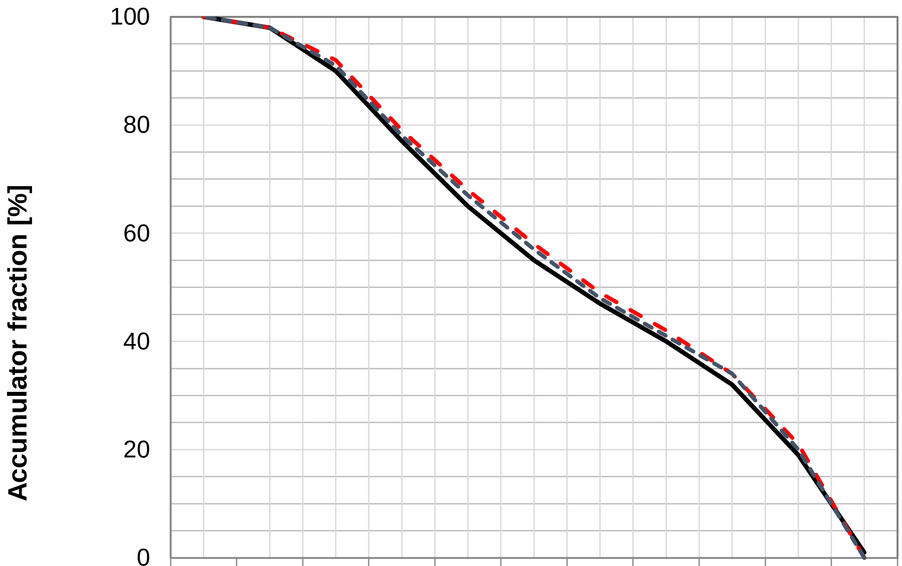
3.4. Results and analysis

3.4.1. Laboratory tests

3.4.1.1. Aggregates

The average particle size distribution curves of the regular aggregates and both recuperated aggregates were very close (Figure 9). This fact indicates that, during the process of recycling, the equipment can separate the cement paste and aggregates without any significant influence on the average size distribution of the particles.

Figure 9 - Reference and recovered aggregates - total aggregate: average particle size distribution (NBR 7211).



	< 0.15	0.15	0.3	0.6	1.2	2.4	4.8	6.3	9.5	12.5	19
Regular aggregate	100	98	90	77	65	55	47	40	32	19	1
Drum recycle aggregate	100	98	92	79	68	58	49	42	34	21	0
Rotary sieve aggregate	100	98	91	78	67	57	48	41	34	20	0

Passing particle size [mm]

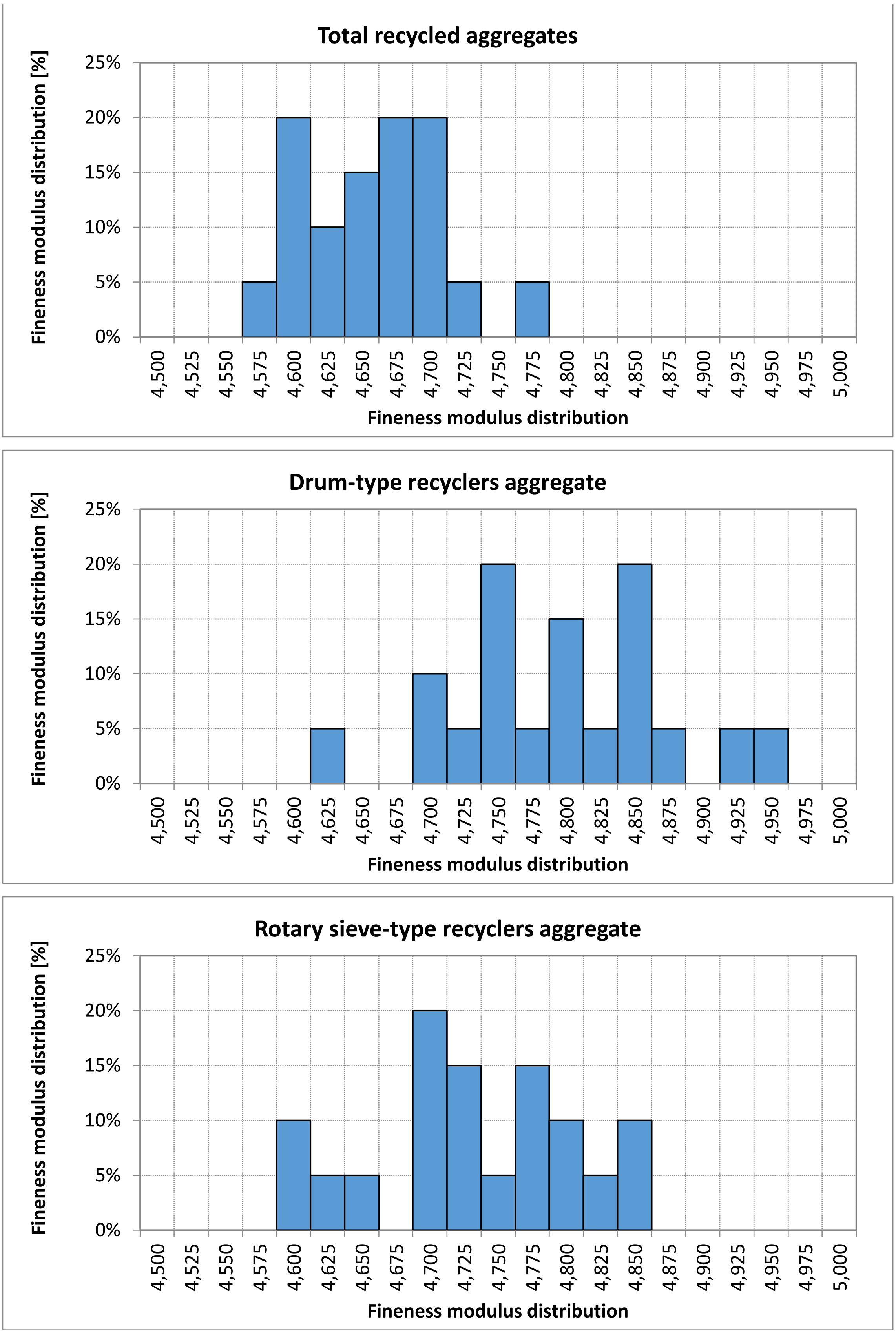
Source: The author

Figure 10 shows the data on the fineness modulus of the different aggregates. The fineness modulus of the regular total aggregate was 4.65, with a standard deviation of 0.05. The maximum and minimum values obtained for this parameter were 4.45 and 4.55, respectively. The total recycled aggregates showed averages fineness moduli of 4.79 and 4.72 for the drum-type and the rotary sieve-type recyclers, respectively. The standard deviation of both cases was 0.08. The maximum and minimum values of the fineness modulus were 4.94 and 4.79, respectively, for the drum type–recycler aggregate, 4.85, and 4.72, respectively, for the rotary sieve-type recycler. This reveals that the recycled aggregates have a slightly higher fineness modulus than the reference. The variation coefficients were 1.08 for the reference aggregate and 1.67 and 1.69 for the drum-type and rotary sieve-type recyclers, respectively. Thus, the variability of the recovered aggregates was very low despite being higher than the reference aggregate.

The average weight percent passing through a sieve of 0.150 mm for the reference aggregate was 1.72%, with a standard deviation of 0.5% and maximum and minimum values of 0.7% and 2.7%, respectively. For the drum-type recycler, the corresponding weight percent average, standard deviation, minimum, and maximum values were 1.74%, 0.64%, 3.0% and 1.0%, respectively. For the rotary sieve-type recycler, the corresponding values were 2.05%, 0.51%, 3.0% and 1.0%, respectively. The average results were very close to those obtained for the reference total aggregate. Similarly, the coefficients of variation for these levels (36.6% and 24.9% for the drum and rotary sieve-type recyclers, respectively) were very close to the coefficient of variation obtained for the reference (29%).

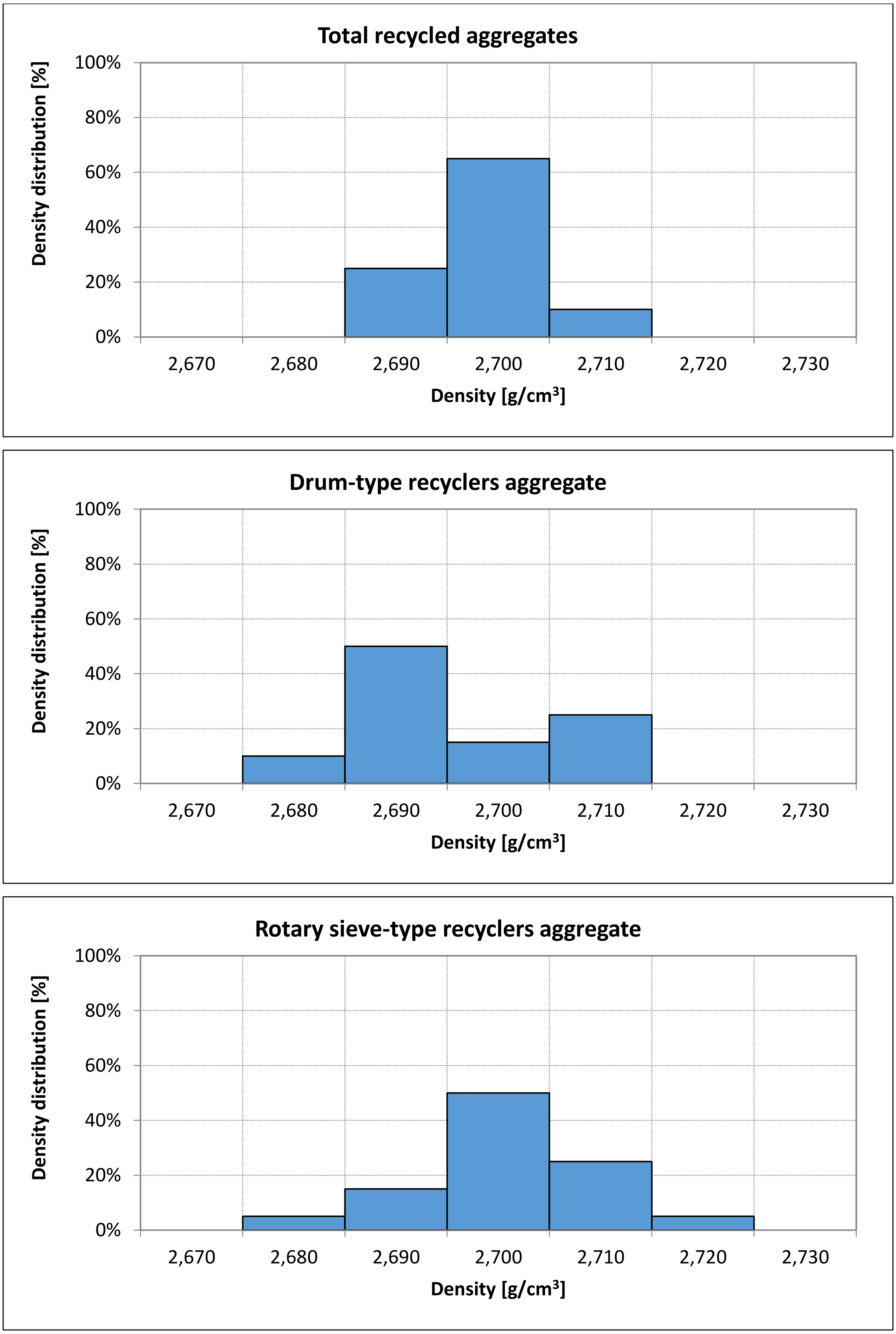
Figure 11 demonstrations the results of the distribution density tests. The density of the reference aggregate was 2.70 g/cm^3 with a standard deviation less than 0.01 g/cm^3 and maximum and minimum values of 2.71 g/cm^3 and 2.69 g/cm^3, respectively. The average density of the aggregates from both recyclers was 2.70 g/cm^3 with a standard deviation of less than 0.01 g/cm^3 and a minimum value of 2.68 g/cm^3. The only observed difference occurred for the maximum value (2.71 g/cm^3 for the drum-type recycler and 2.72 g/cm^3 for the rotary sieve-type recycler). These insignificant differences indicate that there is little quantity of cement paste attached to the aggregates after recycling the concrete in both recyclers, because this is the only means to change these values.

Figure 10 - Reference and recovered aggregates - fineness modulus.



Source: The author

Figure 11 - Reference and recovered aggregates - density

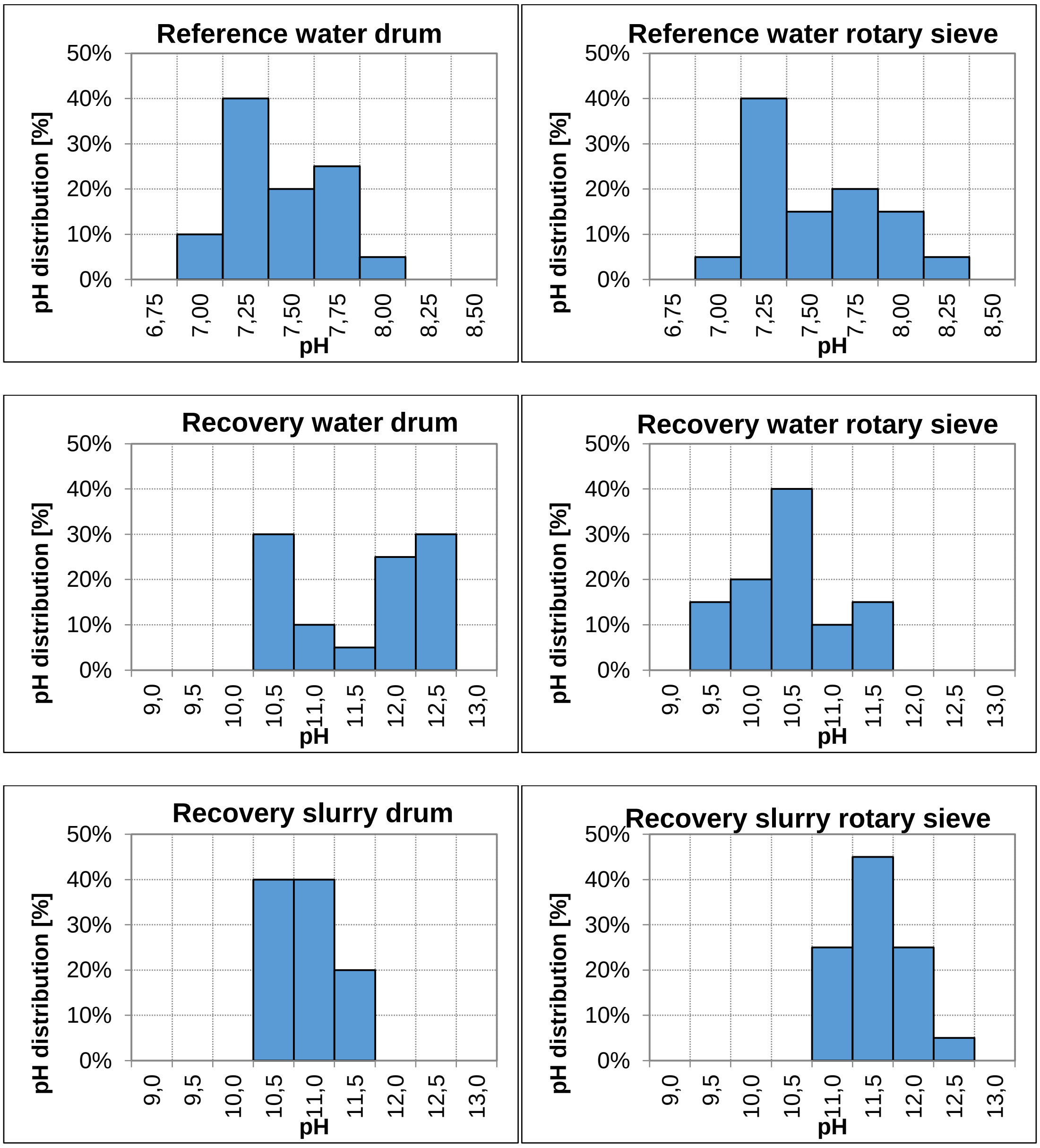


Source: The author

3.4.1.2. Slurry and recovered water

Figure 12 show the test results obtained for the pH values of the reference water, reclaimed water, and slurry. The pH of the reference water in the two stations proved to be nearly identical in terms of the mean values (7.33). The standard deviation of both sets of equipment was also very close, with values of 0.28 and 0.26 for the plants with the drum- and rotary sieve-type equipment, respectively.

Figure 12 - Reference water, Reclaimed water and Grey slurry - pH distribution.

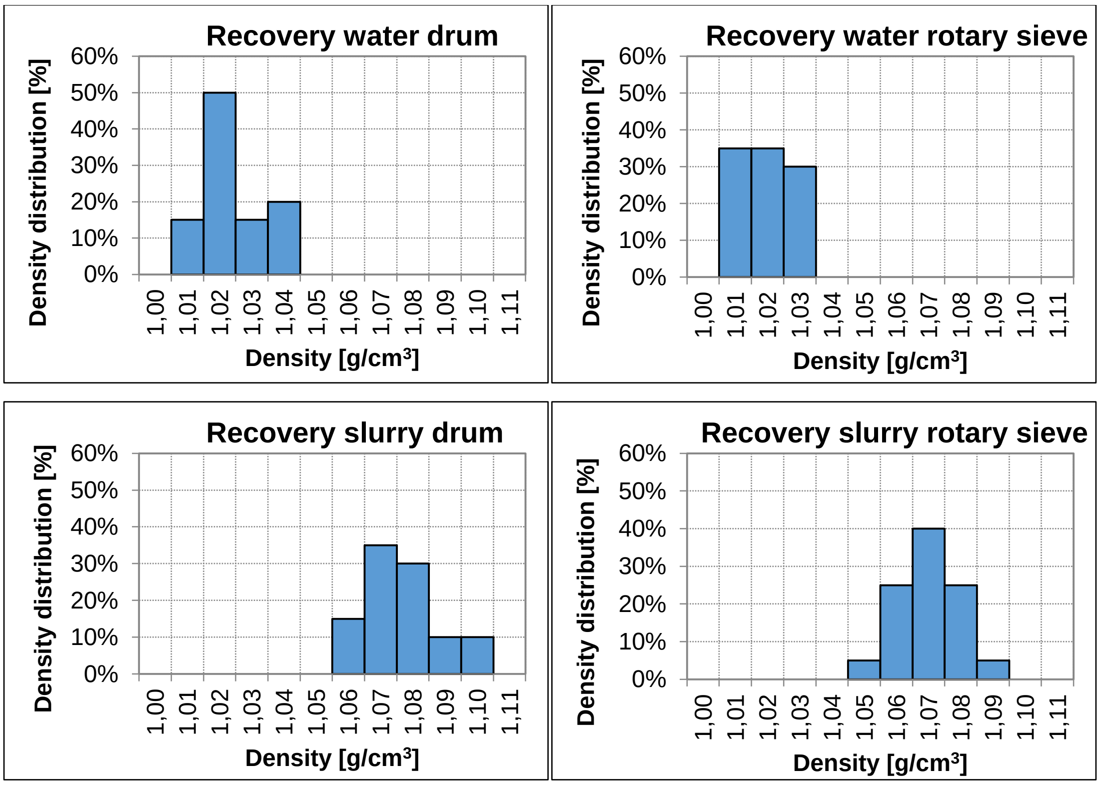


Source: The author

The water recovered with the drum-type recycler was slightly more basic than the water obtained with the rotary sieve-type equipment. However, both were in the same error range, so it was not possible to affirm that there was any significant difference. However, the slurry recovered from the drum-type equipment was more acidic than the rotary sieve-type equipment, which drew attention to the fact, that the standard deviation was reduced compared to that found for the recovery water. This may demonstrate that the high level of particulate material content in the slurry eventually tends to normalise the results.

The water density results for both types of equipment were near 1.01 g/cm^3 and the standard deviation values were very low, resulting in coefficients of variation lower than 1%. This is an excellent result because it shows the homogenization capacity that the equipment provides for this input. In addition, the value obtained is lower than 1.03 g/cm^3 (i.e., below the maximum limit established by references). Thus, it can be concluded that the use of reclaimed water in concrete has great potential. However, the slurry exhibited values of 1.07 g/cm^3 for both types of recyclers, as can be seen in Figure 13. The bulk density of the slurry are above the limit of 1.03 g/cm^3, indicating that there is an excess of fine materials in the slurry, which will leads to a greater impact on water demand.

Figure 13 - Reclaimed water and slurry - density distribution.

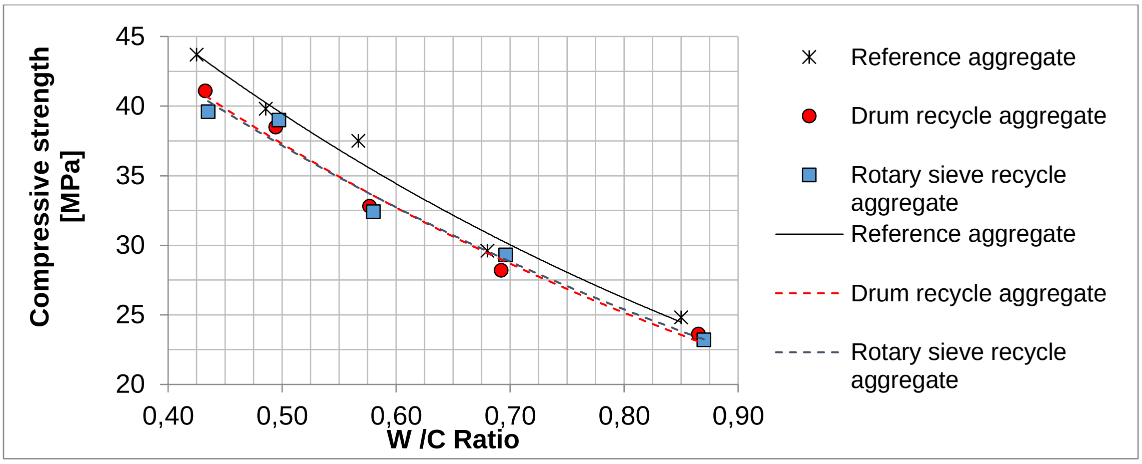


Source: The author

3.4.1.3. Concrete mix design studies

Concrete mix design studies were conducted by replacing reference aggregates with the recovered ones and establishing the slump value of 100 mm. The results obtained in terms of Abrams' curves are shown in Figure 14. The results show that the recovered aggregates demand a higher amount of water in order to obtain the same slump level as concretes produced with the reference aggregates. Regular water was used in these studies. According to the results obtained in the mix-design studies, it was possible to determine the cement consumption required for each class of concrete with 100 mm slump. Table 5 presents the cement consumption values for each concrete strength class.

Figure 14 - Abrams curves obtained for reference and recovered aggregates.



Source: The author

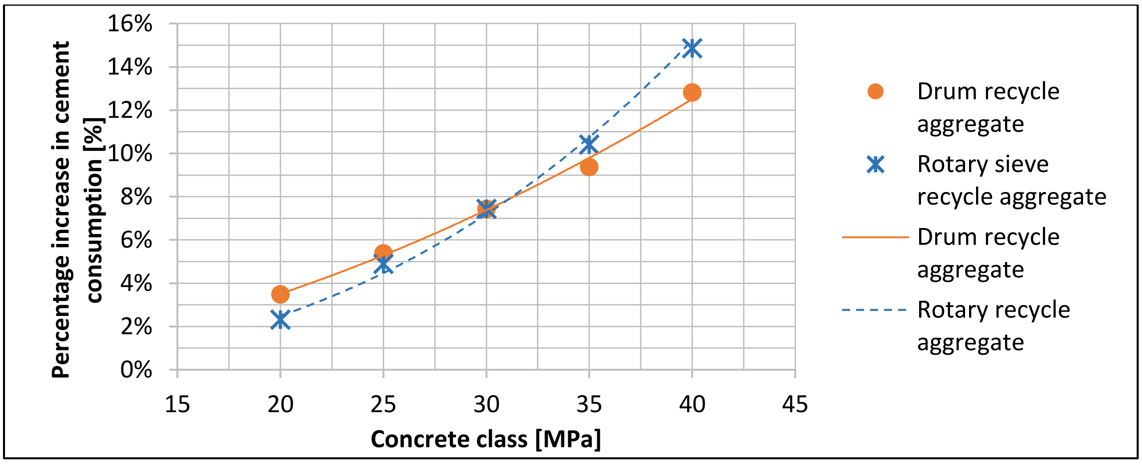
Table 5 - Results of cement consumption for concrete strength class for concretes with reference and recovered aggregates (kg/m^3).

Concrete Strength Class (MPa)	Cement consumption for type of aggregate (kg/m^3)		
	Reference	Recovered	
		Drum recycle	Rotate sieve recycle
C20	172	178	176
C25	204	215	214
C30	242	260	260
C35	288	315	318
C40	343	387	394

Source: The author

There is a strong correlation between the percentage increases in cement consumption with the strength class of the concrete with recovered aggregate. Figure 15 clearly demonstrates that there is a proportional increase in the consumption of cement needed to achieve a strength class of concrete with recovered aggregate when compared to the regular concrete. Correia et al. (2009) used recycled material in mortars and obtained results with similar tendency. The researchers proved that there is a concomitant influence of the amount of recycled material and water on the workability of the matrix. Therefore, if the amount of recycled material reduce the slump value, the tendency is to increase the volume of water in order to compensate this effect, which leads to an increment of cement consumption in order to guarantee the same w/c ratio and the strength in consequence.

Figure 15 - Percentage increase in cement consumption due to the replacement of reference aggregate with recovered aggregate

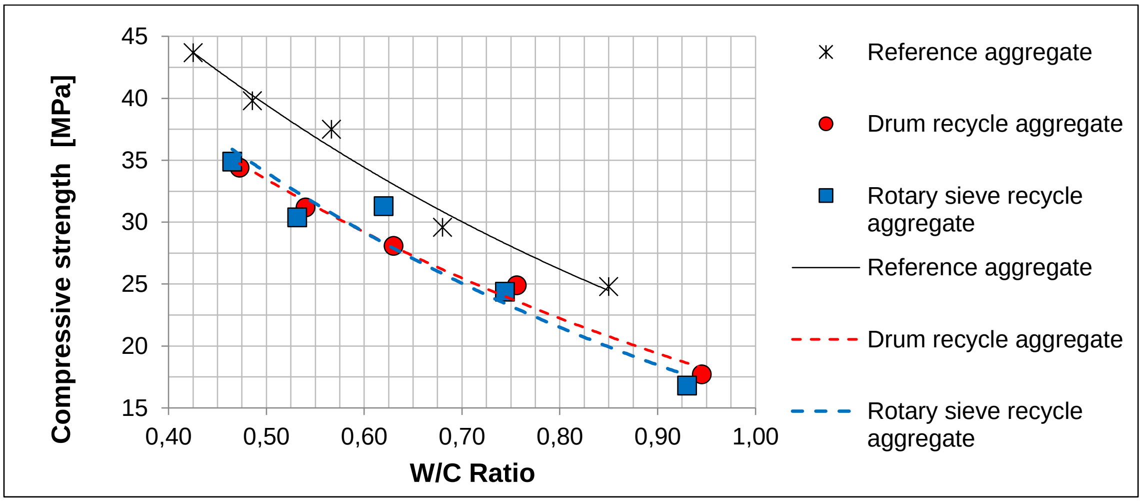


Source: The author

There was also a difference between the two systems because the rotary sieve-type recyclers provided the best results, especially for concrete under 30 MPa. It is important to note that, for this particular level of strength, both types of equipment presented the same level of impact in their increase of cement consumption. Thus, this demonstrates that the best reuse strategy for recovered aggregates is their application in concrete with lower demands for compressive strength, i.e., below 25 MPa, in order to reduce the negative impact in cost caused by the increase of cement consumption. This is particularly true for the rotary sieve-type equipment, which presented a lower level of impact in the cement demand. It is important to emphasize that the reduction of cement consumption brings other non-economical advantages. For concrete with the same level of strength and workability, reduced cement consumption will reduce the costs and its environmental impacts and decrease its drying shrinkage.

The mix design study with the slurry revealed that this material requires an extremely high demand of water to meet an established slump value, which is directly reflected in the compressive strength obtained in the tests as shown in Figure 16. Table 6 shows that to meet the strength classes, it is necessary to significantly increase the cement consumption in the mixes with slurry. In that sense, the direct use of slurry in the concrete is not feasible.

Figure 16 - Abrams' curves obtained for the slurry



Source: The author

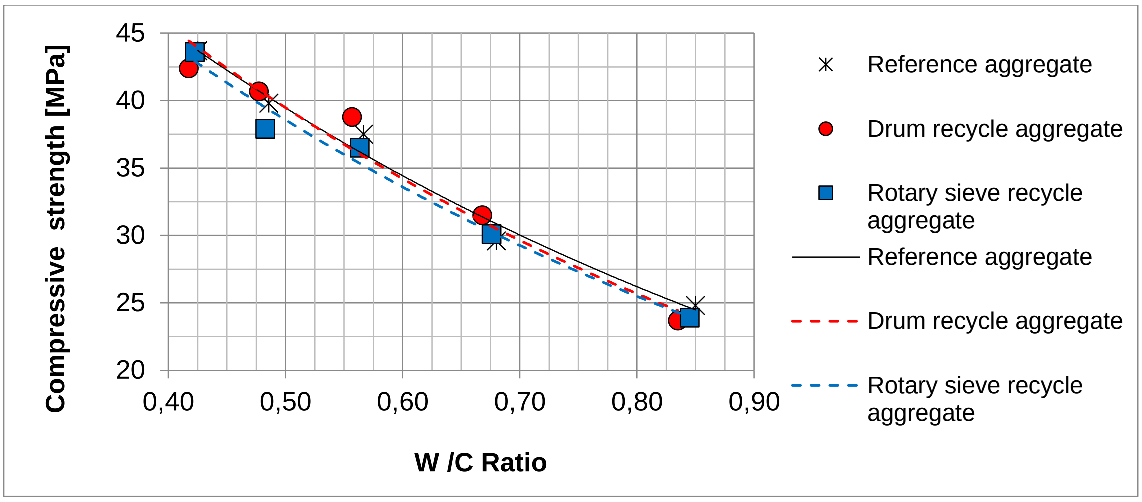
Table 6 - Results of cement consumption for concrete strength classes for concretes with recovered slurry

Concrete strength class (MPa)	Reference water	Cement consumption for recovered slurry (kg/m^3)	
		Drum recycle	Rotate sieve recycle
C20	172	215	219
C25	204	265	265
C30	242	326	320
C35	288	405	386
C40	343	512	472

Source: The author

The mix design studies comparing the replacement of reference water with the reclaimed water did not show any significant difference in the results, as can be seen in Figure 17. This confirms the potential use of reclaimed water as shown by the previous characterization results. Thus, the use of reclaimed water has been shown to not present any impact on concrete behaviour regarding the use of regular water.

Figure 17 - Abrams' curves obtained for reference and recovered aggregates with reclaimed water



Source: The author

3.4.2. Tests in production conditions

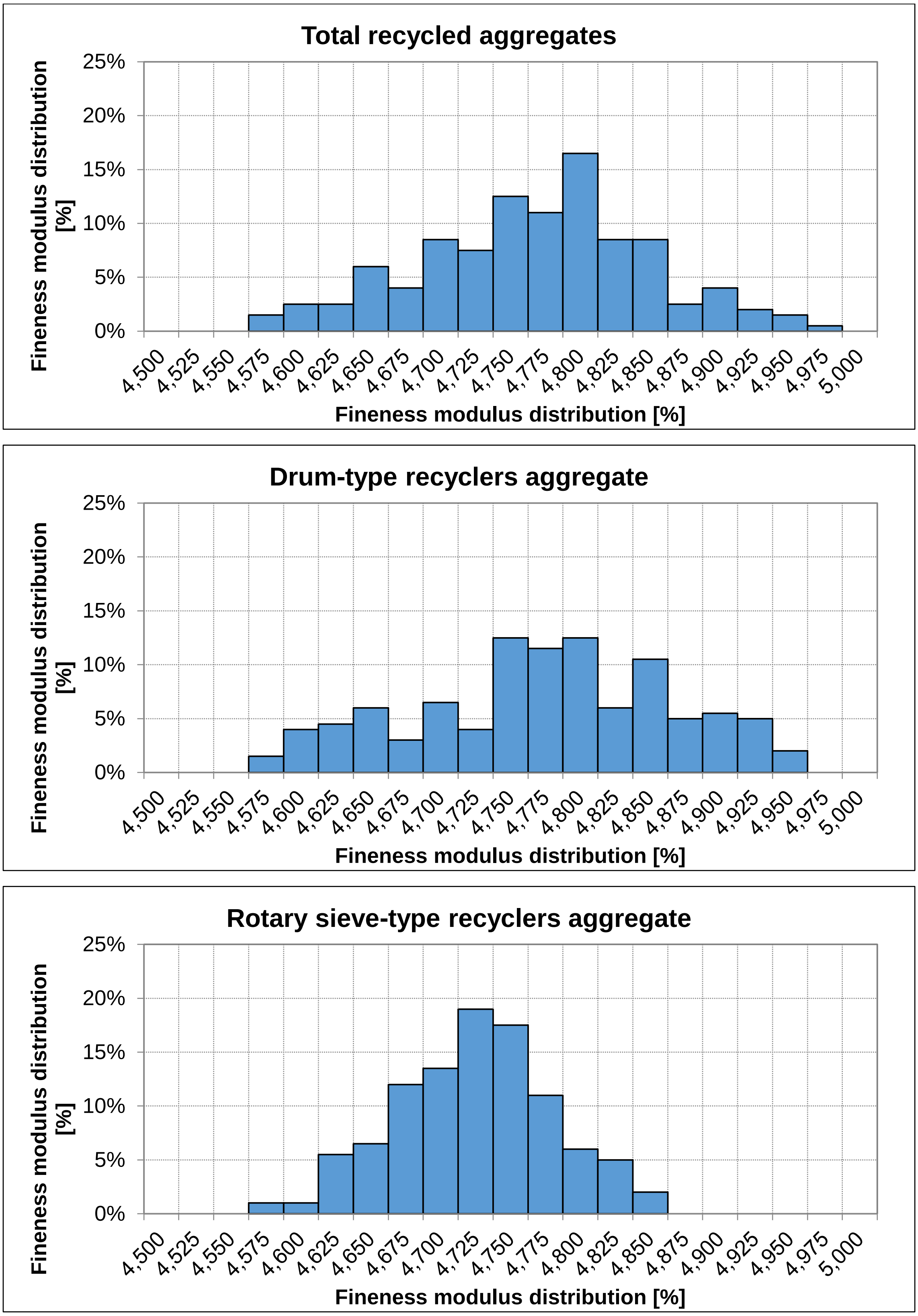
3.4.2.1. Applicability of recovered aggregates

The average fineness modulus for the aggregates recovered with both types of equipment during the regular production of concrete were both approximately 4.76. This value was higher than in the reference aggregate, whose average value was 4.71, as can be seen in Figure 18. This shows that the material has a greater proportion of larger particulate material. That is, the recovered aggregate is coarser than the reference.

Field tests showed that the material passing through the 0.150 mm sieve was lower for the recovered aggregates than the reference value obtained for regular aggregates. This indicates that the recovered material is poorer in fine particles than the reference aggregate. The drum-type equipment had a lower level of fine material produced in relation to the rotary sieve-type recycler. However, the distribution curves were similar and did not present significant difference, as shown in Figure 19.

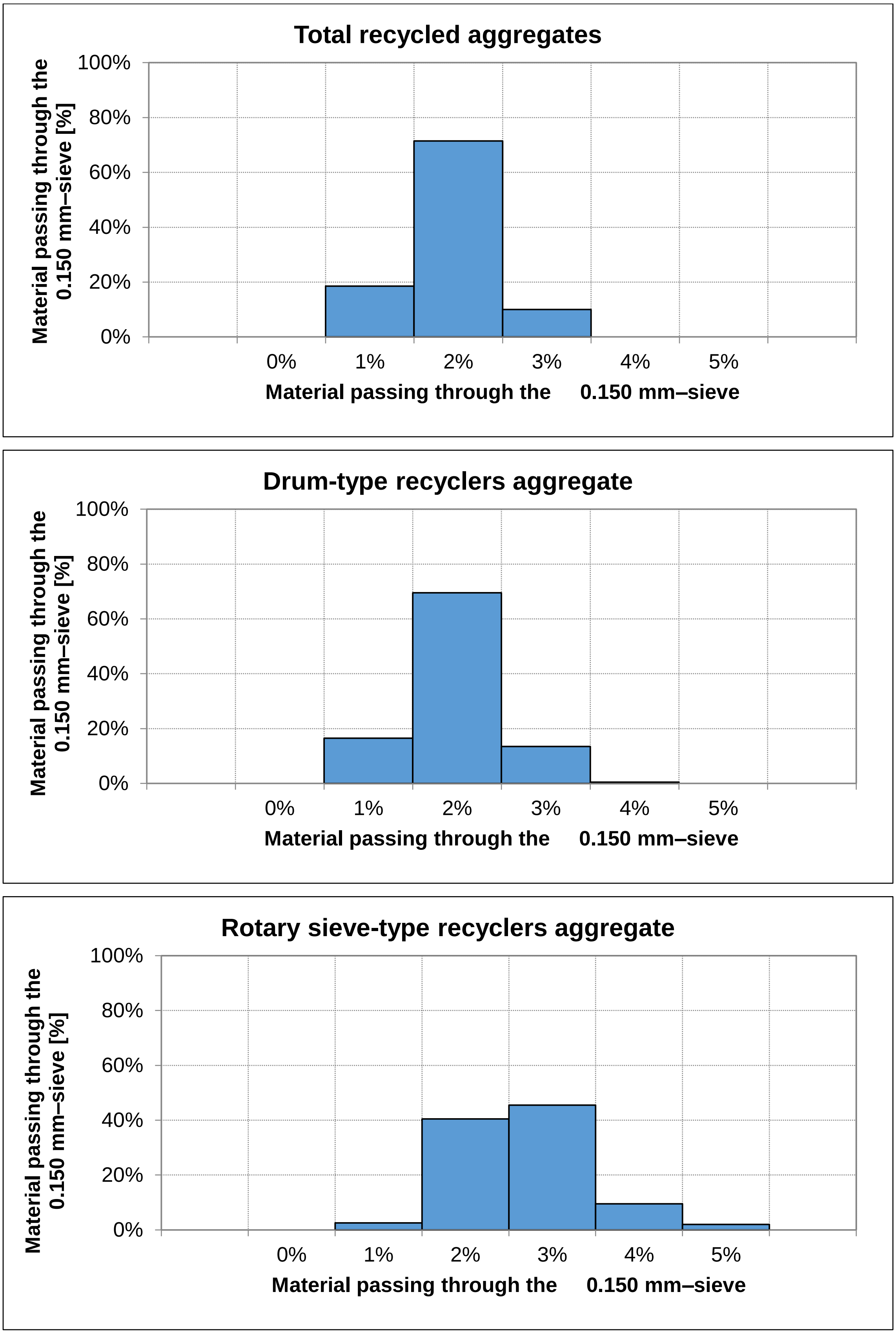
The average results of the density tests for monitoring the field operations confirmed the previous results of the laboratory tests. Interestingly, the density variation of the aggregates recovered from the recyclers was lesser than the one observed for the reference aggregate, as seen in Figure 20. This shows a uniform condition of production of the materials, which generates the potential condition for concrete production with low variability in terms of compressive strength.

Figure 18 - Fineness modulus obtained for reference and recovered aggregates during production quality control



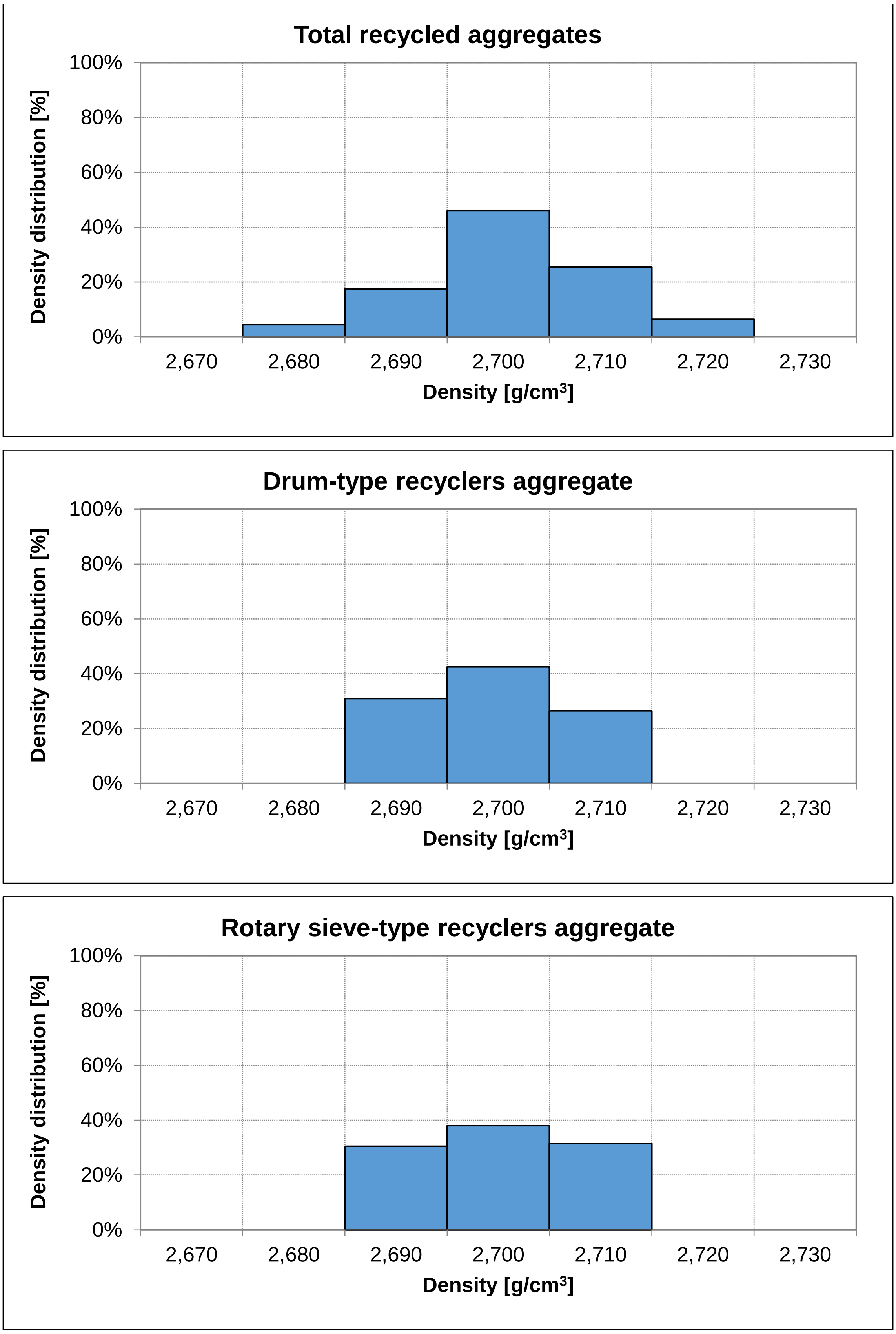
Source: The author

Figure 19 - Amount of fine material passing through the 0.150 mm–sieve obtained for reference and recovered aggregates during production quality control



Source: The author

Figure 20 - Density obtained for reference and recovered aggregates during production quality control

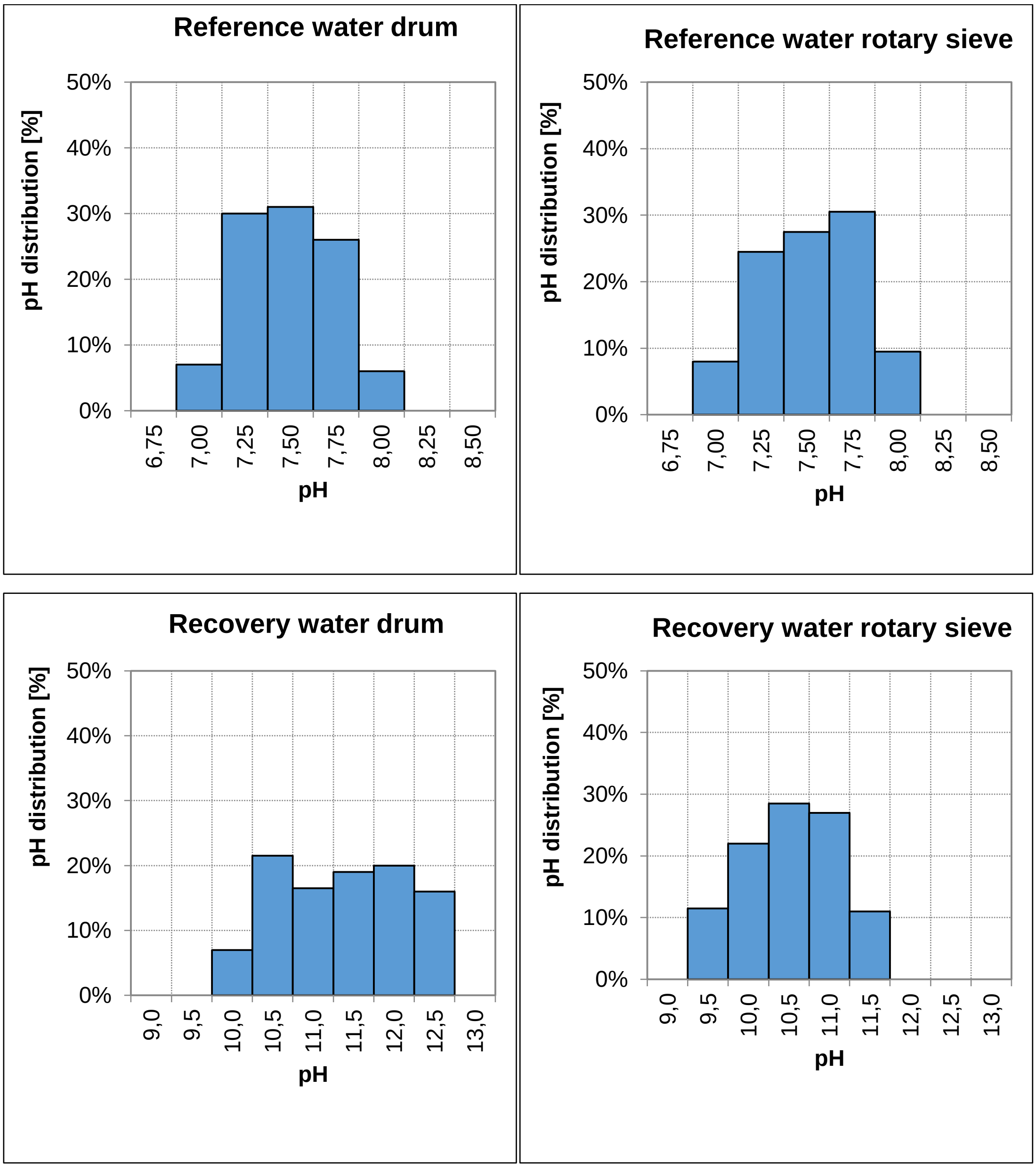


Source: The author

3.4.2.2. Applicability of reclaimed water

The results obtained for the reclaimed water characterization confirmed the low variability observed in the previous tests in the laboratory. This demonstrates the adequacy of the water recycling procedures used in this study and their feasibility for implementation in regular concrete production. Figure 21 demonstrations the distribution of the test results obtained under production conditions.

Figure 21 - Water pH - reference and reclaimed water during production quality control

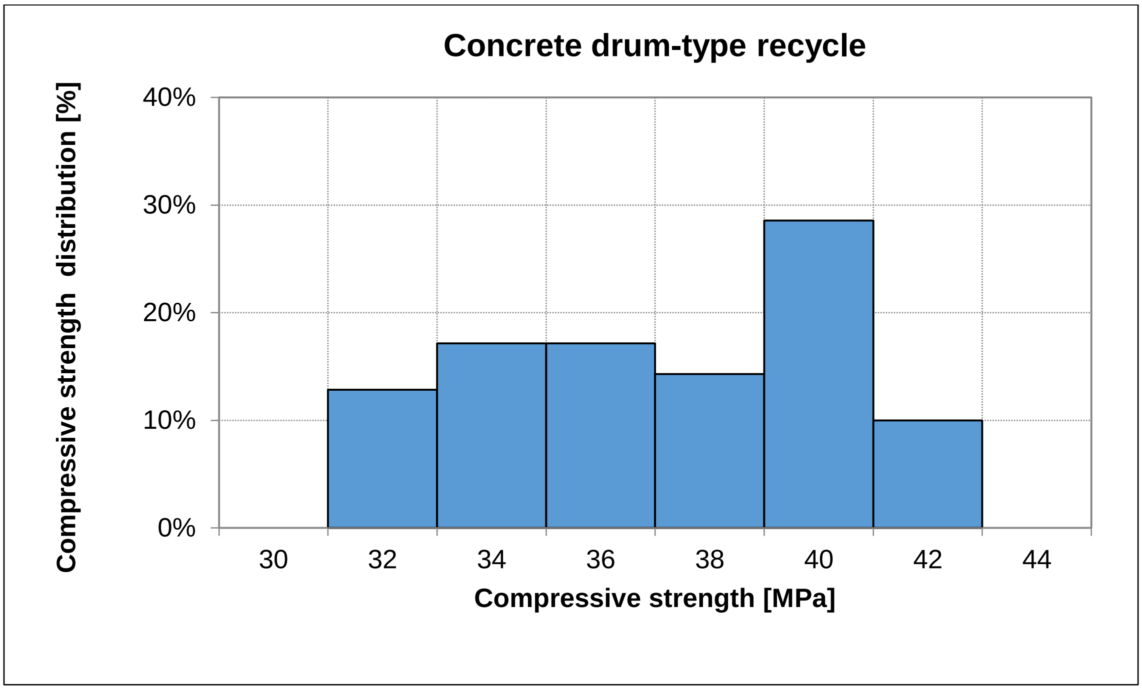


Source: The author

3.4.2.3. Applicability of concrete with aggregate and reclaimed water

The average value of the compressive strength obtained for the concretes with recovered aggregates from the drum-type equipment was 36.3 MPa, with a standard deviation of 3.00 MPa. This results in a characteristic value of 31.3 MPa, which is greater than the specified limit. The minimum and maximum values obtained were 31.1 MPa and 41.1 MPa, showing a low variation range for actual production conditions, as can be seen in Figure 22. The results of the ANOVA analysis exhibit low statistical significance (p = 0.944), betoken that the concrete with aggregates and reclaimed water are similar in terms of compressive strength.

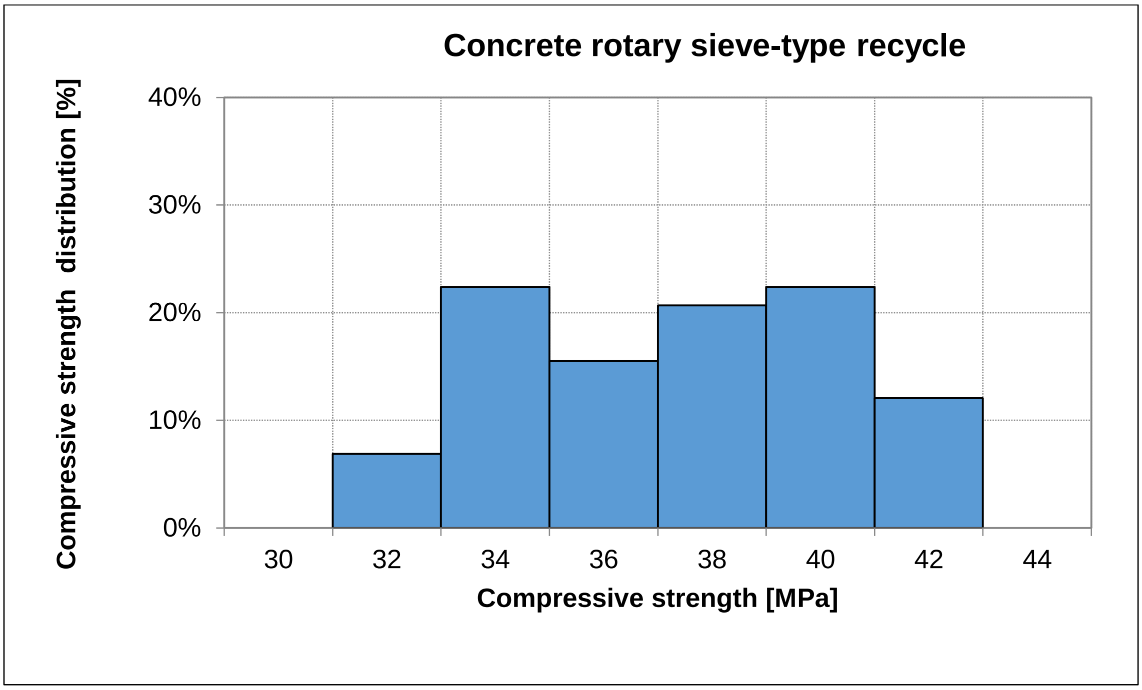
Figure 22 - Control chart of results of compressive strength for concretes with recovered aggregate from the drum-type recycler (concrete class C30).



Source: The author

During concrete production using recovered aggregates obtained with the rotary sieve recycler, 60 concrete truck mixers were charged and sampled individually. The average compressive strength for this C30 concrete class was 36.2 MPa, with a standard deviation of 3.01 MPa, resulting in a characteristic value of 31.4 MPa. The minimum and maximum values obtained were 31.3 MPa and 41.2 MPa, as seen in Figure 23, i.e., practically identical to those obtained for aggregates from the drum recycler. This demonstrated that, from the standpoint of mechanical strength and homogeneity of concrete production, the two recyclers are equivalent. Is important to note that these results confirm the tendency for equivalence observed in the previous mix-design analysis. However, if a lower level of strength was chosen, it is very probable that the rotary sieve recycler would provide the same result with a lower level of cement consumption.

Figure 23 - Control chart of results of compressive strength for concretes with recovered aggregate from the rotary sieve-type recycler.



Source: The author

It is important to note that there is no significant variation of the strength class of concrete using the recovered aggregate and reclaimed water fitting the same requirements usually achieved with normal concrete. These results confirms the same tendency observed by Correia et al. (2009) where the 7-day and 28-day compressive strengths remained within the specified ranges. Therefore, those results helps to confirm the feasibility of this strategy, avoiding the extensively reported effect of axial compressive strength reduction with the use of recycled materials in concrete (Sheen et al., 2013; Shi et al., 2016; Li et al., 2016).

Taking into account the optimal pumping pressure established by the producer, less than 3% of the delivered concrete with regular aggregates and water presented some kind of difficulty. In the case of recovered aggregate with the drum-type recycler, 7% of the concrete was pumped with a pressure higher than expected. In the case of the rotary sieve-type recycler, this occurred in 10% of the cases.

Therefore, the rotary sieve-type recycler produces recovered aggregates that may be more difficult to pump, as shown in Table 7. It is probable that this pumping difficulty lies in the fact that the recyclers are unable to completely remove the cement paste adhered to the particle surfaces, which increases the roughness of the recovered aggregates, thereby increasing the pumping difficulties.

Table 7 - Instances of excessive pumping pressure during the application of concretes with reference and recovered aggregates.

Local	Aggregate	Instances of pumped concrete	Instances of pumped concrete pressure relative to optimal value	
			< 18 MPa	≥ 18 MPa
Ready-mix plant 1	Reference	78	76	2
	Drum recycler	70	65	5
Ready-mix plant 2	Reference	67	66	1
	Rotate sieve recycler	60	54	6

Source: The author

3.5. Conclusions

In this study, the applicability of recovered aggregates and reclaimed water for concrete production were analysed via laboratory and production tests. The recovered aggregate presents particle size distributions very close to that of the reference aggregate, despite having fineness moduli and standard deviations slightly higher than those of the reference; no significant variation was observed related to density. The pH values of the water reclaimed by the two analysed recyclers were very close. Moreover, their densities were below the required limits. The potential use of reclaimed water was also confirmed by laboratory mix-designs studies and by monitoring at an industrial scale; hence, the feasibility of using reclaimed water was confirmed for any characteristic resistance class of concrete. The bulk density of the slurry was well above the established limit of 1.03 g/cm^3. This led to higher water demands in the concrete mix design study, which confirms that it is not feasible to reuse slurry water without additional treatment. The concrete mix-design studies in the laboratory showed that the reuse of recovered aggregates has greater potential for use for concretes with compressive strength demands lower than 25 MPa. This is especially the case for the rotary-type aggregate recycler material. Field tests also showed that there were no significant variations in the properties of both recovered aggregates during the monitoring period. This was reflected by a low level of variability of the concrete produced, ensuring compliance with the characteristic resistance class that was specified. However, this result could be influenced by the fact that the C30 strength class was used, which showed the same results in earlier mix-design studies. These conditions confirm the reliability of laboratory results for previewing the results of actual conditions of concrete production in the plants. It should be noted that greater difficulty was experienced when pumping concrete produced with the recovered aggregates than with the reference concrete. The difficulty in pumping was slightly higher for the rotary sieve-type recycler than for the drum-type recycler, which can be seen as the only aspect that slightly differentiated the two devices. Otherwise, they can be considered as technically equivalent. So, this study suggests that, if carried out adjustments in the mix design of the concrete, the recovered aggregate and the reclaimed water can be used successfully in ready mix production by the technical point of view. However, this is not the same case of slurry because there are many difficulties for the reuse at the ready mix plant. One possible solution for the reuse of slurry is to apply the accelerated mineral carbonation technique as reported by Xian (2016). In that way, the slurry could be converted in substitution to limestone filler, as presented in the study of Audo et al. (2016). Anyway, the solution must guarantee low variation of the properties of the recycled slurry in order to provide uniform conditions for the industrial production of ready-mixed concretes. Therefore, further studies should be carried out focusing the recycled slurry use in real conditions.

This study was limited to the reuse of usual concrete, which correspond to about 90 % of the volume produced by the ready mix plant. Larger studies should be done to verify the possibility of using fresh concrete recyclers to recycle special concretes, such as those containing fibres, pigments, or any other type of addition.

In order to guarantee that the process could be financially viable, it is necessary that the cost reduction derived from the use of recycled materials should be greater than the costs of acquisition, operation and maintenance of recyclers, as well as the additional consumption of cement in concrete mixtures.

4. EVALUATION OF THE USE OF CRUSHED RETURNED CONCRETE AS RECYCLED AGGREGATE IN READY-MIX CONCRETE PLANT

4.1. Introduction

The amount of waste generated in ready-mixed concrete (RMC) plants is too significant to be neglected. In Brazil, recent studies by Vieira and Figueiredo (2013) indicate that approximately 3% of the volume of concrete produced by RMC plants returns to the plant. Accurate determination of the total amount of concrete wasted annually worldwide is difficult, but it is estimated that waste rates for other countries are consistent with Brazilian demand. Sealey et al. (2001) indicated that this volume reached 750 thousand tons per year in the United Kingdom (2.3% of the produced concrete). Obla et al. (2007) estimates that in the United States, 415 million cubic meters of concrete returned to RMC plants in 2006 (1.4% of the produced concrete). A major issue is concrete returned from the job site to the RMC plant inside the concrete truck drum, usually called returned concrete (RC), which in Brazil represents 45% of the waste RMC (Vieira and Figueiredo, 2013).

Handling the waste stream is an environmental and economic problem for the industry. An option to prevent waste from going to dump sites is the conversion of RC into recycled aggregate (RA), which usually requires crushing and sieving. This alternative is interesting, because it converts most of the incoming waste into product and does not require water in the process, as the aggregates are produced by washing non-hardened RC (Vieira and Figueiredo, 2016).

The study carried out by Xuan et al. (2018) pointed out that the RMC industry does not have a systematic approach to compare the different strategies of handling of concrete-processing residues in terms of the economic, environmental, and technical aspects. In that sense, as many countries turn to a more lean production system, current waste-management strategies require updating. This indicates that regardless of the waste-reuse system adopted in RMC plants, to make the system feasible it is essential to analyze the cost of the reuse process. However, it is important to emphasize that previous studies (Silva et al., 2014) have indicated that when RA is produced within the same RMC plant, the cost and environmental impacts of the logistics are greatly reduced, and the cost per ton of recycled aggregate may be lower than the price per ton of natural aggregate (NA). This condition depends on the local cost of virgin aggregates, which is also sensitive to logistics. In addition, the reuse of RC within the RMC production process will bring additional environmental benefits. This occurs, according to Scrivener et al. (2016), because transport is responsible for 1/3 of the CO_2 emission and that recycling concrete produced in the RMC requires less energy because it does not require the decontamination process that is required for demolition residue.

Marinković et al. (2010) demonstrated that when compared to virgin aggregates, even good-quality RA will require approximately 5% more cement to yield the same average compressive strength. Despite this, Quattrone et al. (2014) concluded that high-performance RA is environmentally viable only when NA are scarce and the environmental impact of transporting these aggregates over long distances can be compensated. The life-cycle analysis (LCA) studies of Yazdanbakhsh et al. (2018) and Kleijer et al. (2017), although from different countries, both concluded that the environmental impacts of NA and RA concrete production are similar when the landfill is not considered. This is because the impact due to the demand for additional cement by RA concrete is compensated by a lower transport distance. However, when RA is provided by the RMC instead of recycling plants, and the prevented landfill is accounted for, the environmental impact of producing RA concrete is significantly lower than that of NA concrete. Therefore, an analysis of the feasibility of using RA should consider these possibilities.

In Brazil, a few plants have the equipment and knowledge to produce good-quality aggregates from construction waste (Nagalli, 2016). However, it is possible to crush and sieve the hardened RC to ensure a material with similar dimensions to the aggregates normally used in concrete production. This allows its reintroduction into new mixes that have been specifically formulated to accept the incorporation of this type of RA.

Some interesting studies have already been carried out to evaluate the applicability of RA to RMC. Among them, the studies of Zega and Di Maio (2011) evaluated the use of RA obtained by crushing RMC waste that was deposited without adequate treatment and concluded that for the lowest strength level (17 MPa), the replacement of up to 50% of the aggregate provides concrete with an average compressive strength only 10% lower than that of conventional concrete.

For a higher strength level (30 MPa), the average compressive strength of the recycled concrete was 16% lower than the reference concrete. Thomas et al. (2016) studied the reuse of precast concrete waste on a laboratory scale and concluded that because of the need for a greater amount of cement, not all degrees of substitution have advantages. Fraile-Garcia et al. (2017) concluded that the concrete produced with RA submitted to previous treatment could replace up to 50% of the NA without offering significant modifications in the 30 MPa average compressive strength concrete. Although these laboratory studies eventually verified the potential for application of the material, they obviously cannot assess the conditions of production on a real scale. These conditions may interfere with the applicability (pumpability, for example) and variability of the material at real scale, which directly affects the characteristic strength value required for structural applications. It is important to note that none of the studies used RA (from concrete) less than 48 h old when producing RMC.

According Rashwan and Abourisk (1997), the impact on the compressive strength caused by adhered mortar depends on the cement hydration degree in the RA. In concretes made with crushed aggregates that were reused in less than 24 h, the compressive strength was up to 25% higher than the reference concrete. On the other hand, in concretes produced with aggregates stored for seven days, the compressive strength was 10% lower than that of the reference concrete. Therefore, the study concluded that the use of "young” RA tends to be more suitable for the production of concrete.

One important aspect of RA, from the perspective of RMC producers, is RA homogeneity. Higher heterogeneity and porosity are considered the critical differences between RA and NA (Etxeberria et al., 2007). The induction of greater variability for concrete due to the use of RA could lead to unsafe design conditions if it is not well parameterized (Pacheco et al., 2019). To obtain statistically significant data, Pacheco et al. (2019) analyzed the variation of several physical properties of the concrete produced with RA, including compressive strength, through the production of large batches of concrete in a laboratory (0.35 m^3). The main objective was to avoid the risk of underestimation, due to the typical reduced scale of laboratory experiments, of the variation. However, laboratory conditions are always more uniform than those of plant production during a certain period. In this sense, real-scale studies are needed to evaluate the applicability of RA concrete in terms the influence of this variability on the characteristic compressive strength of the material. Real-scale variability will affect the concrete mix design. Hence, to guarantee safe conditions for structural applications, it must be considered to verify the feasibility of RA concrete production. Therefore, a feasibility analysis of the use of aggregates with greater dispersion of results should be conducted, taking into account their impact on the characteristic strength value obtained on an industrial scale.

To specify the required characteristics of any type of concrete for RMC, one of the main criteria is the slump class. The slump class is a classic parameter to ensure that the concrete could provide adequate compaction as well as adequate finishing conditions for regular applications (Silva et al, 2018). Vieira and Figueiredo (2016) have shown that the use of recovered aggregates, as a form of waste reuse, may be feasible for RMC, but there are losses in concrete pumpability. If the pumping capacity of the concrete is compromised, the use of RA may be impracticable in practice. Thus, it is important to expand the material workability analysis beyond standard laboratory assessment conditions.

Taking into account this scenario, the objective of this study is to present a methodology capable of evaluating the viability of implementing a recycling process of RC used as RA on an industrial scale. In that sense, real-scale application of this methodology is presented to demonstrate its feasibility. Accordingly, the methodology comprising preliminary laboratory studies and real-scale analyses is presented in sequence in a case study, starting with the system implementation.

4.2. System implementation

The magnitudes of the economy and quality of the RA produced by crushing vary according to the technology used (Lima and Chenna, 2000). Recycling RC from hardened concrete (through its transformation into RA) requires the use of crushers. According to Chaves (2006), the choice of crusher must consider the fulfillment of at least three requirements: the equipment must be able to receive the material to be commuted in its crushing chamber, the crusher must meet the volumetric capacity defined in the project, and/or the crusher must generate the desired particle size distribution.

There are several models of crushers available in the market. The characteristics of each piece of equipment will affect the crushing process and the properties of the recycled aggregate. Therefore, the correct choice of crusher equipment is essential, because its influence on aggregate attributes will affect the concrete mix design. Consequently, the crushing equipment could influence the demand on cement consumption and the financial and environmental impact of RA use. Therefore, it is necessary to carry out early analysis to assess the efficiency of the crushing process on an industrial scale.

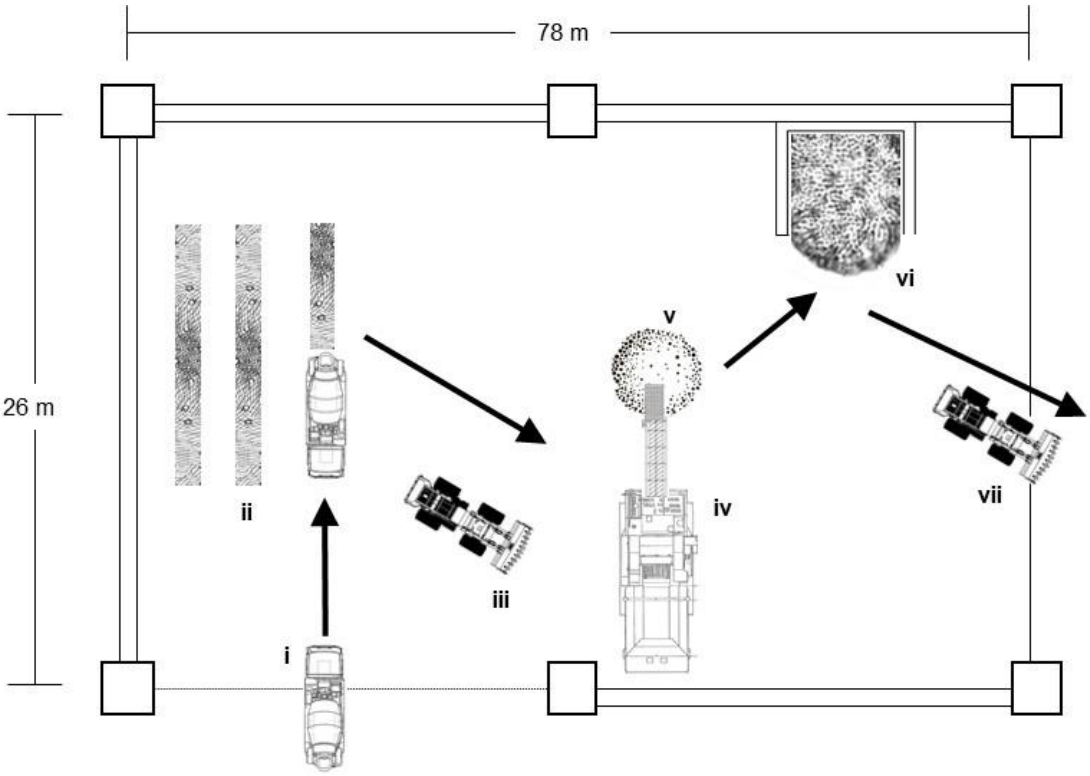
The installation of a crusher requires an analysis of operational factors. Among the most relevant factors are cleaning access conditions, maintenance, and lubrication of equipment (Luz and Lins, 2010). After conducting an analysis that considered acquisition cost, difficulties in operation and maintenance, potential homogeneity of the final product, and characteristic of the product generated, the concrete producer opted for a jaw-type crusher.

The installation of the crusher and sieving system in the RMC plant followed all recommendations of the crusher supplier, who also trained the crusher operating team. Because the crushing process generated a lot of noise, the crushing plant was installed indoors to reduce environmental noise and avoid the dispersion of suspended particulate material. The crushing plant was installed in a shed that already existed in the RMC, with an area of less than 2,000 m2.

To reduce the cost of disposing of waste generated from RMC in landfills, RMC decided to install a crusher in one of its plants, to produce RA to be sold as geotechnical material (landfill and ballast of buried pipelines). However, the company decided that it would also investigate the feasibility of producing RA for concrete use.

After some analysis, it was decided that the wheel loader (equipment already used by RMC to transport the aggregates between the bays and the balance) should feed the equipment and that the crusher should be able to grind all the waste generated daily by the concrete. The crusher should also generate aggregates of appropriate dimensions for use in concrete, have the ability to grind more adherent materials, and be able to crush the young RA with cement that is not yet hydrated. Figure 24 shows the arrangement of the recycling plant.

Figure 24 - Ground floor of the recycling plant installed at the RMC plant



Subtitles

i – Concrete truck with returned concrete inside
ii - Concrete truck unloads all returned concrete in unloading yard
iii - Wheel loader transports collected spread concrete to crushing site
iv - Crushing equipment
v - Recycled aggregate pile
vi - Temporary disposal bay
vii - Wheel loader transports recycled aggregate to production bay”

Source: The author

The crusher must produce aggregates with particle size distributions and limits according to local standards, and as close as possible to regular aggregate. Accordingly, to remove fine material with particle dimensions above that used in concrete, a vibrating sieving system with steel mesh was installed to remove material with particle dimensions greater than 12.5 mm or less than 2.4 mm.

There was no control over the strength of the concrete intended for crushing; that is, almost all concretes produced by the RMC plant with fresh concrete were recycled in a process that consisted of the following stages:

- Unloading all RC directly into the unloading yard in a layer approximately 10 cm thick. The next day, the wheel loader collects all the spread concrete and transports it to the crushing site;
- Crushing and sieving the RC, generating the RA, and collecting and sending the RA to the temporary disposal bay;
- Storing the RA until the end of daily production, when it is transported to the production bay;
- Storing the RA in the production bay, which is outside the recycling plant, until the moment of its use. All the RA stored at production bay was used in a single day of production.

To avoid contamination by fibers, color variation, and low-strength aggregates, non-structural concretes (with compressive strength less than that of C20), pigmented concretes, and concrete fibers were not crushed.

4.3. Methodology

The beneficiation process was designed to take advantage of the RA with non-hydrated cement, i.e., with a maximum age of 48 h. Once a concrete beneficiation system was implemented by RMC to produce RA, feasibility analysis on the use of RA became possible.

The study was divided into two main phases. The first was exclusively developed in the laboratory to characterize the material and conduct the mix design studies. The second phase was developed on a production scale, with the main objective of accurately quantifying the level of variability achieved by RA concrete produced on an industrial scale, together with applicability evaluation through pumpability verification.

The test program also evaluated variation of the characteristics of the RA and its influence on the concrete characteristics, when they were used as the raw material for concrete production in the laboratory, and subsequently in field tests for real-scale production evaluation. Consequently, the preliminary studies were used to carry out an assessment of the impact of RA on the standard deviation of the concrete, and to determine whether the standard deviation from the laboratory tests is representative of the standard deviation of real-scale production.

The ordinary raw materials used in laboratory and field tests were type CP II E 40 Portland cement (which was blended with up to 34% of blast furnace slag, quartz fine aggregate, and limestone coarse aggregate), water reducer, set-retarding admixture, and natural water

To facilitate the visualization of differences of the RA and NA characteristics, histograms were used to represent the variation of its characteristics. The same method was also used to evaluate the variability of the compressive strength results of concrete prepared with these aggregates. In all the histograms, the number of classes was arbitrated according to the Rule of Sturges (Eq. 1), which defines the number of classes (k) based on the size of the data set (n).

$$k = 1 + 3.3 \times \log_{10}(n) \qquad \text{(Eq. 1)}$$

4.3.1. Preliminary laboratory tests

The NA and RA were analyzed before the implementation of concrete with RA, and the results obtained were used in the concrete mix design process. All other raw materials used in the laboratory and in the production conditions by the RMC (cement, additives, and regular aggregates) were kept constant in the study.

The aggregate samples were collected in the aggregate production bay. The material was stacked in the bay, where three partial samples of 100 kg each were collected to form the field sample. Samples were collected in different areas of the stack (top, middle, and bottom) to a depth that was never less than 50 cm from the outer layer of the stack. The samples were homogenized and reduced to test samples by a sample splitter. All samples were tested for specific density (ASTM C 127) and particle size distribution (ASTM C 136).

RA was replaced for NA in a percentage by weight, was fixed for all mixes. The percentage substitution value adopted was determined to maintain particle size distribution of total aggregates composition as close as possible to the particle size distribution of the composition of NA regularly used by the RMC plant.

The RMC used the concept of total aggregate according to NBR 7211, which defines “total aggregate” as the resulting aggregate obtained from the mixture of coarse and fine aggregates. This concept allows adjustments of the size distribution curve as a function of the different aggregate proportions. Thus, the same concept was adopted for the mix design analysis. The laboratory studies also aimed to evaluate the impact of RA on compressive strength variation for constant workability conditions or, more specifically, the slump value and the average value of compressive strength. In that sense, the concrete mix design procedures were performed following the methodology described by Monteiro et al. (1993), which is the most commonly used method by the RMC company, with an aggregate sample that presents values close to the mean value of the characteristics studied. This mix design method enables experimental studies to determine proportions to achieve the desired average compressive strength value. This method of mix design was used to determine the concrete mix proportion that provides the same average compressive strength value achieved as NA while using RA, which enables the evaluation of the standard deviation in equivalent industrial conditions.

4.3.2. Tests in production conditions

To analyze the differences in strength variability of the concrete produced with RA relative to ordinary concrete under real production conditions, 1268 m^3 of concrete with RA was delivered to 6 different construction sites. All the field tests were performed in a two-month period at the RMC plant in São Paulo. The volume of concrete produced was equivalent to the production of 170 concrete trucks.

According to Crepas (1997), the ideal pump operating pressure and the optimum pumping speed are directly related to the type and model of the equipment, and are directly influenced by the characteristics of the concrete to be pumped. In this way, the proper concrete for pumping is one that can be easily pumped without segregation and without clogging the equipment. According to Cooke (1990), the pumping capacity is associated with material characteristics, such as the average particle size; particle size distribution; and size, shape, and texture of the aggregate. The pumpability of all concrete produced with RA was evaluated by comparing the pump pressure normally used for pumping concrete with the reference aggregate. Therefore, during the study, the maximum pumping pressure applied during the application of all concrete with RA was measured. The values obtained were compared to values associated with ordinary concrete in the same conditions of application. The RMC plant alternately loaded concrete with RA and NA, without informing the crew which aggregate had been loaded. This was to avoid prejudicial interference in the evaluation of the concrete performance. The pumping pressure was measured for 170 concrete mixes, half of which contained RA, and half of which were a reference concrete.

Compressive strength tests were carried out to characterize all concretes delivered by the RMC. The field test results were used to obtain the compressive strength of the concrete according to the parameters of ACI 318 and to evaluate the effect of the RA on the standard deviation of real-scale production. The results allow calculation of the characteristic compressive strength of the NA and RA concretes. The average compressive strength of the test should be equal to or greater than the average compressive strength required (ACI 318). The required average compressive strength of concrete for the selected mixes is equal to the larger value obtained from Equations 2 and 3 (for $f'c \leq 35$ MPa) or Equations 2 and 4 (for $f'c > 35$ MPa).

$$f'cr = f'c + 1.34s \qquad \text{(Eq. 2)}$$

$$f'cr = f'c + 2.33s - 3.45 \qquad \text{(Eq. 3)}$$

$$f'cr = 0.90\, f'c + 2.33s \qquad \text{(Eq. 4)}$$

where

- $f'cr$ = required average compressive strength.
- $f'c$ = specified compressive strength of concrete
- s = standard deviation

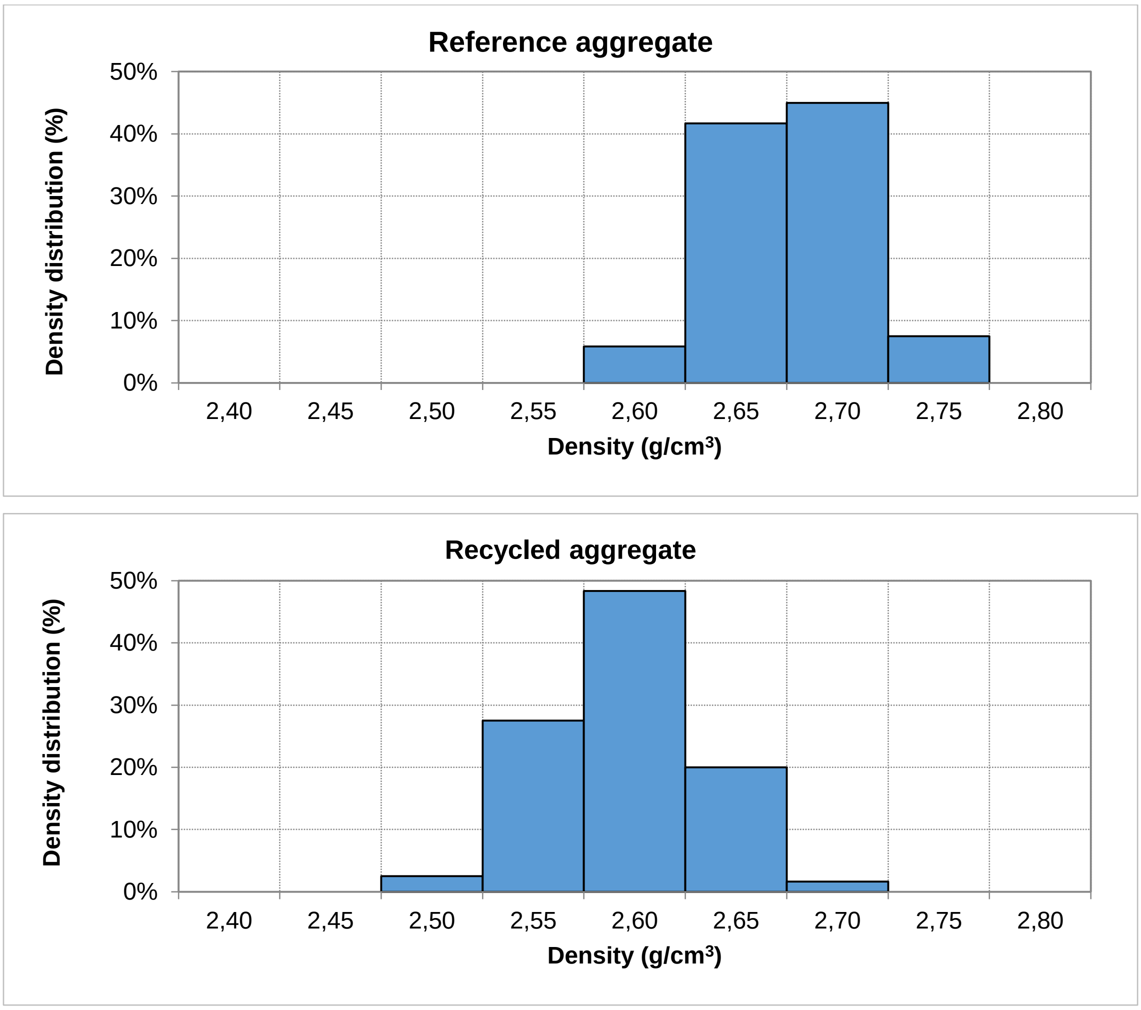
Finally, based on the costs of concrete production and disposal and transportation of the waste to landfills, the economic impact of the use of RA was evaluated based on the concrete mix design to meet the compressive strength class requirements. This analysis allowed the RMC to proceed with a reliable evaluation of the use of the crushed RC as a recycled aggregate in other plants of the company.

4.4. Results and analysis

4.4.1. Aggregates characterization

Twenty samples (collected over two months) showed that the density of the RA ranged from 2.50 to 2.71 kg/m^3, whereas the value ranged from 2.60 to 2.79 kg/m^3 in the reference aggregate, as shown in Figure 25. This shows that the RA is approximately 3% lighter than the reference aggregate. The standard deviation of both aggregates was 0.04. This density difference was expected due to the presence of mortar adhered to the RA.

Figure 25 - Results obtained for the density of the reference and recycled aggregates



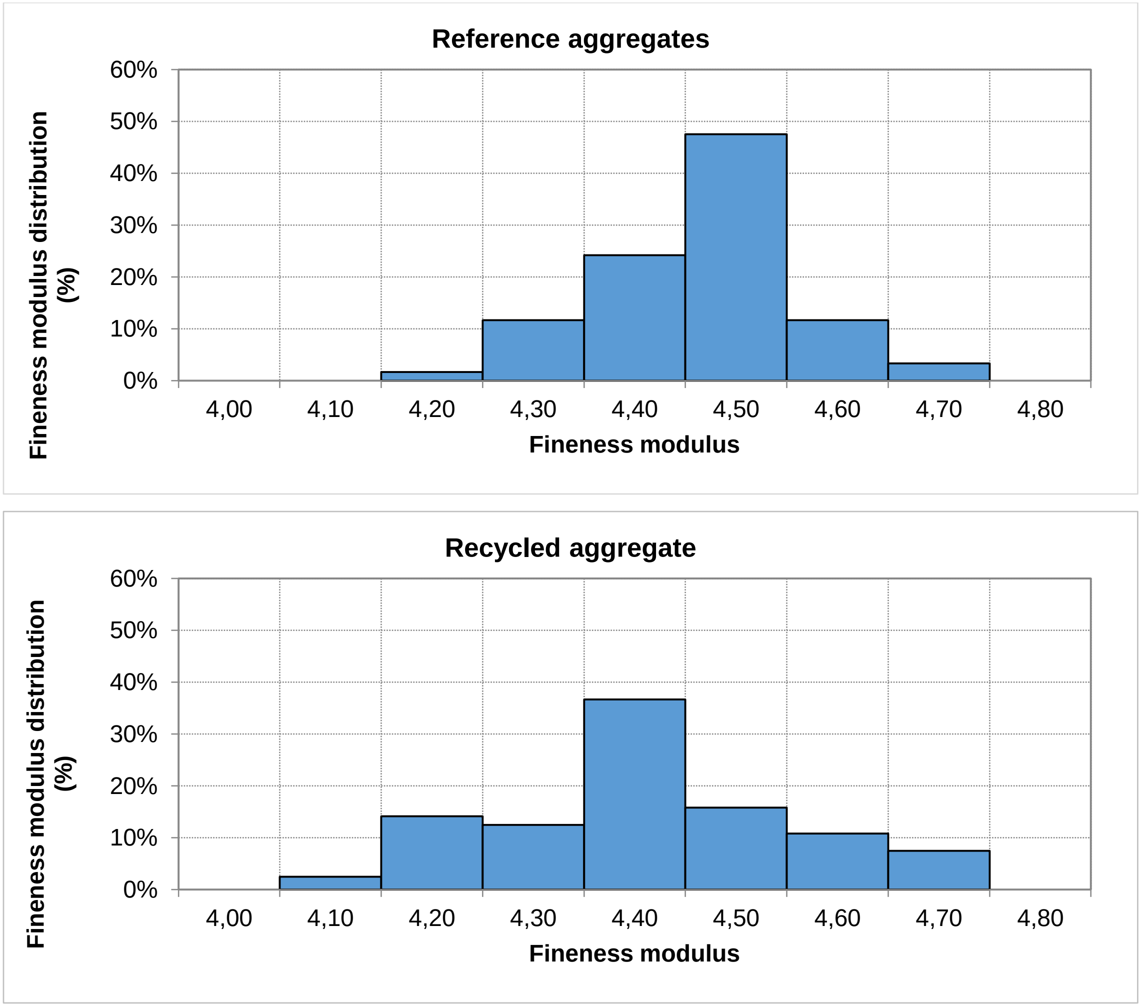
Source: The author

The difference observed in the aggregate's density, which impacts in the total porosity of the material, influences the compressive strength of the recycled concrete, and is normally compensated for by an increase in cement content. The increase in the density variation could lead to an increase in the compressive strength variation of recycled concrete, which also implies an increment in cement consumption. Therefore, both aspects should be evaluated in production conditions to determine whether the extra cement content makes the use of RA infeasible. The analysis of these aspects in production conditions is presented in the next section. The difference between the mean density of RA versus NA was

3%. This value is similar to that found by Thomas et al. (2016), whereas the studies by Zega and Di Maio (2011) found a slightly higher difference (9%). These variations in results emphasize the need for accurate characterization for each production condition to enable its application.

The RA has a fineness modulus slightly smaller than the reference aggregate. This result indicates that the water demand of the concrete with RA will be higher for a same level of slump. Therefore, the real impact of this parameter must be analyzed in conjunction with the workability conditions. The difference between the fineness modulus of the NA (4.51) and RA (4.46) in the production test was slightly higher than 1% (Figure 26). These values are similar to those found in the characterization tests of the material, which shows that the crushing process is stable and produces RA with low variability.

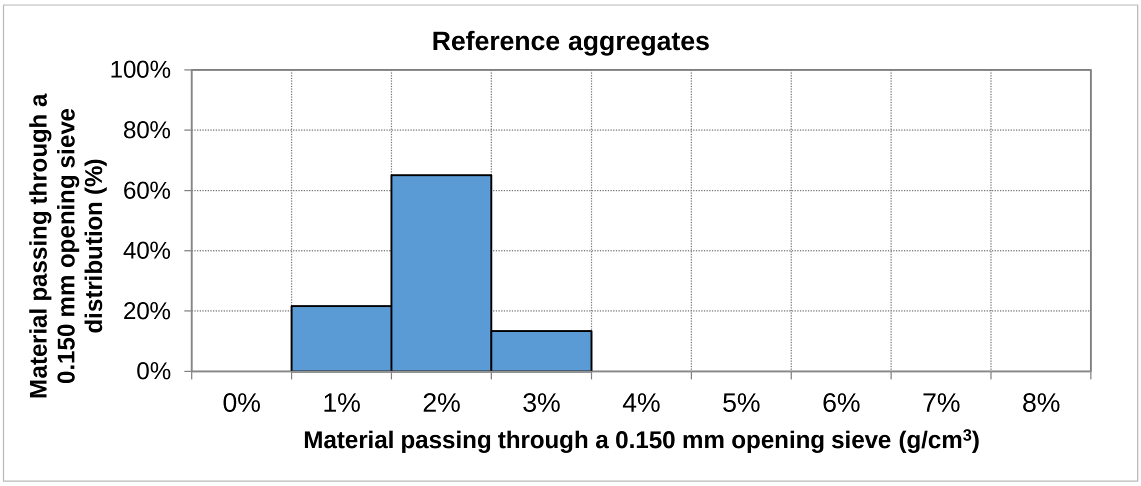
Figure 26 - Results obtained for the modulus of fineness of the reference and recycled aggregates

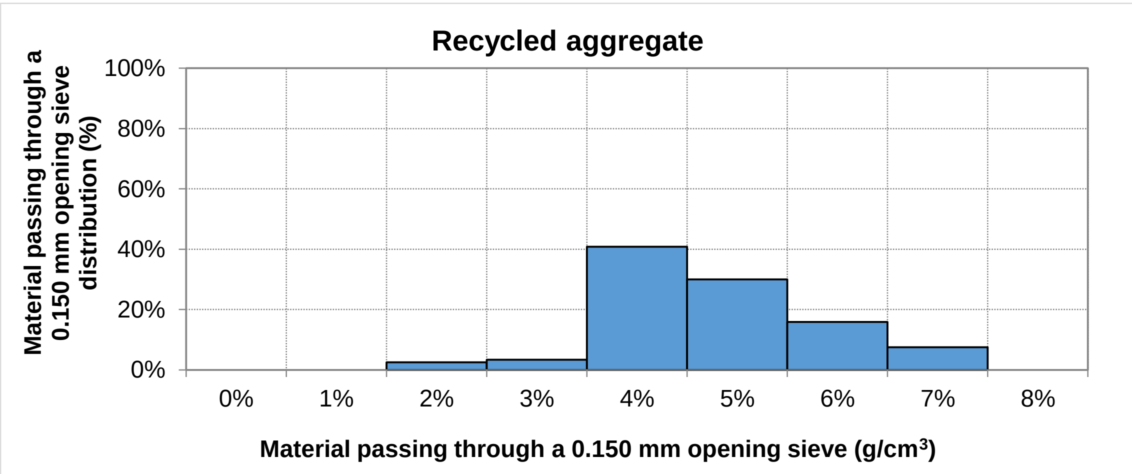


Source: The author

The results of determining fine material passing through the 0.150-mm sieve (Figure 27) in the total reference aggregates was 2% on average, whereas that in the total recycled aggregate was 5%. Considering all these factors, it is possible to state that the total recycled aggregate is slightly finer than the total aggregate reference. It is well known that the presence of fine material passing through the 0.150-mm sieve at a content greater than 5% can negatively affect the workability of the concrete (Poon et al., 2007). A practical result of the decrease in the workability is the increase in the cost of the concrete. This is because it will be crucial add more admixtures, water, or cement to maintain the water/cement (w/c) ratio to correct slump loss. Further, there is an increasing tendency toward concrete shrinkage, which can cause cracking. However, a better condition of evaluation is obtained when the concrete is evaluated in terms of pumping capacity, as discussed in the next section.

Figure 27 -- Results obtained for the material passing through the 0.150-mm sieve of reference and recycled aggregates

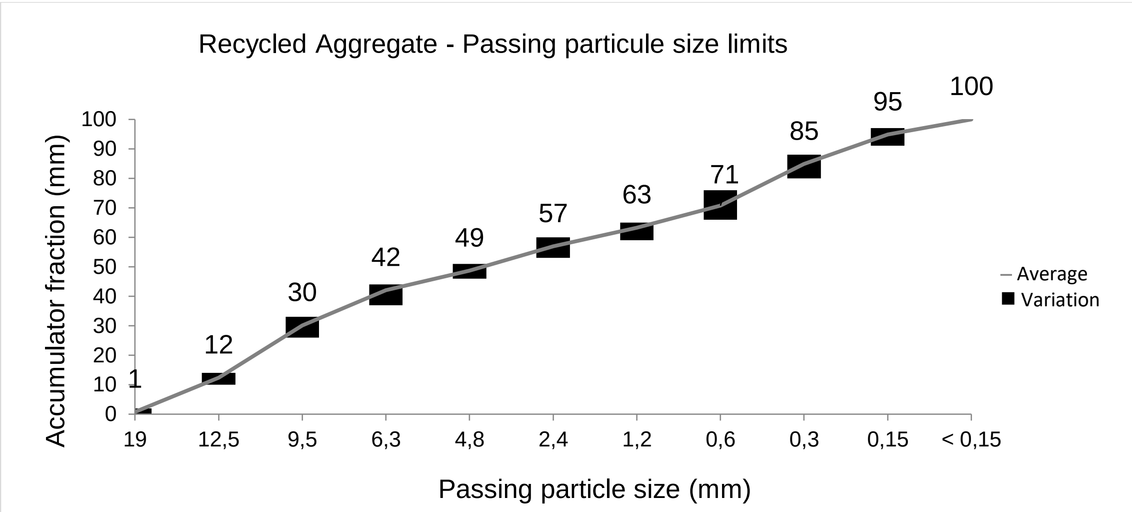


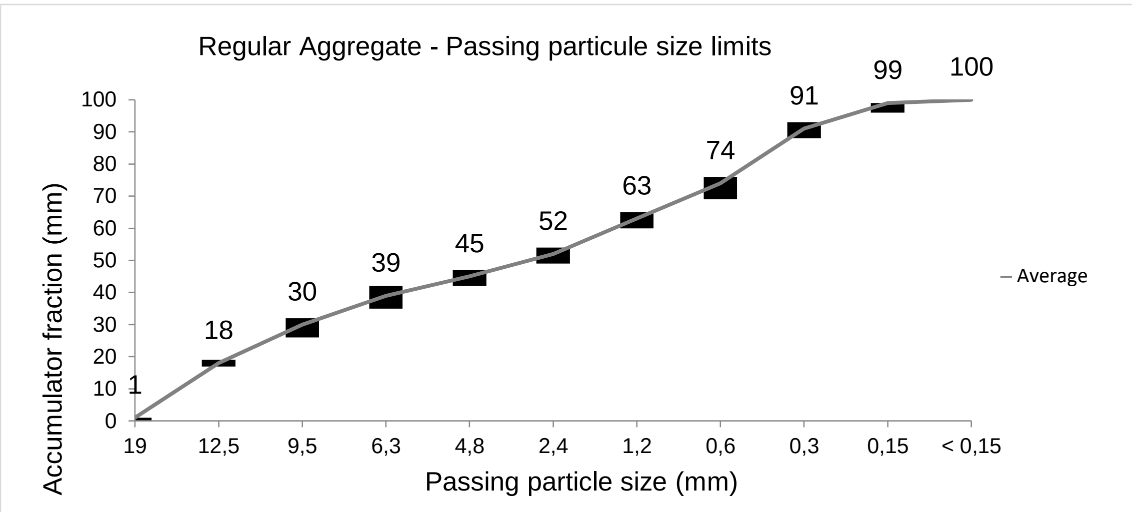


Source: The author

As noted previously, to maintain the particle size distribution of natural and RA as close as possible to the reference particle size distribution, a study was carried out to evaluate the particle size distribution of the 20 samples previously collected, resulting in a 20% replacement of the NA volume by RA. The particle size distribution curves of the NA and RA (Figure 28) show that there is a slight difference between the amounts of material retained in each sieve and that the variation between the material retained in the sieves was higher in RA than in NA. During crushing of the hardened concrete, a significant quantity of fine particles are generated, affecting the average particle size distribution. This result corroborates studies by Rashwan and Abourisk (1997) who concluded that both the aggregate-adhered mortar and the crushing process affect the particle size and particle size distribution curve of the RA.

Figure 28 - Total particle size distribution obtained using reference and recycled aggregates



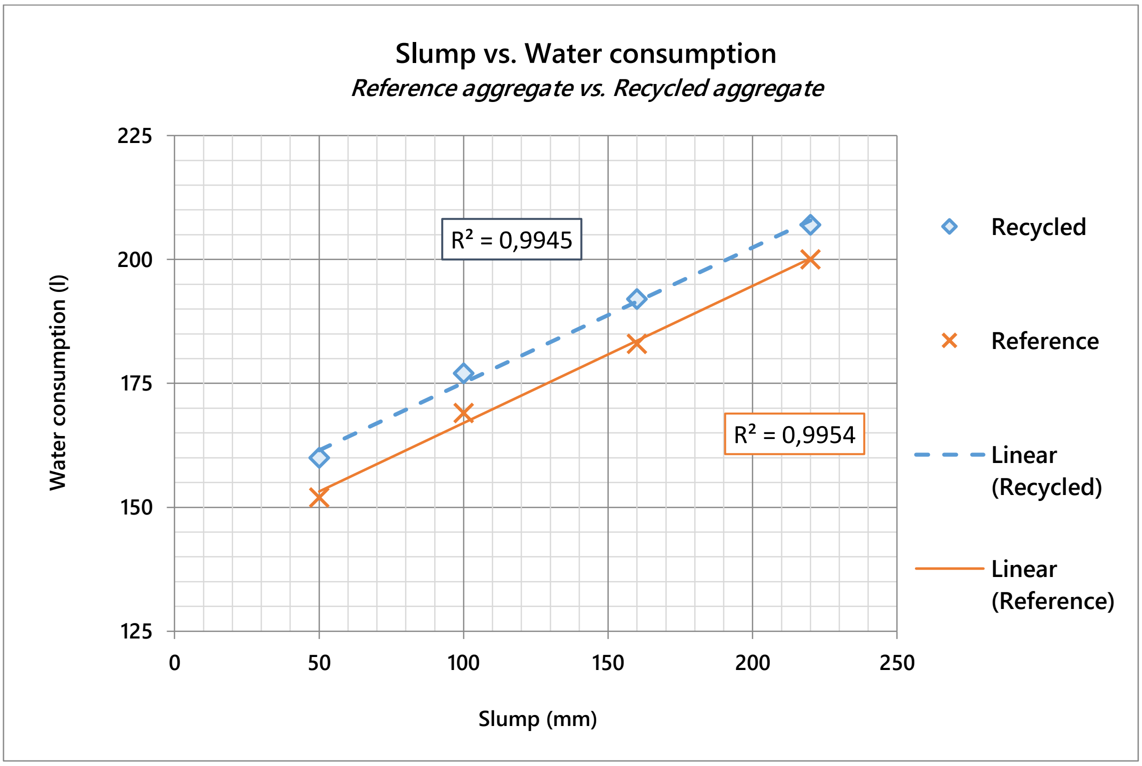


Source: The author

4.4.2. Concrete mix design

Through the mix design study, it was possible to establish a relationship between the water consumption and the slump level of the concrete, as presented in Figure 29. The concrete mix design demonstrates that the concrete with RA required an additional 8 L of water per cubic meter of concrete, on average, compared to reference concrete. This can be explained by the difference in physical characteristics between NA and RA, especially the amount of fine material passing through the 0.150-mm sieve. This increment in water content was constant for all slump levels analyzed. However, the amount of mortar (by mass) required for the concrete with RA can be decreased, as demonstrated by the results obtained through the concrete mix design. In that sense, the obtained mortar content was 52% for concretes with RA, whereas that of the reference concrete was 55%.

Figure 29 – Relation between the water consumption (reference concrete and concrete with RA) and slump of the concrete.

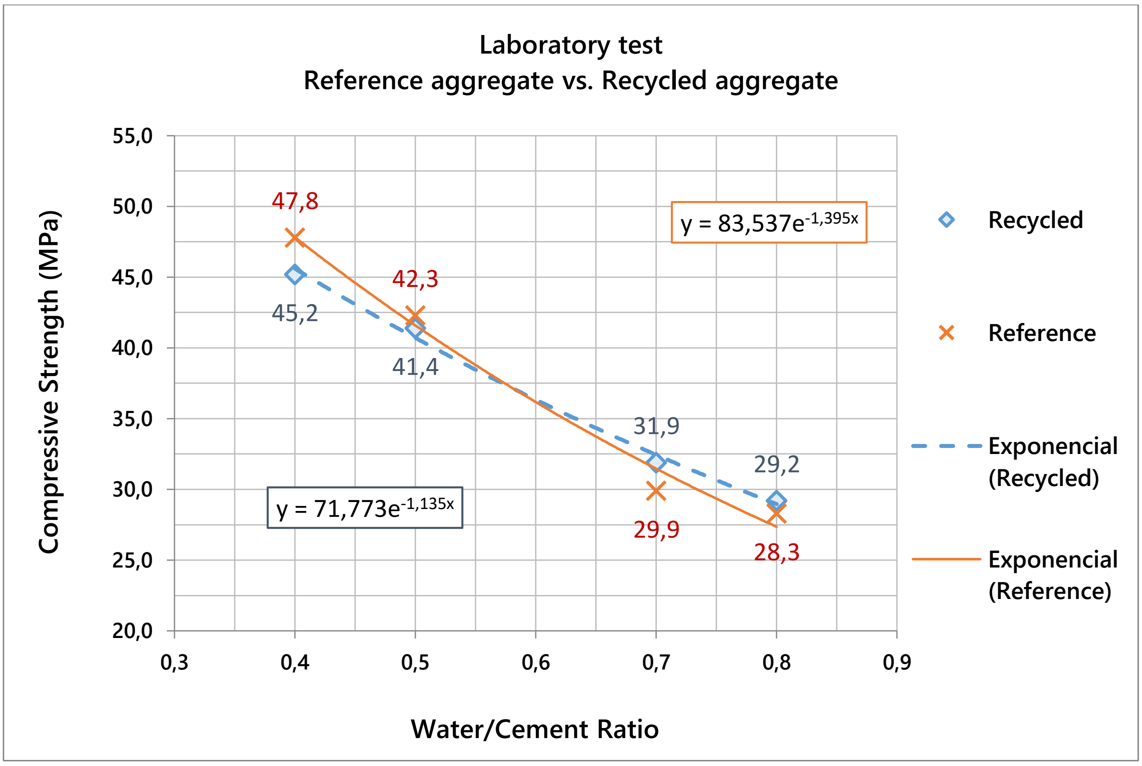


Source: The author

Figure 30 demonstrates that during the concrete mix design in the laboratory, the concrete with RA, in terms of average compressive strength, had poorer performance than the reference concrete when the w/c ratio was less than 0.575.

However, this behavior was reversed in concrete designed for higher w/c ratios. This corroborates the results observed by Rashwan and Abourisk (1997) and Ryu (2002), who concluded that the impact on the quality of concrete with RA is more noticeable in concretes with lower w/c ratio and higher compressive strength. The non-hydrated cement particles contribute to increasing the strength of concrete with a higher w/c ratio, because increases the amount of hydrated cement more significantly. On the other hand, when the w/c ratio is lower, the cement content becomes enough higher to make the contribution of non-hydrated cement present at the RA insignificant. In some of the cases where the w/c ratio is higher, the increase in compressive strength obtained with RA overcomes the decrease in strength caused by the increased demand for water to keep the slump unchanged. It is possible to affirm that the use of RA increases the water demand, but could positively affect the compressive strength of the concrete with higher w/c ratio.

Figure 30 - Average compressive strength vs. w/c ratio for concrete obtained in laboratory for concrete reference and concrete with RA.



Source: The author

Analyses were performed in the laboratory to obtain concrete mixes with equivalent values of average strength. Through the mix design process, two mix proportions were determinate to achieve the same average compressive strength (42 MPa). The mix proportions are presented in Table 8. Both concrete mixes were then put into production at the RMC plant and sent to the job sites for monitoring of the pumpability conditions and parameterization of their variability, as presented in the next section.

Table 8 – Mix proportions of the concrete tested on production conditions

Materials	Mix proportions (kg/m^3)	
	NA concrete	RA concrete
Cement	400	400
Fine aggregate	1052	660
Coarse aggregate	785	772
Recycled aggregate	0	360
Admixture	2.80	2.80
Water	196 a/c = 0.49	205 a/c = 0.51

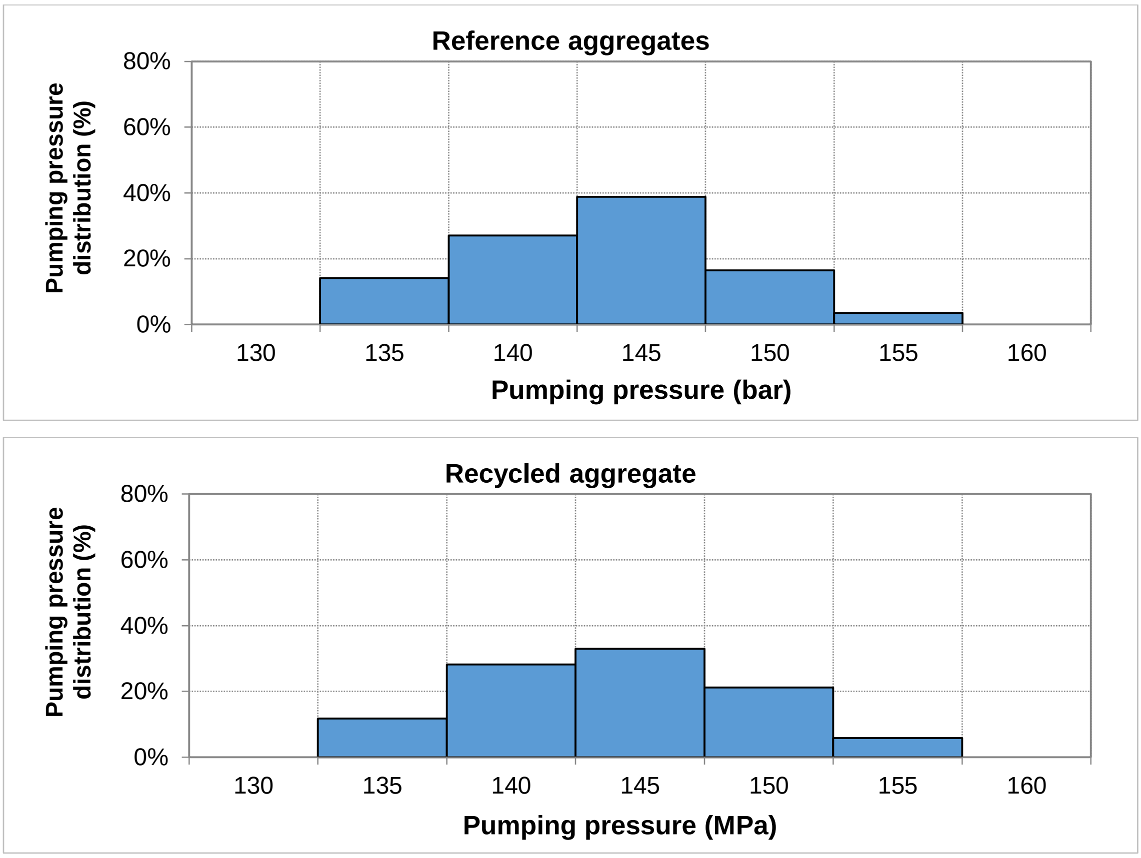
Source: The author

4.5. Concrete tests on production conditions

The evaluation of pumping capacity showed that RA did not affect the concrete pumping pressure; there were no reports of irregularities in concrete quality in any of the 170 measurements made. The pumping pressure was always less than the pumping pressure limit established by the company (180 bar).

The pumpability tests showed that both concretes prepared with RA and reference aggregate were pumped with a mean pressure slightly greater than 145 bar (145.6 for reference concrete and 146.4 for RA concrete) and that the dispersion of the results (Figure 31) of both types of concrete were very similar. This demonstrates that the substitution of 20% RA for NA did not significantly interfere in the pumpability of the concrete. This finding also demonstrates the adequacy of the mix design procedure based on fixing the slump and the determination of the optimum mortar content to guarantee the applicability of the material.

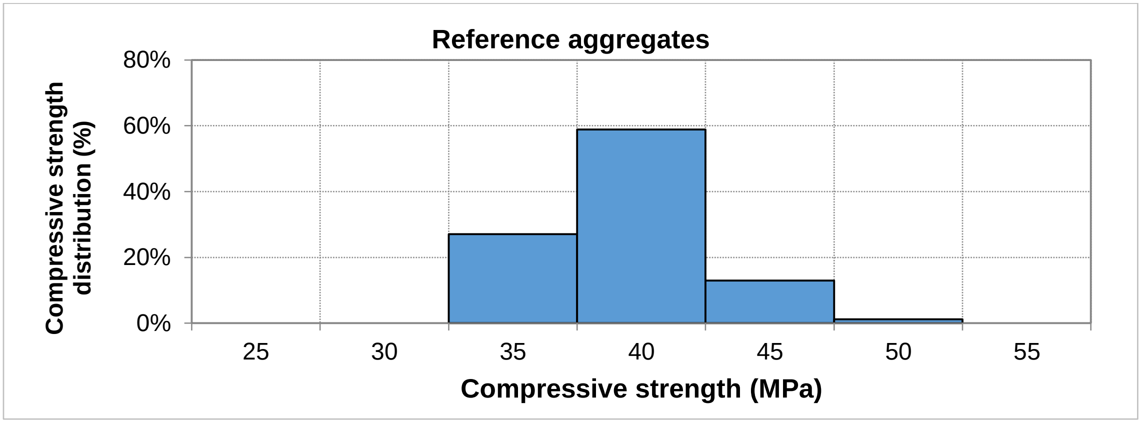
Figure 31 – Concretes pumping pressure distribution obtained for reference and recycled concrete during the production period

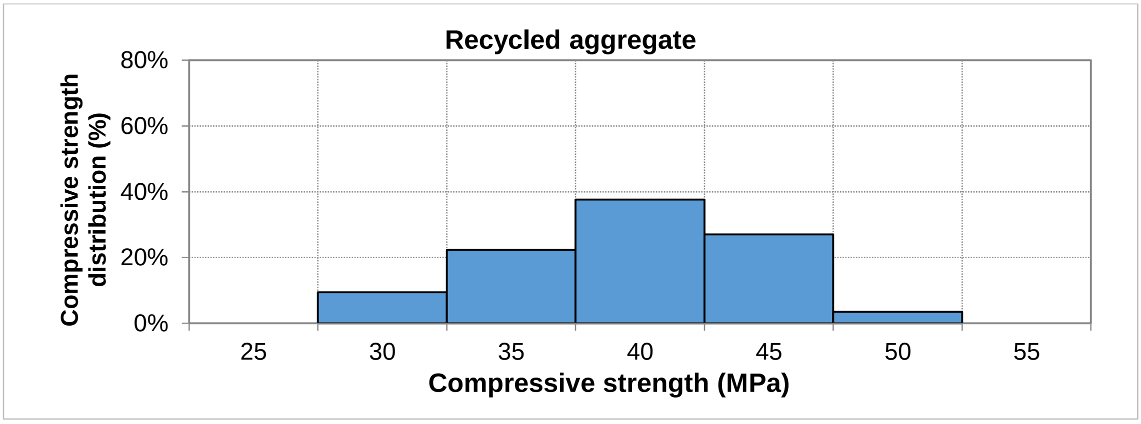


Source: The author

The standard deviations obtained for each concrete were significantly different, as can be observed in the histograms presented in Figure 32. The concretes with RA presented a standard deviation of 4.7 MPa, which is 80% greater than the value obtained with the reference aggregate concrete (2.6 MPa). On the other hand, the compressive strength measured in the production test (Figure 33) showed that the compressive strength distribution was very similar in terms of average values. The average value of the compressive strength for both concretes was almost the same. The average value obtained using RA was 41.8 MPa, and that of concrete with NA was 42.2 MPa. The relative difference was approximately 1%, which is negligible. These values are also very close to the expected compressive strength of 42 MPa. The confidence intervals of the two average values overlap, which indicates that the differences between the average values of the sample population is not statistically significant. This hypothesis was confirmed from Test T, which presented a p-value of 0.647.

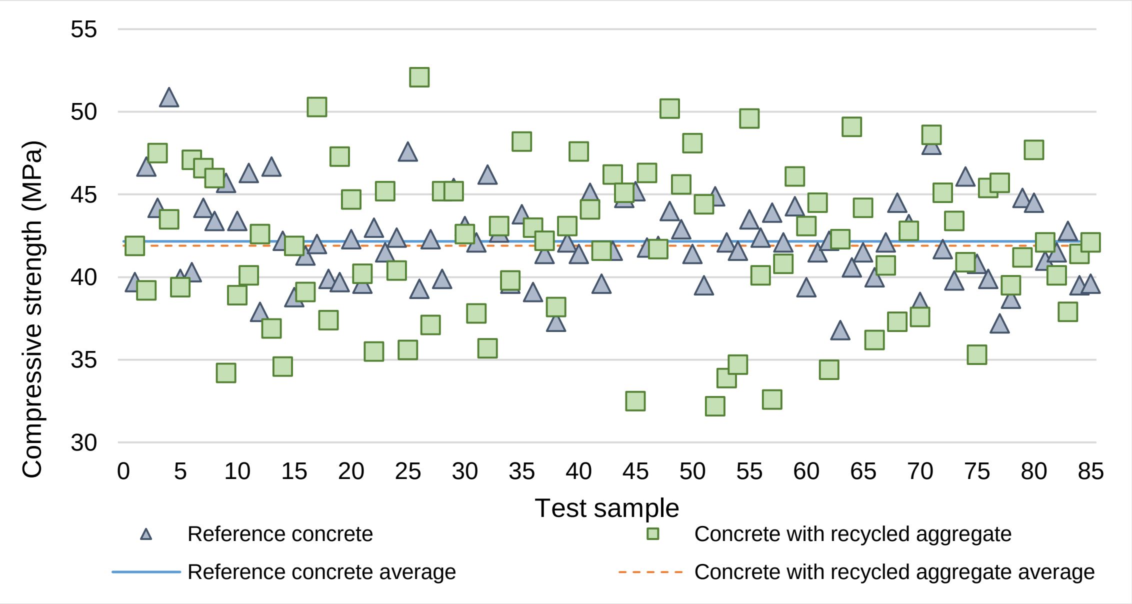
Figure 32 - Compressive strength results distributions obtained in the field test for the (a) reference and (b) concrete with recycled aggregates.





Source: The author

Figure 33 - Compressive strength values obtained for reference concrete and concrete with recycled aggregates during the production period in the RMC plant



Source: The author

The variation in the characteristics of the recycled aggregates affected the concrete variability in the concrete full-scale production conditions. This increase in variability could be parameterized by the standard deviation of the concrete compressive strength. The greater standard deviation obtained when recycled aggregates was used implies in an increase in the required average concrete strength (f´c) to meet the requirements of characteristic values (f´cr) determined by Equations 2 and 4.

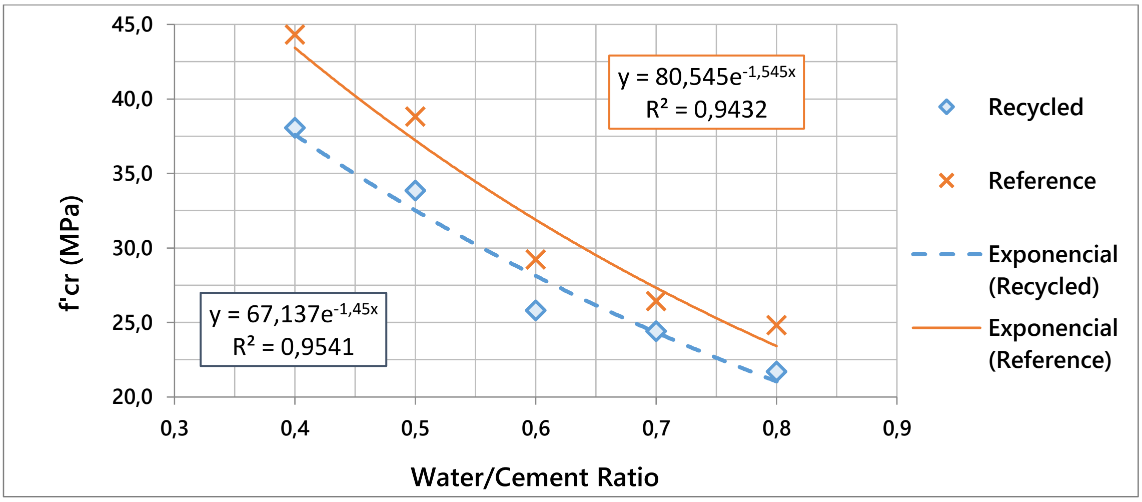
The results obtained by Pacheco et al. (2019) demonstrated that the variability of RA concrete is higher for higher strength classes. In this sense, because the concrete evaluated at the real scale was in a superior range of strength relative to those analyzed in the mix design study, it is possible that this assumption is very conservative. This is because when maintaining the same standard deviation for lower-strength classes, there is an increase in the coefficient of variation considered for concretes produced with higher w/c ratios. As a result, the required average compressive strength (f´c) used as the basis for the selection of concrete mixtures will be different for concrete produced with RA and with NA.

Therefore, the graphs of Figure 34 were produced using the concrete mix design results and considering the standard deviations obtained in the field tests to visualize the impact of RA on the maximum w/c ratio of the concrete to meet the characteristic strength (f´cr) requirements. For example, the characteristic compressive strength of 30 MPa was achieved with a w/c ratio of 0.55 for RA and 0.64 for NA.

The desired workability is achieved by a given level of water consumption; hence, the need to reduce the water/cement ratio results in an increase in the cement demand for concrete with recycled aggregates.

Consequently, the viability of the use of recycled aggregates will depend on the condition in which the increase in cost caused by the increased in cement consumption does not exceed the costs associated with the use of the recycled material. This analysis is presented in the next section.

Figure 34– Characteristics compressive strength (f'cr) vs. w/c ratio obtained in field test for NA concrete and RA concrete.



Source: The author

4.5.1. Feasibility analysis

Table 9 presents the cement consumption obtained for the concrete mix design of NA and RA concrete for each class of characteristic compressive strength. The values were obtained considering the 200-mm slump class (S 200) and using the mix design parameters and standard deviation obtained in the production conditions. It is possible to verify that the lower the characteristic strength (f´cr) of the concrete the lower is the difference in the cement consumption of the concrete mix design. However, the minimum increment in cement content provoked by the use of RA was 10%, which is the double the value obtained by Marinković et al. (2010). This difference could be because the referred study considered average values of compressive strength instead of characteristic values. Thus, this result highlights the importance of considering the variability of concrete with RA under production conditions.

Table 9 Results of cement consumption for concretes with recycled aggregate.

Strength Class	Cement consumption (kg/m^3)		
	Reference	Recycled	Relative difference (%)
C40	433	574	141–33
C35	363	456	93–26
C30	307	369	62–20
C25	259	301	42–16
C20	217	245	28–13
C15	180	198	18–10

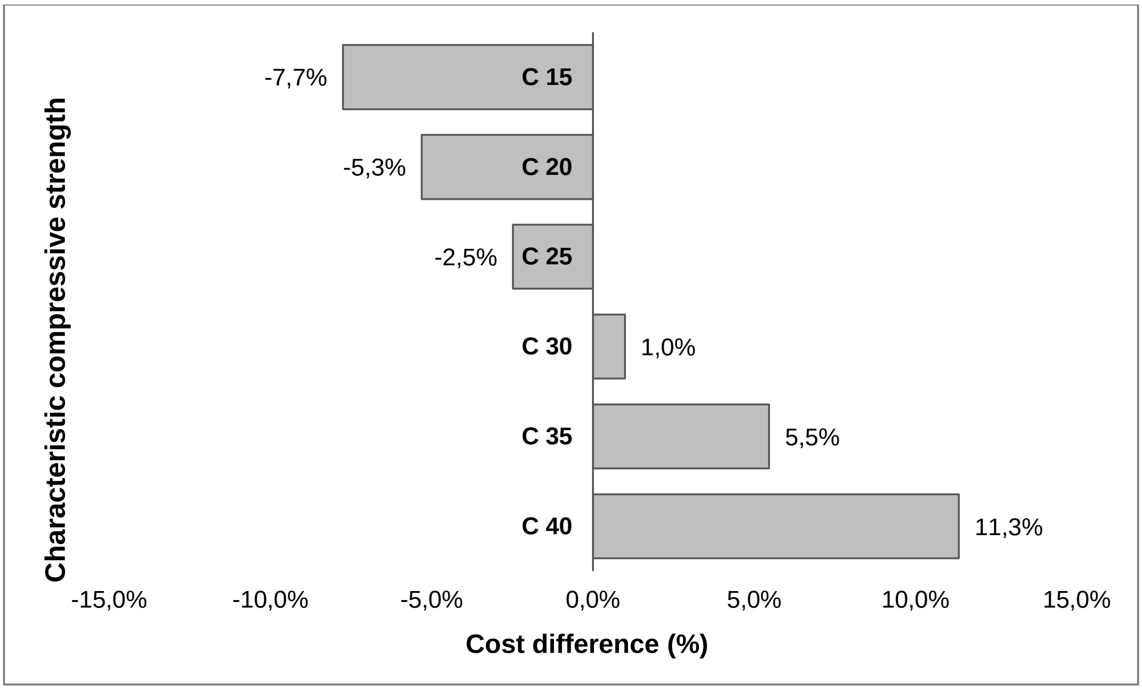
Source: The author

The difference in cement consumption affects the production cost of the concrete. Other local factors also influence cost and should be considered:

- The prices of the raw materials used in the concrete vary in each plant because they depend on certain factors, such as availability and distance between the place of production and the ready-mix plant. In Brazil, the aggregate price is approximately 15% of the cement price. Although water accounts for approximately 15% of the volume of concrete, its cost generally accounts for less than 1% of the total cost of the concrete.
- The amount of admixture used in the concrete varies as a function of the quantity of cement and slump requirement. Therefore, when increasing the consumption of cement, there will be an increase the amount of admixture used in the concrete, which negatively impacts the cost of the ready-mix concrete.
- The process of producing RA involves costs that will vary depending on factors such as the type of equipment, the number of workers at the plant, and how the equipment was purchased or financed.
- The use of crushed returned concrete as a recycled aggregate decreases (or even eliminates) the cost of transporting and disposing of concrete waste in landfill. In some places in Brazil, this cost may even exceed the cost of concrete. For example, the cost per ton of concrete waste sent to landfill in São Paulo city can exceed the production cost of the concrete by up to 10%, depending on the distance between the ready-mix concrete plant and landfill site.
- The impact of adding recycled aggregate to the concrete will also reflect the cost of storing the material and preparing the concrete ready-mix concrete plant.

Accounting for these aspects, and using the prices practiced in the plant in which the scale tests were carried out, it was possible to determine that even with the increase in cement consumption, there is financial gain for the use of RA in concretes whose characteristic compressive strength is up to 25 MPa (Figure 35). In the specific case of concrete with a characteristic strength of 30 MPa, the cost difference was minimal (1%), which indicates the possibility of using the recycled material for environmental advantages and a negligible increase in cost of RMC.

Figure 35- Cost difference between RA and NA concrete for each strength class



Source: The author

4.6. Conclusions

In this study, the use of RA generated from the crushing of concrete remnants of RMC plants for the production of concrete was analyzed through laboratory and production-condition tests. It was possible to verify that the use of this type of waste as RA can be viable, even if its use has negative impacts on the workability and standard deviation of the concrete. The observed increase in the variability of the concrete with RA relative to that with NA in the conditions of production led to an increase in cement consumption that was greater than that found in previous studies, which considered only the average instead of the characteristic values of compressive strength. To ensure that the process is economically viable, the cost reduction due to the use of recycled materials must be greater than the cost of purchase, operation, and maintenance of the crusher, as well as that of the additional consumption of cement in the new concrete mixtures.

In the case evaluated here, there are financial gains with the use of RA in concretes of up to 30 MPa of compressive strength. In that sense, a key condition is to control the age of the RA used in the concrete production. The tests demonstrate that the RA used within 48 h of its production has good potential for use, because it can provide a reduction in the extra cement consumption.

The pumpability of the concrete was not affected by the use of RA, demonstrating the importance of development of a proper mix design analysis. However, this assessment should be made for each specific condition of production and should not be extrapolated indiscriminately. This study was also limited to the reuse of typical concrete, which corresponds to approximately 90% of the volume produced by the RMC plant. More comprehensive studies should be performed to evaluate the possibility of producing RA from special concretes and to produce special concretes with RA, as presented in the study by Chan et al., (2019) that focused on the use of RA in concretes containing fibers. In that study, the feasibility analysis did not depend as strongly on the impact on compressive strength.

5. IMPLEMENTATION OF THE USE OF HYDRATION STABILIZER ADMIXTURES AT A READY-MIX CONCRETE COMPANY

5.1. Introduction

According to Vieira et al. (2019), the amount of concrete residue generated in a ready-mixed concrete (RMC) plant corresponds to approximately 3% of the total volume of concrete produced. Although this percentage is quite small, considering that approximately 25 billion tons of concrete are produced each year worldwide, the waste generated could be approximately 750 million tons. A considerable part of this is produced in RMC plants. Therefore, it appears quite clear that the problem cannot be overlooked.

Concrete production at RMC plants always generates waste (Kazaz & Ulubeyli, 2016). There are two different types of waste generated in RMCs: adhered concrete and waste concrete. Adhered concrete is the material impregnated inside the drum of the concrete mixer truck after its total unloading. Returned concrete is the remaining concrete that is not discharged at the construction site. While returned concrete is generated occasionally, adhered concrete is a constant residue because it is always present every time the ready-mixed concrete truck returns to the plant (Vieira et al., 2019). One of the strategies applied by RMC companies to reduce the volume of waste disposal in landfills is to use admixtures such as cement hydration stabilizers (Xuan et al., 2018).

The use of hydration stabilizer admixtures (HSAs) generates favorable conditions of reutilization of the returned concrete and even of the adhered concrete. This strategy provides conditions for the total elimination of waste using the returned concrete as a whole and avoids the generation of slurry and high consumption of water, which is the case of the concrete recycling equipment used to reuse the aggregates separately (Vieira & Figueiredo, 2016). According to Gebremichael et al. (2019), HSAs allow the returned concrete to remain fresh for up to 72 h longer, permitting its reuse. This research also indicates that the use of stabilized concrete with an HSA as a raw material for new concretes can increase the compressive strength of the final product in some cases.

Cheung et al. (2018) indicated that the use of HSAs was a good strategy to improve the sustainability in RMC production because these admixtures avoid losses of entire truckloads owing to problems that occur during transport. A study by Haddad et al. (2013) confirmed the tendency of overall compressive strength reduction of concrete in a laboratory study. Despite its effect on the final compressive strength, the use of HSAs causes a reduction in the compressive strength at an early age (Mali, 2016).

According to Shaikh (2016), the HSA acts like a high-range retarder; it differs from conventional retarders because it prevents the hydration of tricalcium aluminates (C_3A). In addition, the physical properties of stabilized concrete are as good as those of untreated control concrete.

An HSA affects the induction period of the hydration reactions of the cement in such a manner that once its effect has waned, the hydration reactions return to a normal rate (Kouhrausch, 2010); (Plank et al., 2015). Thus, the higher the amount of HSA added, the longer is the initial setting time, with a slight change between the initial and final concrete setting times. However, above a certain amount of HSA, the increase in the dose of HSA has no effect (Borger, 1994); (Okawa et al, 2000).

The stabilization period varies according to the type of cement and the type of mineral admixtures used. Naturally, the uncertainties produced by the variation in the results causes difficulties in the implementation of the technology under industrial operation conditions. Therefore, it is important to ensure an adequate mapping of the behavior of the interaction between returned concrete and the HSA to enable its implementation at RMC plants. The higher the amount of clinker in the cement, the higher is the admixture content required to stabilize the concrete for a given period (Shaikh, 2016).

The time of stabilization of the recycled concrete is reduced when the new concrete is added in order to complete the volume of the truck load (Paolini & Khurana, 1998). Previous studies by Benini (2005) demonstrated that it is possible to activate the stabilized concrete with 1% HSA in the weight of the cement with the addition of incremental cement in a proportion of 1:1. This positive horizon of additive application has been emphasized in previous laboratory studies (Borger et al., 1994; Lobo et al., 1995). However, doubts arose regarding the risk of real-scale production behavior variations for the effective implementation of this technology.

To facilitate the introduction of the use of HSA in the RMC production process, it is necessary to define which concrete can be reused. This selection is particularly important to better understand the impact of different amounts of HSA on the setting time of the returned concrete, which is a critical aspect for RMC operation in urban centers with traffic difficulties, such as the city of São Paulo. In addition, it is necessary to understand if it is possible to apply the results obtained in laboratory studies in the day-to-day operation of an ready-mix concrete plant. Taking the above into account, this chapter presents a case study of the operational procedures and results obtained during implementation of the process of reusing concrete returned with an HSA in one of the largest RMC companies in Brazil.

5.2. Methodology

Different tests were carried out to verify the feasibility of recycling concrete with an HSA. The returned concrete stabilized with an HSA (stabilized concrete) was analyzed in terms of the setting time and compressive strength. Tests were performed in order to evaluate both the influence of HSA on the compressive strength of stabilized concrete and the use of stabilized concrete on new concrete formulations (new concrete). The concrete setting time was measured through the ASTM C 403 standard test, and the compressive strength was measured according to ACI 318. All specimens were produced with raw materials used by the RMC plant in regular production.

As a preliminary measure, a laboratory test was carried out to determine the correlation between the hydration stabilizer admixtures content and the concrete setting time, and to verify possible influences on the compressive strength of the concrete. The temperature effect was also evaluated. The results of the preliminary tests allowed for defining the percentage of HSA in relation to the cement content (in mass) that is necessary to reach the required concrete setting time. Afterward, laboratory tests were carried out using actual returned concrete to analyze the impact of the use of stabilized concrete on the compressive strength of new concrete. These tests were performed as immediate preparation for industrial-scale application tests. These laboratory tests were used to properly verify if the stabilized concrete could be used as raw material for new concretes. After these laboratory tests, scale tests were performed for the returned concrete to confirm the results under production conditions.

The hydration stabilizer admixtures used to recycle the adhered concrete was evaluated on an industrial scale in other full-scale tests. The procedure specified by the hydration stabilizer admixtures manufacturer for the adhered concrete was evaluated for its feasibility together with the possibility of dosage optimization. The use of HSAs to eliminate the need for washing the adhered concrete present in the concrete mixer drum was then evaluated.

5.2.1. Preliminary tests

The preliminary tests were performed on a concrete mixture typically provided for job sites demanding the S100 slump class. This type of concrete represents approximately 20% of the total volume of concrete produced by RMC plants.

Table 10 shows the mix design of the S100 slump class—compressive strength classes C20, C25, C30, and C35—and the cost of raw material.

Table 10 - Mix design as tested

Raw material	Concrete mix design (kg/m^3)				Cost of material (US$/t)
	C20	C25	C30	C35	
Cement	236	271	298	317	93.16
Fine aggregate	1000	974	938	931	10.11
Coarse aggregate	993	994	996	997	7.87
Admixture	1,17	1,31	1,5	1,54	297.06
Water	170	170	170	170	0.13
HSA	-	-	-	-	540.34
Cost of concrete raw material (US$/m^3)	40,28	43,33	45,55	47,27	

Source: The author

The producer of the HSA reported that the admixture influence on the setting time of the concrete starts from a dosage of 0.2% (by mass of cement). Therefore, this was the minimum content of admixtures used in the laboratory test. Dosages above 1% could delay the setting time of the concrete by more than 48 h. In total, five different dosages of the HSA (0.20%, 0.4%, 0.6%, 0.8%, and 1.0%) were used in the test program in order to correlate this dosage with the setting time of the concrete and possible impact on the concrete strength.

According to Benini (2005), the addition of HSA to concrete within 4 h after the start of the mixture does not compromise its stabilizing effect but, beyond this period, there is the risk of the admixture being unable to stabilize the concrete. Therefore, the HSA was added to the concrete within 4 h from the beginning of the mixing in this experiment. It is also important to mention that only 1% of the concrete returned to the RMC plant arrives after 4 h (Vieira et al., 2019).

The influence of temperature on the concrete setting time was also evaluated. Three different temperatures (15°C, 25°C, and 35°C) were used to measure the influence of temperature in combination with the HAS on the setting time. This range was fixed considering that the average minimum and maximum monthly temperature in Brazil varies between 15°C and 30°C (INMET, 2019). It was considered that this temperature range would cover most of the typical working temperatures of the locations where RMC plants are located in Brazil. The results of the preliminary laboratory tests allowed for defining the dosage of HSA as a function of the temperature of the returned concrete in order to achieve the required setting time of the concrete.

In order for the ambient temperature to be maintained constant throughout the laboratory tests, all concretes were prepared in a room with air conditioning set to the temperature desired for the test. Prior to the start of the tests, all raw materials and equipment used were stored in this room for a minimum period of 24 h. Therefore, the materials had a temperature very similar to room temperature. All setting-time tests were performed in this room. The cylindrical specimens cast for the compressive strength test remained in this room within the mold for 24 h. After this period, the specimens were identified and sent to a curing chamber at a temperature of 23 ± 2°C, as recommended by Brazilian standards.

5.2.2. Laboratory tests of actual concrete leftovers

The concrete leftovers used in the tests were returned by “over order,” that is, the user returned the concrete owing to differences between the volume of concrete requested and the volume required for concreting. This is the main cause of returned concrete at RMC companies (Vieria et al., 2019). The reuse of concrete produced with unconventional additions (fibers, pigments, etc.) was excluded from the analysis.

Owing to the admixture producer's recommendation, a maximum 50% of the cement content of the new concrete originated from the stabilized concrete. Therefore, to reuse 3 m^3 of concrete with 300 kg/m^3 of cement, it was necessary to add at least another 900 kg of cement to produce the new concrete. The tests were restricted to concrete slump class S100 and compressive strength classes C20, C25, C30, and C35. In addition, only concrete leftovers with a temperature between 15°C and 35°C were stabilized.

The temperatures were measured with an infrared thermometer when the concrete was inside the truck drum. A sample of approximately 70 l of concrete was taken for the tests only if the concrete met the requirements of the compressive strength class, slump class, and temperature.

After 4 h counting from the start of the mixture, the sample was divided into two parts: the first with 10 l and the second with 60 l.

With the 10-l sample, a pair of specimens were cast to perform compressive strength tests. The value obtained from this sample was considered a reference for the stabilized concrete and could be compared with the results obtained with new concrete. This new concrete was produced using the second sample.

The 60-l sample was weighed, and the amount of cement in the sample was determined using the density of the concrete. This concrete sample was then stabilized for 24 h. The content of HSA added to the concrete was defined according to the results obtained in the preliminary tests considering the desired stabilization time (24 h), cement content, and temperature of the concrete.

Homogenization of the HSA with the 60-l concrete sample was performed in a laboratory mixer for 10 min. After that, the samples with the stabilized concrete were removed from the concrete mixer and placed into a plastic container for 24 h. The plastic container was covered with a damp cloth throughout this period.

After 24 h, the 60-l sample of stabilized concrete was fractionated into four smaller samples of approximately 15 l each. Each of the 15-l samples was weighed, and the amount of cement in the sample was determined using the density of the concrete. The 15-l samples with stabilized concrete were then used for the production of new concretes with the aim of achieving the compressive strength classes of C20, C25, C30, and C35.

To produce the new concretes, virgin raw materials were added to the stabilized concrete. The new concretes were produced with 50% of the cement content from the stabilized concrete and 50% of the “virgin” cement. To reduce possible variations, the "virgin" cement used was collected at the RMC plant on the same day that the returned concrete was produced.

Compressive strength tests were performed to characterize the stabilized concretes and new concretes produced from concrete leftovers. In order to consider the variation in the results, the characteristic compressive strengths of the stabilized concretes and new concretes were calculated. The average compressive strength of the concrete sample should be equal to or greater than the required average compressive strength (ACI 318) that guarantees the specified characteristic value of strength. The required average compressive strength should equal the higher value obtained from Equations 1 and 2:

$f'cr = f'c + 1.34s$ (Eq. 1)

$f'cr = f'c + 233s - 3{,}45$ (Eq. 2)

Where

$f'cr$ = required average compressive strength

$f'c$ = specified compressive strength of concrete

s = standard deviation

5.2.3. Full-scale tests of actual concrete leftovers

After the laboratory tests were carried out, real-scale concrete production tests were performed to verify the applicability of the use of an HSA under these conditions. The parameter used to analyze the stabilized concrete was the characteristic compressive strength obtained for each strength class using the same criteria presented in the last section. The study also ensured compliance with workability requirements. The reuse process of concrete leftovers was evaluated in the Jaguaré plant located in the city of São Paulo.

For six months, all returned concretes that met the previous conditions established in laboratory tests (ordinary concrete returned by over order, temperatures between 15°C and 35°C, and loading time of less than 4 h) were recycled and delivered to job sites.

Samples of all recycled concrete were cast, and the average values and standard deviations obtained in the compressive strength tests were compared with the results obtained in reference concretes produced exclusively with the usual "virgin" raw materials. The following procedure was implemented to reuse the returned concrete:

- When the RMC truck arrived at the plant with returned concrete, a trained employee measured the weight and temperature of the concrete and registered the information, together with the horary in which the concrete truck had been loaded and the cause of the return.
- The plant manager checked if it were possible to reuse the concrete in a subsequent load based on the previous information.

- If so, then the amount of HSA required to stabilize the concrete was calculated according to the data that had been obtained in the laboratory test. For the calculation, the following data were used: concrete temperature, volume of concrete returned, and time of stabilization of the concrete (the time between the addition of the HSA and the end of the unloading of the concrete at the construction site).

If the volume of concrete returned was greater than 50% of the concrete mixer drum capacity, half the volume was transferred to another RMC truck using a load transfer ramp Figure 36. This procedure allowed 50% of the cement content of returned concrete was used in the production of new concrete load.

Figure 36 - Load transfer ramp (photo from author’s personal archive)

Source: The author

The returned concretes were discarded from the test in the following cases:

- When there were special concretes (e.g., pigmented, with accelerating admixtures, and fiber-reinforced concretes)
- When there were concrete with temperatures below 15°C or above 35°C

- When there were no concrete deliveries within 24 h from the time the RMC truck returned with leftovers.
- When the difference between the time of return of the RMC truck and its initial mixing of concrete was more than 4 h.
- When the reason for returning the concrete was related to its quality (e.g., segregated concrete or slump above the specified amount) or to mechanical problems in the concrete truck that prevented the unloading of concrete (e.g., hydraulic engine or planetary gear malfunctions).

To ensure better homogenization of the returned concrete, water was added to concrete with slump values less than 100 mm prior to addition of the HSA. Subsequently, during the phase of reloading the truck with the stabilized concrete, the water was discounted.

The HSA was added to the returned concrete and homogenized in the truck for 10 min. After this homogenization period, the truck was shut down, and the concrete remained in the truck drum until the time of the next load.

The loading of the trucks with concrete (for delivery of the subsequent load) was done by discounting the quantity of raw materials in the stabilized concrete from the quantity of raw material required in the mix design of the new concrete to be delivered to the job site.

5.2.4. Full-scale tests of actual adhered concrete

Due to the differences between the drum geometry of the concrete mixer truck and the available laboratory mixer there is no conditions to perform preliminary laboratory tests to verify the amount of HSA needed to stabilize the adhered concrete. Therefore, the process of reusing the adhered concrete was evaluated directly in field-scale tests at the Jurubatuba RMC plant, also located in the city of São Paulo. Only concretes of compressive strength class C20 were used in these tests.

The procedure adopted for the reuse of adhered concrete under full-scale conditions followed the dosage specifications and mixture procedures specified by the HSA producer:

- At the construction site, after ensuring total discharge, the RMC driver should add at least 20 l of water through the pressure hose of the RMC truck to wash the charge hopper and the blades. This ensures that coarse aggregates adhered to the internal surface of the truck drum do not fall when the truck returns to the plant.
- Then, the RMC driver must add 100 l of water to the drum through the truck's water dosage unit. This ensures that any truck that returns only with adhered concrete has the same amount of water and avoids any errors related to amount of water added to the next load.
- If there is no subsequent scheduled delivery, then the RMC driver should add 1 l of HSA and 100 l of water inside the drum, mixing them for 3 min at the usual mixing speed. This ensures proper homogenization of these materials.
- Then, the RMC driver should park the RMC truck at the vehicle's parking lot.
- When the concrete truck receives the next load, the volume of water previously added during the concrete stabilization process is discounted.

It is important to note that although the procedure specified by the HSA producer is quite practical and operationally feasible, the amount of water added to the concrete adhered in relation to its volume is quite high. Thus, the adhered concrete is transformed into slurry, which standardizes the working conditions.

The procedure was tested across half the truck fleet of the plant (six concrete mixer trucks). The other concrete mixer trucks continued to undergo the normal procedure to remove the adhered concrete, i.e., removal of the material by pressure washing with water.

To verify the effectiveness of reusing the adhered concrete on a weekly basis, the RMC maintenance team, which was instructed to report the presence of adhered concrete inside the concrete truck drum, inspected the interiors of all concrete mixer drums.

To analyze the impact of the adhered concrete reuse process on the compressive strength, concrete samples produced in the first load of the day were cast for 28 days in order to determine their compressive strengths. The trucks that produced concrete in which the HSA was applied and the trucks that used the procedure of washing and removing the residue with water were then compared in terms of the characteristic compressive strengths by using the previous criteria (ACI 318).

Every five weeks, the amount of HSA was reduced by 50% in order to check if it was possible to reduce the amount of HSA recommended by the admixture producer. Under this new condition, there was another verification as to whether concrete had adhered inside the concrete drum, and the impact of the HSA on the compressive strength of the first loads. Tests were performed continuously and were uninterrupted for 15 weeks. Thus, the amount of the HSA was reduced to 0.25 l. The tests to evaluate the adequate HSA content were finalized when the inspections in the concrete drum showed that the number of trucks with concrete added increased in relation to the procedure of withdrawal with pressurized water. In total, almost 900 compressive strength tests and 30 adhered concrete inspections were performed.

5.2.5. Impact on concrete production cost

An analysis of the impact of HSAs on concrete production costs in the recycling of returned and adhered concrete was conducted. This analysis compared the cost of the HSA with the cost of recycled raw materials that were reused within the process. The values used to calculate the impact on concrete production costs were average values of raw material in São Paulo as of January 2017.

The RMC producer was conservative in their financial evaluation. Thus, the cost of disposing concrete waste in landfills was not considered, nor were the possible benefits regarding the image and reputation of the RMC plant owing to the reduction of environmental impacts.

The cost analysis of leftover concrete production was based on the reuse of 1 m^3 of concrete of the S100 class. This is the type of concrete most used by RMC plants (60% of total production). The need to stabilize the concrete leftovers for a period of approximately 24 h was considered in this calculation since this is the ideal situation when using the largest amount of HSA.

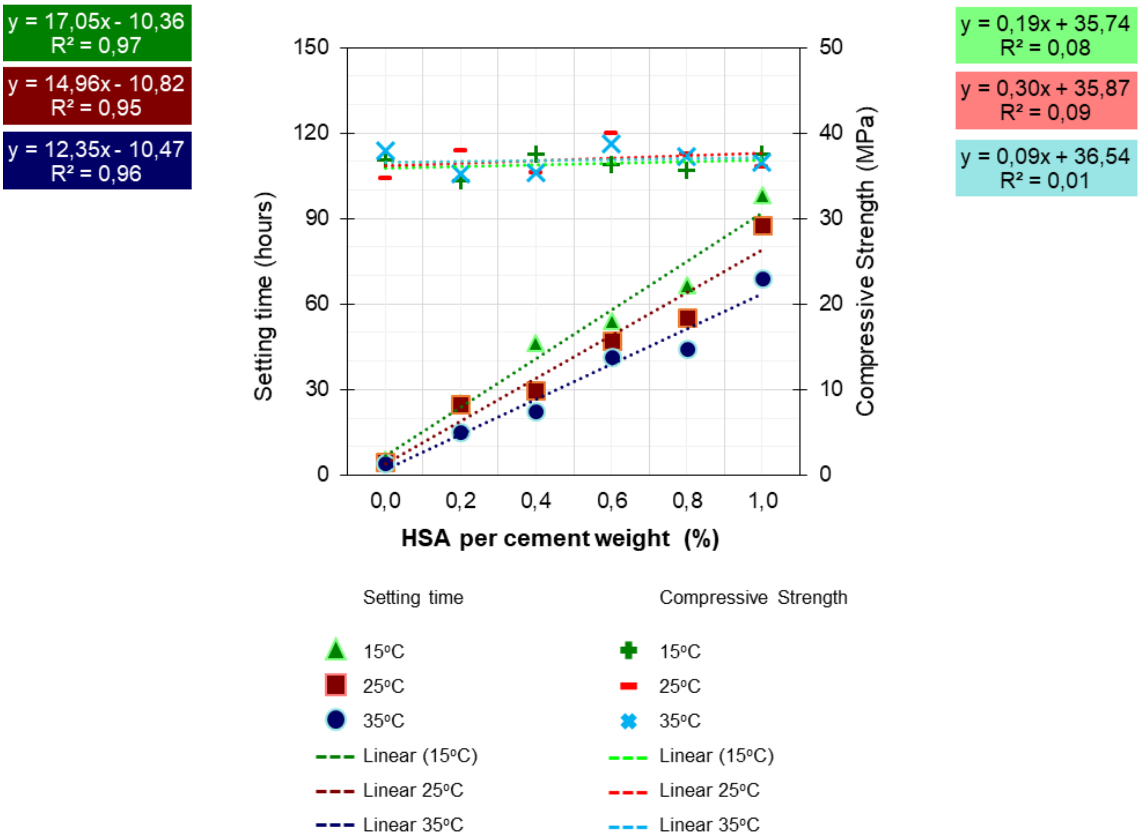
An analysis of the economic viability of the use of HSAs to help reuse adhered concrete involved data collected in a previous study (Vieira et al., 2019). Therefore, the analysis adopted as its premise that 67 l of concrete remained adhered in the truck drum because this is the lowest value obtained in the referred study. This strategy was adopted to verify the feasibility of using an HSA even under this critical condition of the minimum volume of adhered concrete.

5.3. Results and analyses

5.3.1. Preliminary laboratory tests

Preliminary laboratory tests showed that there is a strong correlation between the setting time of the concrete and the amount of HSA per weight of cement, and a weak correlation between the concrete compressive strength and the amount of HSA per weight of cement (Figure 37).

Figure 37 - Concrete setting time variation and compressive strength variation correlation with content of HSA and temperature



Source: The author

The correlation between the setting time of the concrete and the amount of HSA per weight of cement is linear and varies as a function of the temperature of the concrete. This correlation allows for a determination of the required amount of HSA to stabilize the concrete for the desired period of time depending on its temperature and the cement consumption.

On the other hand, there is no correlation between the amount of HSA and the concrete compressive strength. This shows that there was no significant variation in the compressive strength of concrete owing to the use of the HSA. This condition allows the use of this admixture without compromising the final strength of the material. Therefore, there is no need for a cement consumption increment to compensate for this possible reduction.

5.3.1.1. Laboratory tests on concrete leftovers

Table 11 lists the results obtained in the laboratory concrete leftover tests that evaluated the influence of the addition of virgin raw materials in the production of concrete with 50% of the cement coming from the HSA-stabilized returned concretes vs. the reference concrete.

Table 11 - Results of compressive strength in concrete leftovers in laboratory and field tests

	Reference concrete				Recycling concrete			
Strength class	C20	C25	C30	C35	C20	C25	C30	C35
Samples	10				10	10	10	10
Average	26,3				25,6	32,8	37,5	41,7
Sd	2,3				2,2	2	2	2,1
f’cr	23,2				22,7	30,1	34,8	38,9
Strength class	C20	C25	C30	C35	C20	C25	C30	C35
Samples		10			10	10	10	10
Average		28,5			29	30,7	38	43,2
Sd		1,9			2	2,4	2,5	2,7
f’cr		26,0			26,3	27,5	34,7	39,6
Strength class	C20	C25	C30	C35	C20	C25	C30	C35
Samples			10		10	10	10	10
Average			37,4		28,3	31,1	37,3	42,2
Sd			2,4		2,6	2,6	2,5	2,9
f’cr			34,2		24,8	27,6	34,0	38,3
Strength class	C20	C25	C30	C35	C20	C25	C30	C35
Samples				10	10	10	10	10
Average				41,7	27	32,3	36,9	42,3
Sd				2,7	2,8	2,9	2,1	2,9
f’cr				38,1	23,2	28,4	34,1	38,4

Source: The author

The laboratory results demonstrate that the concretes produced by this process have compressive strengths similar to those of the reference concretes, regardless of the strength class of the returned concrete or the concrete to be produced. The ANOVA analysis for compressive strength classes C20, C25, C30 and C35, showed low statistical significance ($p = 0.571$; 0.711; 0.898; 0.479, respectively), which shows that the reference concrete and the concrete produced with stabilized concrete leftovers are similar in terms of compressive strength.

The laboratory tests recycled 160 concrete loads that were compared to 40 reference concretes (not stabilized concrete); the results indicated that the use of the HSA in the recycling of concrete within the molds used by the RMC plant is technically feasible. This is because the results for the compressive strength and the standard deviation found in the recycled concrete were similar to those of the reference concrete.

The tests additionally confirmed that the equations obtained from the preliminary laboratory results could be used to determine the amount of HSA needed to stabilize the concrete for a desired time. The results obtained in the laboratory tests generated the necessary confidence for the accomplishment of the field full-scale tests.

5.3.1.2. Full-scale tests on concrete leftovers

Table 12 lists the results obtained in full-scale concrete leftover tests that evaluated the influence of the addition of virgin raw materials in the production of concrete with 50% of the cement coming from HSA-stabilized returned concretes vs. the reference concretes.

Table 12 - Results of compressive strength in concrete leftovers in full-scale field tests

	Reference concrete				**Recycling concrete**			
Strength class	C20	C25	C30	C35	C20	C25	C30	C35
Samples	1151	2440	3608	1899	126	198	339	191
Average	25,8	31,3	35,8	42,2	25,8	31,1	35,9	41,5
Sd	2,8	3,0	2,8	2,9	2,7	2.9	3,0	2,8
f’cr	22,0	27,3	32,0	38,3	22,2	27,2	31,9	37,7

Source: The author

No negative influence on the characteristic strength of the concrete was observed, as demonstrated by the results in Table 12. There is no significant difference between the results of the reference and recycled concretes, which is the desired condition. The ANOVA results proved the low statistical significance (p = 0.974; 0.548; 0.453; 0.592) for the compressive strength classes C20, C25, C30 and C35 respectively.

The scale tests carried out over 6 months recycled more than 850 concrete loads and verified the results obtained in the laboratory tests. In other words, the recycling procedure of the HSA concrete leftovers could be effectively incorporated into the productive processes of the RMC plant during day-to-day operations.

5.3.2. Adhered concrete

Table 13 lists the results of the scale test performed to evaluate the recycling procedure of the adhered concrete. The results show that the amount of HSA recommended by the admixture producer was overestimated since the inspections carried out inside the concrete truck drum showed that with half the admixture content, no truck had adhered material. Tests with only 0.25 l of the HSA (a quarter of the admixture supplier's recommended value) showed that approximately 40% of the inspections reported the presence of adhered concrete, so the use of only 0.25 l of the HSA was discarded.

Table 13 - Influence of HSA on compression strength of concrete produced with concrete adhered stabilized concrete and related adhered concrete in drum

	Week 1 to 5		Week 5 to10		Week 11to15	
	Reference	HSA	Reference	HSA	Reference	HSA
Admixture content (liters per truck)	-	1	-	0.5	-	0.25
Samples	141	151	156	158	149	138
Average	27,1	28,3	27,4	28,3	27,6	27,9
Standard deviation	2,8	3,1	2,9	3,5	2,5	3,1
f'ck (MPa)	22,6	23,2	22,5	22,6	23,5	22,7
Number of inspections	30	30	30	30	30	30
Number of inspection related concrete adhered in the drum	0	0	0	0	0	12

Source: The author

The influence of the HSA on the compressive strength of concrete was also noticed in the trucks that carried out the process of recycling the adhered concrete. The average results for the compression resistance and the standard deviation of the first loads with the addition of 1% and 0.5% (half the value recommended by the HSA supplier) were slightly higher than the reference results, that is, the trucks that were cleaned using the traditional method. The ANOVA test confirmed that the use of stabilized bonded concrete in the first concrete load has a statistically significant influence ($p < 0.01$). Although a small increase in the average compressive strength of the stabilized concrete was observed, the increase in the standard deviation resulted in concretes with similar compressive strengths.

5.3.3. Impact on concrete production costs

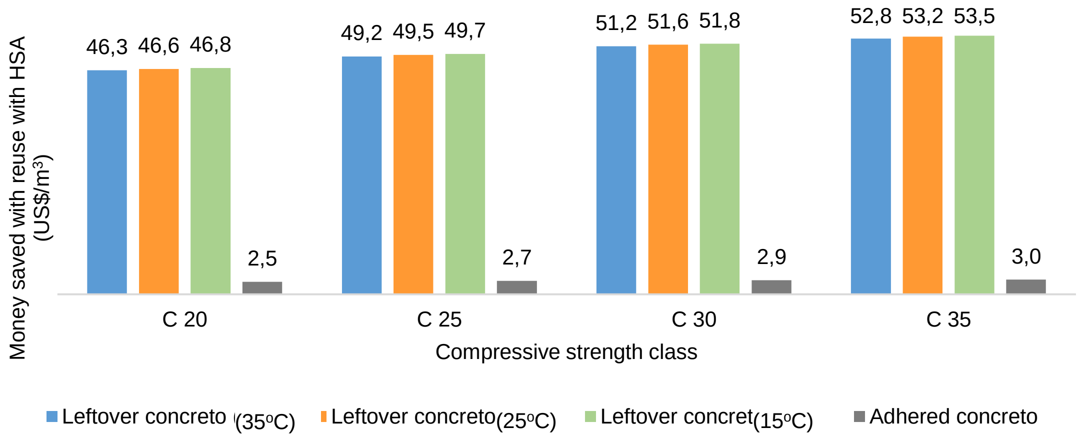
The results obtained in the field tests demonstrated that using the HSA-stabilized concrete does not negatively affect the compressive strength of the produced concrete. Therefore, in an analysis of the impact on concrete production costs, it was considered that the concrete mix design of concretes produced using concrete stabilized with an HSA was equal to the concrete mix design of the reference concretes (produced with virgin raw materials).

The analysis demonstrated that the recycling of concrete with an HSA is economically advantageous and feasible. This is because in all cases analyzed, the cost savings associated with the use of raw material is higher than the cost of the admixture.

The cost savings associated with the use of an HSA to recycle the adhered concrete is lower than that obtained with the returned concrete. This is expected because the percentage used to recycle the concrete inside the concrete truck drum is high in relation to the amount of cement. On the other hand, the cost analysis of concrete leftover production shows that higher savings are achieved when the returned concrete is recycled owing to the savings associated with the reuse of raw materials.

Figure 38 shows the difference between the cost of reused raw materials and the cost of the HSA in the reuse of 1 m^3 of concrete leftovers.

Figure 38 - Difference between cost of raw materials reused and cost of HSA used in reuse of 1 m³ of concrete leftovers



Source: The author

5.4. Conclusions

The reuse of waste generated in an RMC plant's concrete production with an HSA is feasible from a technical and financial point of view. The implementation process does not require drastic changes in the weighing and loading processes of the concrete.

From a technical point of view, it was clearly demonstrated that the use of an HSA is feasible. However, as the temperature and stabilization setting time affect the concrete behavior, this influence must be parameterized in preliminary laboratory tests. The study also showed that the use of an HSA does not negatively impact the compressive strength of the concrete and that laboratory tests can be used to define with great precision the amount of HSA that should be used to stabilize concrete leftovers. The procedure for reusing the concrete adhered within the concrete truck drum as specified by the admixture producer was validated. However, it was observed through real-scale tests that the amount of admixture that would effectively stabilize the adhered concrete was lower than the specified value.

From a financial point of view, the recycling process with an HSA leads to a reduction in costs. Returned concrete that would usually be converted into waste and disposed of in landfills can be reused as raw material in the composition of new concrete without loss of performance, thereby reducing the production costs associated with an RMC plant. It was demonstrated that there is a more relevant financial gain with the reuse of concrete leftovers than with the reuse of the adhered concrete. This is because the proportion of mixture used in the recycling of adhered concrete is greater than that used in the recycling of returned concrete.

It is important to highlight that the use of an HSA has very interesting environmental advantages, such as the elimination of the need to place waste disposal in landfills, low water consumption in the process, and the fact that it does not produce secondary residues such as slurries. Therefore, this technological strategy is very attractive for implementation in RMC plants.

6. COMPARATIVE STUDY OF THE AMOUNT OF WASTE DISPOSAL AND CO_2 EMISSIONS OF DIFFERENT STRATEGIES FOR THE REUSE OF WASTE GENERATED BY MIXED CONCRETE PLANTS.

6.1. Introduction

Ready-mix concrete (RMC) is a major product on cement markets in most countries. In Brazil, RMC constitutes ~21% of all cement produced in the country (SNIC, 2013). According to ERMCO (2016), the average fraction of the cement market taken by RMC is 50% for the European Union; in the USA and Japan this fraction is above 70%. Considering the consumption of cement, water, and aggregates, RMCs have a sizable environmental impact and, as a consequence, a high mitigation potential.

The average values of raw material consumption in the production of RMCs reported in the survey by Lima (2010) indicate that the annual quantity of concrete produced by RMC plants in Brazil is ~50 million cubic meters. Consequently, 14 million tons of cements, 98 million tons of aggregates, 9 million tons of water, and 70 thousand tons of cements, are used annually.

Much attention has been given recently to the dosage optimization for reducing the carbon footprint (John and Glasser, 2016). However, relatively little attention was paid to the aspects related to the resource use efficiency, such as the generation of concrete residues by RMC plants. In many countries, the cost of disposing such waste in landfills is growing, which requires developing strategies for minimizing the generation of waste in their operation. According to John (2010), although construction companies use large amounts of waste from other industries, recycling rates are low and the mere fact that a product contains waste does not guarantee that its environmental impact is lower than a product consisting of virgin materials.

According to Xuan et al. (2018), there are three main methods for diverting residues from landfills: (a) reuse of concrete in the fresh state by using hydration-stabilizing admixtures (HSA); (b) recycling concrete aggregates by separating the aggregates from the cement paste before concrete hardening ; (c) recycling of concrete in the hardened state by crushing, transforming it into recycled aggregates. Selecting the best strategy for residue minimization and management depends on technical conditions, costs, and even on cultural factors.

For reusing waste concrete when it is still fresh, hydration reactions of the cement present in the waste that returns to the RMC plant are delayed for a few hours or even for a few days by adding special chemical products, called hydration-stabilizing admixtures (HSA). Gebremichael et al. (2019) demonstrated the possibility of adding the HSA to stop the hydration of the concrete and allow its reuse. They also indicated that in some cases using HSA-stabilized concrete as a raw material for new concrete may increase the compressive strength of the final product. Haddad et al. (2013) concluded that the reuse of HAS-treated concrete could be viable from both economic and technical points of view.

Removal of aggregates from returned concrete in the fresh state can be achieved by rotational sieving and washing by water. This process allows the reuse of recovered aggregates (Tam and Tam 2007) but yields a slurry as a secondary waste. Scale tests using two different types of recyclers, carried out by Vieira and Figueiredo (2016), concluded that the physical characteristics of the obtained washed aggregates are similar to those of the original aggregates, and the influence of the equipment type is negligible. The produced slurry can be treated using decantation systems, recovering most of the water and reducing the amount of disposable waste (Lobo and Mullings, 2003). The other route consists of submitting the slurry to a filter-press system (Zervaki et al, 2013). Therefore, this approach in general incurs an extra work to eliminate the entire residue volume produced in the RMC production.

The third approach is to use hardened concrete as crushed recycled aggregates. The resulting aggregates have higher porosity than ordinary aggregates. They are normally processed to have the same particle size distribution as the original coarse aggregates, to enable the reintroduction of this residue into new formulations (Manzi et al., 2013). Fines generated during the crushing process are usually transformed into new waste, reducing the recovering rate to ~30–50% (Quattrone et al. 2014). Because higher-porosity recycled aggregates yield lower-strength concretes than regular aggregates, higher cement content may be required to compensate for this loss (Silva et al. 2014; Angulo et al. 2010).

Therefore, partial substitution of natural aggregates for recycled aggregates could be an interesting venue. The substitution percentage likely depends on the properties of crushed recycled aggregates and strength requirements for the new concrete (Etxeberria et al. 2004).

The reuse of waste by RMC companies using different recycling techniques is a relatively well-established practice in many markets, such as in North America (Jin et al., 2015), China (Xiao et al., 2016), and Turkey (Kazaz and Ulubeyli, 2016). However, there are no studies of industrial-scale comparison of the environmental efficiency of these recycling methods, at least to the knowledge of the authors.

According to Damineli et al. (2010), comparative assessment of the environmental efficiency of concretes can be performed in terms of the ratio of the cement consumption per cubic meter of concrete per unit of compressive strength obtained for the material. This consideration is convenient for measuring the overall environmental impact of any level of strength of structural concrete. Therefore, this study aimed to evaluate the environmental impact of the three main methods of concrete waste reuse, in terms of specific CO_2 emission and the waste reduction capacity during the concrete production by RMC plants. In that sense, this work compares the production of conventional concretes and concretes that use reused materials obtained using different strategies.

6.2. Methodology

This study consists of two parts. In the first part, the different strategies are evaluated in terms of their capacity of waste reuse in the concrete production together with the potential sub-product generation. In the second part, these strategies are evaluated in terms of their generated CO_2 emission. In both parts of the study, the different strategies are compared. The first part of the study was performed using previously published data for individual strategies: 1) reuse of fresh concrete residues with stabilizer admixtures (Vieira and Figueiredo, 2019), 2) recycling of fresh concrete by mechanical processing through washing and sieving (Vieira and Figueiredo, 2016) and 3) recycling of hardened concrete by crushing. In this study, two different types of equipment used in fresh concrete recycling by mechanical processing were evaluated: 3.1) drum-type (D) and 3.2) rotary sieve-type (R) (Vieira et al., 2019). It is important to mention that, owing to the lack of reliable data, this study did not account for the capacity of these processes to reduce the amount of water used to wash concrete trucks, moisten aggregates, and clean the plant floor.

The notation used to represent the recycled concrete was as follows:

- Reuse - HSA: Concrete produced by reusing fresh concrete waste with a stabilizing admixture
- Recovery - D: Concrete produced from aggregates recovered by recycling fresh concrete by mechanical processing and drum-type equipment
- Recovery - R: Concrete produced from aggregates recovered using the mechanical concrete recycling method and rotary-type equipment
- Recycle - C: Crushed concrete aggregates obtained using the crushing hardened concrete recycling method

To estimate the waste reduction capacity in the production of RMC, the present study was limited to ordinary concrete only or, in other words, to those cases where ordinary raw materials are used, which corresponds to ~90% of concrete produced by RMC plants (Vieira et al., 2019). This is because normal concretes are more easily reusable than special concretes, such as those containing fibers, pigments, or any other addition. The present study also separately analyzed the impact of each one of the concrete reuse procedures according to the type of waste generated.

The differences that involve the reuse of adhered concrete and concrete leftovers have also been considered. According to Sealey (2001), adhered concrete is a fraction of ready mixed concrete that returns because it remains adhered to the inner surface of a mixer drum and is removed only by washing. Leftover concrete covers fresh concrete that for various reasons is returned to the plant (Corbu, et al., 2015). Vieira et al. (2019) showed that, in Brazil, the volume of adhered concrete ranges between 90 and 200 liters per truck trip, and the volume of concrete leftovers is mainly associated with two factors: excessive concrete order and excessive application time. The average volume of leftovers is under 1.5 m^3 and only occurs in 5% of deliveries. The efficiency analysis took into account the potential capacity of each strategy to reuse each of these waste volumes:

adhered concrete and leftovers. The volume of the total waste generated corresponds to ~3.1% of the volume of concrete produced, which corresponds to 55% of the waste (1.4% of the volume produced) owing to adhered concrete and 45% of the waste (1.7% of the volume produced) owing to leftovers (Vieira et al., 2019). Taking to account the volume of concrete produced by the RMC plants in Brazil, it is estimated that nearly 405 thousand tons of cement, 2,925 thousand tons of aggregates, and 270 thousand tons of water are returned to the Brazilian RMC plants each year.

CO_2 emission of concretes produced exclusively using "virgin" materials and those produced using inputs from waste reuse/recycling techniques was compared for concretes in different strength categories (C20, C30, C30, C35, and C40). To enable this comparison, all concretes were mix-designed according to the method used by RMC producer (Monteiro et al., 1993). The dosage curves for the concrete produced using conventional raw materials and using reused raw materials were reported previously by some of the authors of this article (Vieira & Figueiredo, 2016), (Vieira & Figueiredo, 2019), (Vieira et al, 2019).

In a comparative evaluation of the CO_2 emission, the impact of raw materials and their transportation from the place of production to the RMC plant and the transportation performed during the preparation and delivery of the concrete were analyzed. The impact of reuse/recycled inputs on the mechanical strength of concrete and the CO_2 emission of the respective production process, as well as the impact of the emission owing to the waste transportation from the concrete plant to landfill were analyzed. The compositions studied refer to the concrete in the S100 category (slump class of 100 mm) and strength classes C20, C25, C30, C35, and C40.

The CO_2 emission of concrete was calculated by multiplying the CO_2 emission factor of each input by the CO_2 emitted in the concrete production process at the plant. This calculation accounts for loading raw materials into the plant and their mixture. Therefore, the final CO_2 emission factor represents all of the CO_2 emission generated in the entire production process of concrete.

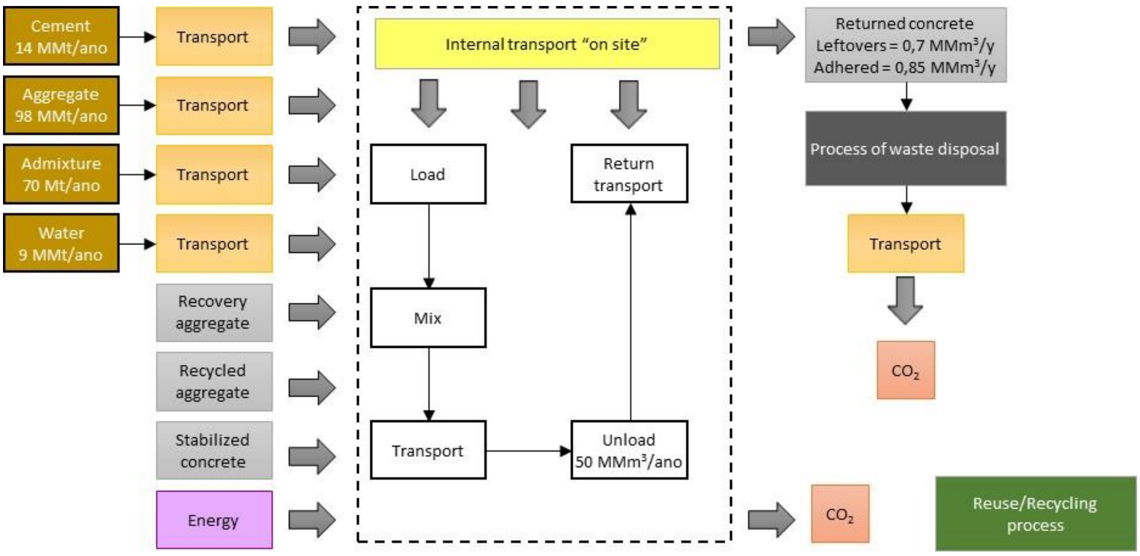
The present study considered only Brazilian cement CP II E 40, which is produced at the Santa Helena plant of Votorantim Cimentos. The cement production process includes the phases of extraction of raw materials, processing, homogenization, flour production, clinker production, cooling, milling, storage and dispatch of the concrete material; internal transportation at the plant was also factored in.

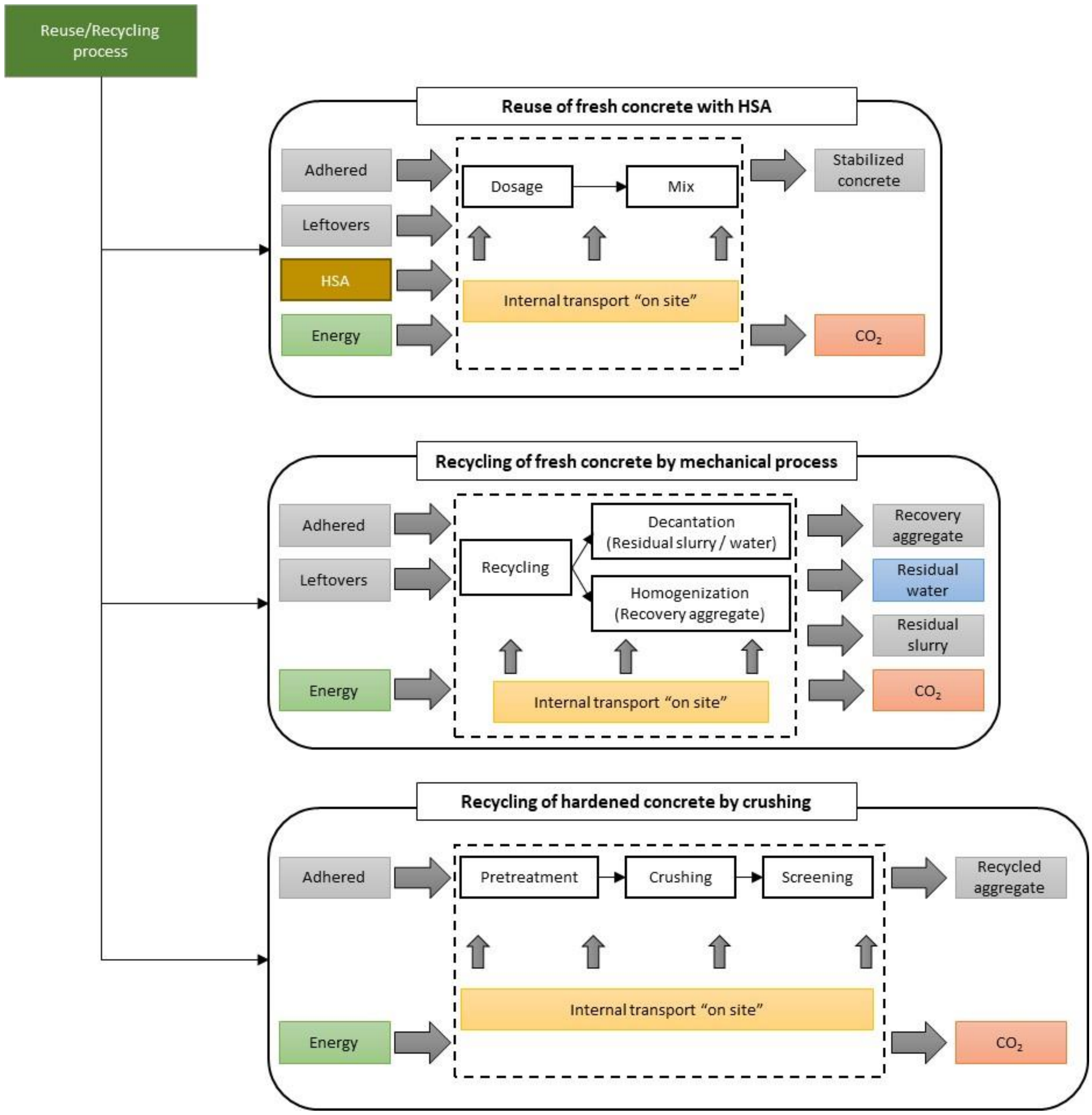
The processes of production of conventional aggregates include multiple stages: extraction of resources, processing, sieving, storage and dispatch of materials for the RMC plant, and internal transportation. Usually in the Brazilian market “natural sands” refers to the aggregates derived from sandbanks, while fine aggregates from rock crushing are known as “artificial sands”. The present study used these designations. Natural sands account for ~20% of all aggregates used by the analyzed RMC producer.

The mixing water used by RMC producers is a mixture of water from semi artesian wells, reused rainwater, and water for cleaning the mixing trucks. The present study analyzed concretes formulated using a water-reducing plasticizer admixture and an HSA, respectively classified as Type A and Type D admixtures according to ASTM C494.

The boundaries of the concrete production and waste reuse system (Figure 39) considered the mass quantity of inputs used in the production of concrete and the volumes of produced and returned concrete. In the present study, the used recycled waste was considered to be free of the CO_2 emission, with the exception of the emission attributed to the reuse process itself.

Figure 39 - Boundaries of the RMC production system





Source: The author

The production process of concrete involves weighing all raw materials, their homogenization, transporting the concrete to the job site, unloading the concrete, and returning the truck to the plant. This process also assumes that all of the movement and transportation of the materials is performed at the plant. The data used for the inventory analysis of the concrete production process were obtained by direct measurements, which were performed for the elaboration of the environmental product declaration, registered in the International EPD System: SP-00896, which indicates that the CO_2 emission factor of the concrete production at the RMC plant is 0.0065 t CO_2 / t.

The nominal capacity of operation, power and energy consumption considered for the calculation of the CO_2 emission factor related to the production of reused and recycled aggregates were obtained directly from the technical specifications of each equipment type (Liebherr - LRS 806, 2019); (Schwing-stetter – RA 12, 2019); (Metso Nordberg – C80, 2019). The CO_2 emission factor owing to the generation of electric energy was obtained from official data published by the Ministry of Science and Technology (MCT, 2018).

The CO_2 emission of concrete can be calculated by incorporating the CO_2 emission factors of all raw materials, based on the amount of raw materials. To the obtained value, one should add CO_2 emission owing to the concrete production and transport operations, as explained by Hong (2012). Table 14 lists the CO_2 emission factors associated with the production of different raw materials used in this study.

Table 14 - CO_2 emission factor for virgin raw material

Material	CO_2 emission factor (t CO_2/t)	Source
Cement	0,787	EPD - Registration number: S-P-00895
Fine aggregate - Natural sands	0,0069	Souza, 2012
Fine aggregate - Artificial sands	0,0016	Falcão et al 2013
Coarse aggregate	0,0013	Rossi, 2013
Admixture	1,8800	EPD - Registration number: EFC-20150091
Water	0,0007	SABESP 2018

Source: The author

Calculation of the transportation-related emission accounted for the average distances obtained from truck drivers, and also accounted for loading and unloading of the materials. The CO_2 emission factor was calculated according to the inventory proposed by the Brazilian Program GHG Protocol (Brasil, 2016), and accounted for the characteristics of national fuels and vehicles. The values adopted in this study for the CO_2 emission analysis were 0.174 kg CO_2/t.km for silo and tipper trucks and 0.260 kg CO_2/t.km for tanker and drum trucks.

6.3. Results and discussion

6.3.1. Efficiency analysis

The method that reuses fresh concrete with HSA can be utilized for reusing adhered concrete and leftover concrete that is returned to a plant within 4 hours of starting the cement hydration (Benini, 2005). Studies by Vieira et al. (2019) showed that, in Brazil, ~99% of concrete residues that are returned to plants satisfy this requirement. Thus, this method has the potential to reuse 89% by mass of raw materials that are returned to a typical RMC plant, which corresponds to the volume related to all ordinary concretes.

The method that recycles fresh concrete by washing and sieving can also be utilized for reusing adhered concrete and leftover concrete. Full-scale tests performed by Vieira and Figueiredo (2016) concluded that reused recovered aggregates are often used in concretes with compressive strength of up to 25 MPa. However, using slurries in new concrete mixtures is not economically viable. Therefore, in practice, this technique allows to reuse only the water and the aggregates that are contained in the adhered and leftover concrete that are returned to RMC plants; this method can account for ~88% of the mass amount of leftover concrete. Considering only ordinary concretes, this method can reuse only 36% (by mass) of the materials that are returned to a typical RMC plant.

The method that recycles concrete in the hardened state by crushing and producing crushed aggregates that are used within 48 hours from the beginning of the cement hydration as natural aggregate substitutes, increases the mechanical strength owing to a high w/c ratio, because a portion of this aggregate consists of the cement that is not fully hydrated (Rashwan and Abourisk, 1997). A study by Vieira and Figueiredo (2019) showed that this technique can be successfully used with concrete leftovers returned to RMC plants. However, reusing adhered concrete is not operationally feasible as the amount of water necessary to remove the adhered concrete from the inside of the concrete mixer drum prevents this residue from being crushed within 48 hours. Considering only ordinary concretes, it can be deduced that this method allows to reuse 41% (by mass) of the materials that are returned to a typical RMC plant.

The methods of recycling fresh concrete by washing and sieving, or the methods of recycling hardened concrete by crushing and producing recycled aggregates, are operationally suitable for reusing concrete leftovers. However, they are not suitable for reusing concrete that is adhered to the concrete truck drum. The reuse method of fresh concrete with HSA allows both the reuse of adhered and leftover concrete. However, there is one important limitation, in this particular case - it is only possible to reuse concrete with cement for which hydration had been started at most 4 hours before. On the other hand, this method does not generate slurries, which is a significant advantage for RMC plants, implying the plants do not have to deal with this secondary waste.

Individually, none of the analyzed methods can completely eliminate the residues generated during the RMC plant operation (Table 15). One main limitation is the fact that there are operational difficulties associated with reusing certain concretes that are considered as "specials" (e.g., concretes with fibers, concretes with pigments). Therefore, the analysis of the waste reduction capacity was performed considering only the regular concrete volume. In addition, the calculation of the waste reduction ability assumed that 45% of the waste is leftover concrete and 55% is adhered concrete.

Table 15 - Waste reduction capacity of each evaluated method in terms of regular concretes produced at an RMC plant

Method	Ability to waste reduction				
	Nominal		Real		
	Leftover	Adhered	Leftover	Adhered	Total
Reuse of fresh concrete with HSA	99%	99%	89%	89%	89%
Recycling of fresh concrete by mechanical process	88%	0%	79%	0%	36%
Recycling of hardened concrete by crushing	100%	0%	90%	0%	41%

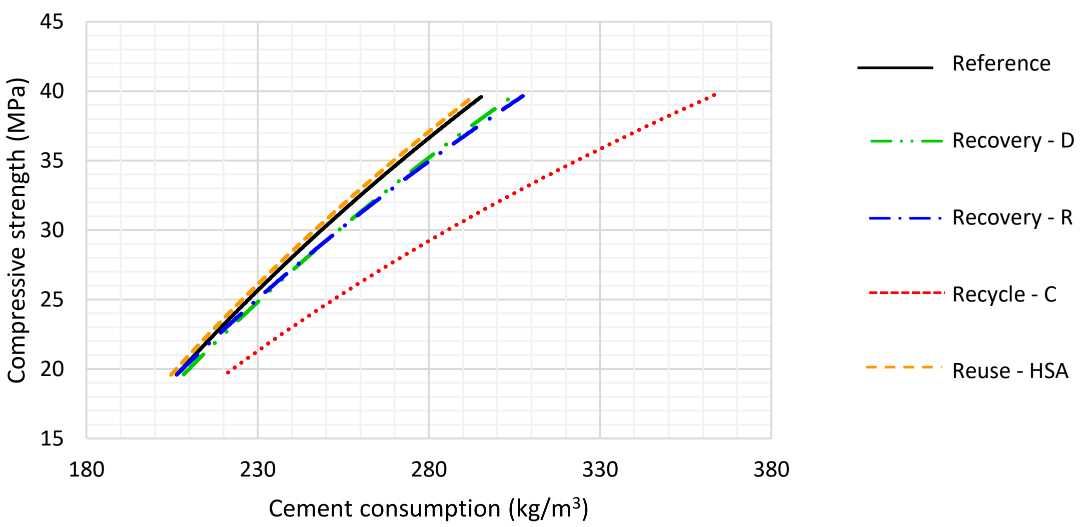
Source: The author

From the operational point of view (process implementation) it is important to keep in mind that, in the case of the method that reuses fresh concrete through HSA, concrete truck drivers need to be very well trained in reuse procedures. In addition, there is always a risk of concrete hardening inside the mixing drum. The processes that recycle fresh concrete by mechanical processing and recycle hardened concrete by crushing are simpler to implement, because there is no need to train the concrete truck drivers, and there is no risk of concrete hardening in the trucks' mixing drums because concrete recycling is not accomplished in the concrete trucks' drums.

6.3.2. CO_2 analysis

Figure 40 shows the dosage curves for concretes produced using conventional components that are normally used by RMC producers, and for other concretes considered in this study, based on the previous studies by the authors: Reuse - HSA (Vieira and Figueiredo, 2019); Recovery - D and Recovery - R (Vieira and Figueiredo, 2019); Recycle - C (Vieira et al., 2019).

Figure 40 - Concrete mixing design curves



Source: The author

The method that reuses fresh concrete with HSA does not require investing into the equipment acquisition, and the electricity and water consumption of the plant are not affected. The other methods analyzed in the present study require equipment-related investments; in addition, using such specialized equipment increases the power and water consumption of the plant.

The measurements performed by the RMC producer with respect to the equipment installed in the plant, based on the equipment producer information, show that:

- The spiral recycler (drum) has the capacity of 12 m^3/ h, power of 24.5 kw, and energy consumption of 1.13 kwh/t.
- The rotary-type equipment has the capacity of 15 m^3/ h, power of 20.7 kw, and energy consumption of 0.77 kwh/t.
- The jaw crusher used in the production of recycled aggregate has the capacity of 25 m^3/ h, power of 75 kw, and energy consumption of 1.20 kwh/t.
- The HSA is transported in a 12-ton-capacity tank truck from Sorocaba/SP to São Paulo/SP (74 km from the producer to the concrete plant).

Capacity, power, and energy consumption data allow to calculate the CO_2 emission factors for each type of raw material produced using the different reuse techniques; these factors are listed in Table 16.

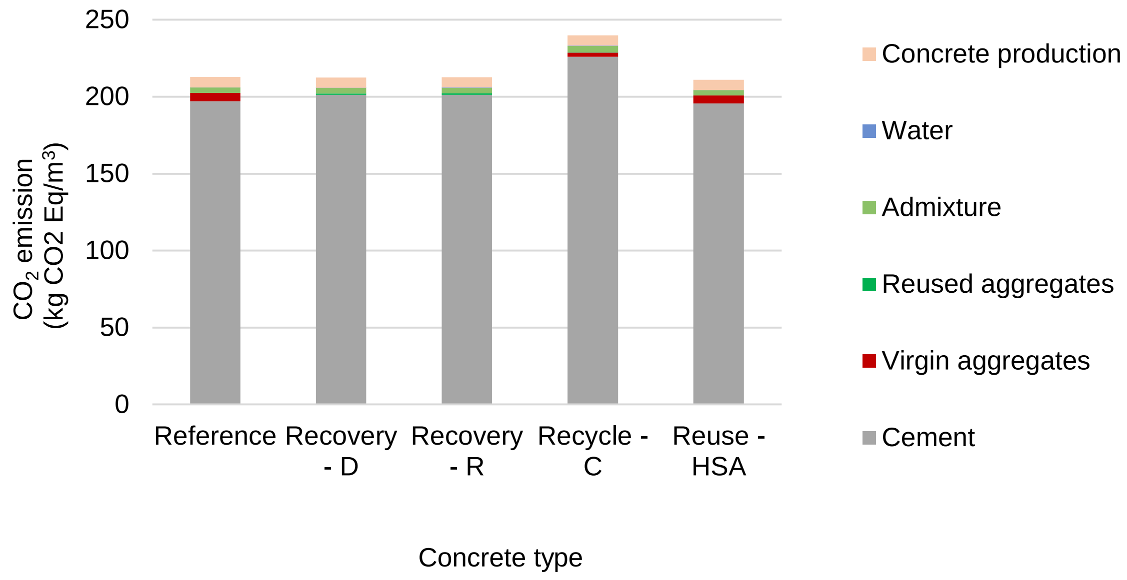
Table 16 - CO_2 emission factors for reused raw materials

Material	CO_2 emission factor (t CO_2/t)
Reuse – HSA concrete	0,0003
Recycle aggregate (C)	0,0004
Recovery aggregate (D)	0,0005
Recovery aggregate (R)	0,0005

Source: The author

CO_2 emission analysis (Figure 41) shows that the type of cement explains more than 90% of CO_2 emission. Concrete production is the second most important influencer of the CO_2 emission factor, explaining 3%, mostly owing to the impact of concrete transportation between the plant and work sites. In turn, the aggregate type and the admixture type explain only ~2% and ~1.5%, respectively. Considering the overall CO_2 emission, the emission associated with the Reuse - HSA case is 1% lower than the emission associated with the reference concrete case, and is nearly the same as the emission associated with the concrete produced using recovered aggregates (Recovery - D and Recovery - R). The emission associated with the concrete produced from recycled aggregates obtained from crushed hardened concrete (Recycling - C) is 13% higher than the reference case.

Figure 41 – CO_2 emission levels for compressive strength class c 30 concrete



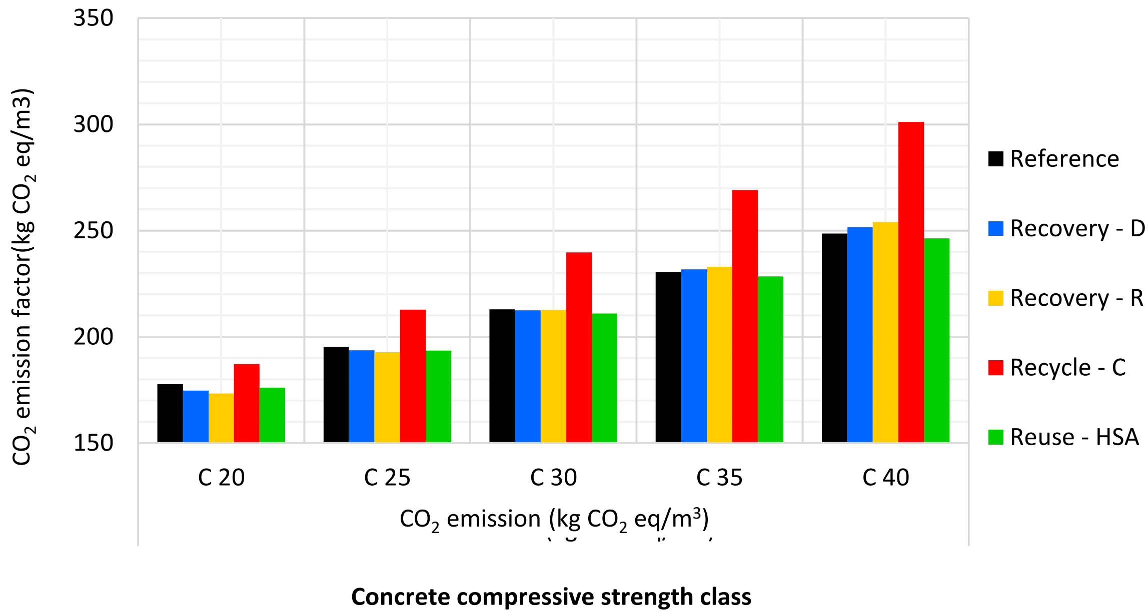
Source: The author

Within the constraints of the system and the methods used in this study, it was possible to estimate CO_2 emission factors associated with the production of one cubic meter of concrete slump 100 mm, as shown in Figure 42. The CO_2 emission factor increases with increasing the compressive strength, confirming the conclusions of Flower and Sanjayan (2007) and Oliveira et al. (2016).

The CO_2 emission factor for concretes prepared using recycled aggregates (Recycling - C) is higher than that of all other concretes, for all considered compressive strengths. On the other hand, the smallest emission factor was obtained for the concretes prepared using stabilized concretes (Reuse - HSA), for all considered compressive strengths. The concretes prepared using recovered aggregates (Recovery - D and Recovery-R) lower weaker CO_2 emission than the reference concrete when the concrete compressive strength was below C30; the effect was the opposite for the concrete compressive strengths above C30.

This increase in emission is attributed to the requirement that the complementary cement used in concrete to mitigate the loss of strength caused by the use of waste. In the case of concrete with compressive strength under 30 MPa, the lower CO_2 emission resulting from the replacement of "virgin" aggregates with recovered aggregates is sufficient to compensate the CO_2 emission owing to the increase in the cement amount. Note that the higher the concrete compressive strength, the higher is its load capacity. Therefore, higher load capacities require smaller amounts of concrete, as pointed out by Habert et al. (2012).

Figure 42 - CO_2 emission of 1 m^3 of concrete with 100 mm slump, for different concrete types

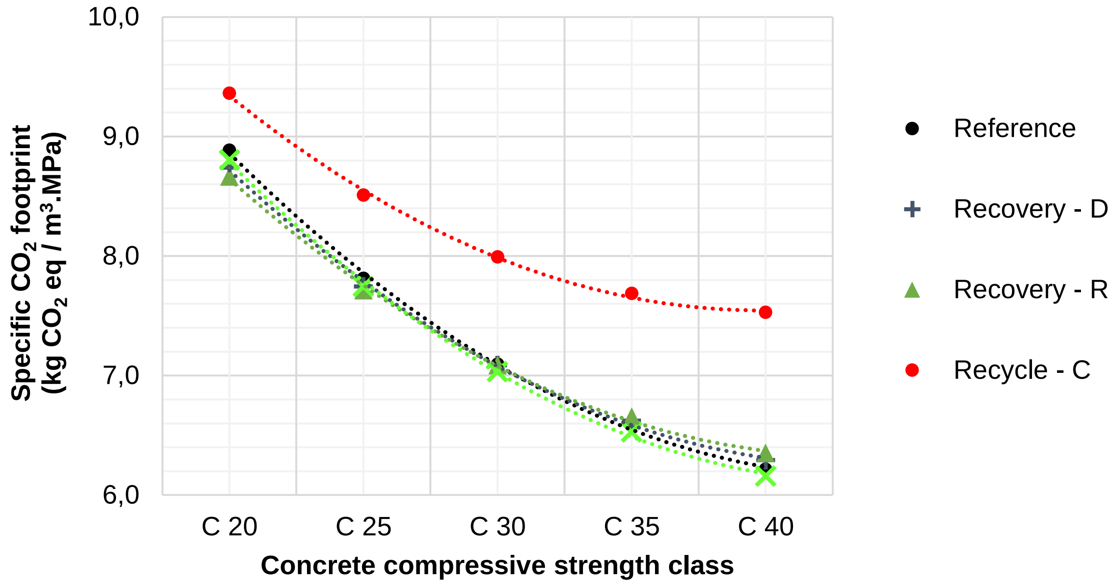


Source: The author

From the observed results (Figure 43), it is possible to state that the waste reuse strategy that uses HSA (Reuse - HSA) is more efficient with respect to the specific CO_2 footprint than the approach that uses virgin raw materials (Reference concrete), regardless of the concrete compressive strength.

In the case of concretes with compressive strength C20, the method that recycles fresh concrete by mechanical processing (Recovery - D and Recovery-R) yielded the highest overall efficiency in terms of the specific CO_2 footprint. For C25 compressive strength concretes, recycling of fresh concrete by mechanical processing and reusing fresh concrete with HSA yielded the same specific CO_2 footprint. For the concrete compressive strength C30, the reference concrete had the same specific CO_2 footprint as that obtained by recycling fresh concrete using mechanical processing. This reflected the need to add an incremental amount of cement to compensate the strength loss of recycled concrete. Therefore, there is a critical compressive strength (C35), above which replacing recovered aggregates with virgin aggregates increases the specific CO_2 footprint.

Figure 43 – Specific CO_2 emission of 1 m^3 of concrete with 100 mm slump, vs. concrete compressive strength



Source: The author

6.4. Conclusions

Despite being within the world average, the RMC industrial sector in Brazil generates a significant amount of waste. This creates significant problems and incurs a high cost on the transportation and proper disposal of this waste.

The method that reuses fresh concrete with HSA is capable of reusing leftovers and adhered concrete. Using this method allows to eliminate 89% of the concrete that returns to RMC factories; however, its implementation requires training concrete truck drivers, and there is a risk of concrete hardening inside the mixer drum. Operationally, the other methods analyzed are simpler to implement in RMC plants; however, these other methods require investments for the specialized equipment acquisition, as well as an area for the equipment installation; this can be an impediment, especially for plants in large urban centers, where little area is available. The crushing recycling method has a 5% higher waste reuse capacity than the fresh concrete recycling method that uses mechanical processing. This is because, in practice, scale tests performed by Vieira and Figueiredo (2016) show that slurry recycling is not feasible.

Approximately 90% of the CO_2 emission associated with concrete comes from cement. Consequently, the recycling methods that require the addition of incremental cement exhibited, in general, higher CO_2 emission rates and higher specific CO_2 footprints. The concrete produced using the method that reused fresh concrete with HSA yielded a lower CO_2 emission factor than the reference concrete. This was attributed to the fact that it was not necessary to add extra cement during the process, as well as to the small amount of HSA used.

The CO_2 specific footprint analysis clearly identified that concretes with compressive strength above 30 MPa are likely to generate higher total CO_2 emission when concrete is produced with aggregates recovered by recycling fresh concrete. Consequently, the increase in the CO_2 emissions owing to the need for additional cement to compensate the loss of strength of recycled concrete has a greater influence on the specific CO_2 footprint than the volume of virgin aggregates replaced by recovered aggregates.

Recycling of fresh concrete by mechanical processing is the best solution for mitigating the CO_2 emission for concretes with compressive strength below C25. For higher compressive strength, using hydration-stabilizing admixtures is the best solution for reusing the concrete waste by RMC plants. This latter method is also the best option for reducing the waste generation in general, as it allows to reuse almost all of the generated waste (adhered concrete and leftovers), with the exception of concrete returned with cement that started its setting over a period of more than 4 hours.

The method that recycles concrete in the hardened state by crushing and producing crushed aggregates offers an intermediate waste reduction strategy, between those of the method for recycling fresh concrete using mechanical processing and the method that reuses fresh concrete with HSA. However, in terms of the CO_2 footprint reduction, this method exhibits the worst performance among the evaluated methods as well as the reference concrete.

7. FINAL CONCLUSIONS

This thesis analyzed the main existing methods of reuse in real scale tests and was able to conclude that the reuse of fresh concrete with HSA technique is more effective than the others in terms of the reuse capacity of the waste generated in the production of RMC and the CO_2 emission. It was also possible to conclude that the recycling of fresh concrete by mechanical process technique and the recycling of hardened concrete by crushing technique increase the specific CO_2 footprint in new concretes when the desiered compressive strength class is higher than C30. This is a limiting factor to the implementation of these techniques in terms of sustainability. Based on the results obtained in this thesis was possible to conclude that the evaluation method used in this thesis, based on previous laboratory studies followed by full scale implementation studies for the global assessment of technologies, may be employed for other possible recycling techniques that may arise. Thus, the local specificities of the region where the RMC is installed as well as the momentary conditions associated with this analysis may be adequately taken into account. However, the parameterization obtained in the study focusing waste generation production, performed on a national scale, can be used as a starting element in the previous analyzes for future studies.

The HSA reuse method has the greatest waste reduction capacity generated in the concrete production by RMC plants, as it allows the reuse of almost all waste generated by the RMC plant, except for concrete with cement that started its setting in a period greater than four hours. The method of recycling by mechanical process has the lowest capacity, because the reuse of slurry generated in its process is not economically viable.

In terms of concrete compressive strength CO_2 emissions the HSA reuse method has a lower CO_2 emission than concretes produced with the usual materials used by the RMC plant. The mechanical and crushing recycling methods have practically the same CO_2 emission, which is less than the CO_2 emission of concretes produced with usual materials used by the RMC plant in concrete with compressive strength is less than 30 MPa.

The HSA fresh concrete reuse method is the cheapest alternative to be deployed in RMC plants, as this technique requires no investment in equipment procurement and does not affect the electricity and water consumption of the RMC plant. However, as there is a risk of hardening the concrete inside the mixer drum, it is necessary to train the mixer conductors in the concrete reuse procedures with this type of mix.

The mechanical process fresh concrete recycling method has the advantage that it does not require training of concrete mixer drivers and the fact that a single person can operate the recycler. However, this method does not allow reuse of cement at subsequent loads, increases the plant's electricity and water consumption and requires investment in equipment procurement. In addition, the implementation of recycling equipment requires the plant to have area availability, which is not always the case, especially in plants located in large urban centers.

The crushing hardened concrete recycling method has characteristics similar to the mechanical fresh recycling method, with the advantage of not increasing the plant water consumption, since the crushing process used by this technique does not require water. However, the crusher installation area and concrete discharge site are larger, which can make this option difficult to be installed in plants with low area availability and large concrete production.

It is important to keep in mind that neither method alone can totally eliminate the waste generated in the production of ready mix concrete. The reuse method of fresh concrete with HSA does not allow the reuse of concrete with cement that started hydration for more than four hours. The method of recycling fresh concrete by mechanical process generates significant amounts of slurry and since slurry is a difficult material to be reused, this makes the use of this method in the use of bonded concrete impossible. The crushing hardened concrete recycling method is also not useful for the reuse of adhered concrete as its removal from the interior of the concrete mixer drum will require large amounts of water and will prevent crushing and reuse within less than 48 hours. Therefore, an RMC plant that wants to completely eliminate waste generated will need to implement at least two of these methods.

The research conducted on the reasons that generate waste during the RMC production activities, show that approximately 3% of the volume produced ends up returning to the RMC plant. About 55% of this volume is due to adhered concrete and 45% due to leftovers. This knowledge can guide specific actions to reduce waste generation by the RMC producer. Therefore, given that adhered concrete is an inherent condition for RMC production, it is virtually impossible to eliminate the return of concrete loads. Therefore, the RMC plants should have of a routine recycling process, which should be as simple as possible to reduce the amount of concrete waste that is sent to landfills and the costs associated with this operation.

The applicability of reclaimed aggregates and reclaimed water for concrete production, has been proven. The results showed that it is possible to reuse reclaimed aggregates for concretes with compressive strength demands of less than 25 MPa, although this concrete is more difficult to pump than concrete produced with usual aggregates. It was also demonstrated the viability of the potential use of recovered water for any characteristic strength class of the concrete and the non-viability of reusing the slurry without further treatment.

The analysis of the crushing hardened concrete recycling method proved to be feasible. However, negative impacts on workability and increased standard deviation of compressive strength of RA concrete in relation to NA concrete were noted. Nevertheless, the RA used within 48 hours of its production has a good potential of use, since the material provides a reduction in the extra cement consumption, which, in the case studied, resulted in financial gains in concrete of compression strength class up to 30 MPa.

The reuse of fresh concrete using hydration stabilizing admixtures method is feasibility. The use of HSA does not negatively affect the compressive strength of concrete and that the method can be used to reuse adhered concrete and concrete leftovers. The financial analysis showed that there is a more relevant financial gain from the reuse of leftovers concrete than from the reuse of adhered concrete. This was due to the higher proportion of HSA by cement weight, used in the recycling of adhered concrete than in the leftovers concrete.

The concrete reuse method with HSA has clear advantages over the other methods analyzed from the environmental and financial point of view, which makes this technological strategy very attractive for the implementation in RMC plants. However, the risk of hardening of the concrete inside the mixer truck drum could not be ignored and, together with this, the necessity of training activities for the mixer truck conductors in order to guarantee the adequacy of concrete reuse procedures with this type of technique.

7.1. Final Comments

Despite being within the world average, due to the scale issue, the volume of wasted concrete by RMC plants in Brazil is significant, it is possible to estimate that the volume of waste generated annually is over one million cubic meters, which amounts to about 300 million CO_2 Eq are no longer emitted into the atmosphere. This value indicates that the implementation of methodologies for waste reuse by producer RMC cannot be neglected as the increased demand for materials and waste generation generate environmental and financial impacts.

The industrial scale study proved to be of great value for the accurate evaluation of waste reuse methods in RMC. This type of unprecedented approach allows a more accurate assessment of the technical, economic and environmental feasibility of alternatives for recycling these wastes.

Moreover, field tests performed to analyze the applicability of the various methods of waste reuse confirm the reliability of the laboratory results for the visualization of the results of the real conditions of concrete production in the RMC plants. In this way, laboratory tests can be used to define with great precision the impact of materials generated by each reused method (reclaimed aggregate, reclaimed water, slurry, recycled aggregate and stabilizer concrete) as raw materials in new concrete.

This research was able to detail the reasons that resulted in the return of concrete loads (total and partial) that should have been delivered to the job sites. This allows the discussion of mitigation strategies to enable better decision-making conditions for the RMC producers. It is also important to mention that the research analyzed the financial impact of the solutions. Thus, the cost of the concrete produced with each of the different reused raw materials was compared to the cost of the reference concrete.

Academic studies are rarely performed on a full scale, in part this is certainly related to the cost and operational difficulties of performing the amount of testing that is needed to reach conclusions that can be used to create procedures that are added to the routine of the companies. The tests carried out in chapters 2 to 6 involve the participation of many people and hundreds of measurements and determine the real viability of implementing reuse processes from the operational and economic point of view of the business. In addition, this type of study was able to integrate the knowledge developed in the academy with the real needs of the Brazilian RMC companies. Because of these initiatives, a cooperative environment has been created where technology transfer increases the competitiveness of companies and the acquisition of knowledge by academia.

7.2. Suggestions for future research

Development and evaluation of methods for the reuse of waste from special concretes such as fiber reinforced concrete and pigmented concrete.

Development of alternatives to make the use of slurry feasible under real RMC operating conditions.

Creation of alternative methods for waste reuse in order to increase the number of options available to RMC plants.

Development of models able to simulate the implementation and operation process of innovative recycling systems in concrete plants.

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