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ORIGINAL ARTICLE

Analysis of CO_2 emissions and waste elimination capacity of different recycling strategies applied in ready-mixed concrete plants

Análise das emissões de CO_2 e capacidade de eliminação de resíduos de diferentes estratégias de reciclagem aplicadas em centrais dosadoras de concreto

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Abstract: The volume of waste generated by ready-mix concrete (RMC) plants in Brazil is significant. According to Oliveira et al. [1] waste from construction and demolition in Brazil was approximately 45-79 million tons and most of those waste is sent to landfills (79%). This study presents an assessment of the RMC plant waste reduction capacity using 3 different methods: (a) reuse of concrete in the fresh state by using hydration-stabilizing admixtures (HSA); (b) recycling of concrete aggregates by separating the aggregates from the cement paste before the concrete hardens; (c) recycling of hardened concrete as aggregates through the crushing process. Results indicated that concretes with compressive strengths up to 25.0 MPa are more effective in reducing CO_2 emission and consequently CO_2 footprint when using method (b); if evaluating higher resistance classes, method (a) was the most effective.

Keywords: ready mix concrete waste, CO_2 footprint, field test, recycled aggregate, hydration stabilizing admixtures.

Resumo: O volume de resíduos gerados pelas centrais dosadoras de concreto (CDC) no Brasil é expressivo, de acordo com Oliveira et al [1] o resíduo de construção e demolição no Brasil foi de aproximadamente 45-79 milhões de tons e grande parte desse resíduo é enviada para aterros sanitários (79%). Este estudo avalia a capacidade de redução de resíduos da CDC usando 3 diferentes métodos: (a) reaproveitamento do concreto no estado fresco por meio de aditivos estabilizadores de hidratação (AEH); (b) reciclagem dos agregados de concreto separando os agregados da pasta de cimento antes que endureça; (c) reciclagem de concreto endurecido como agregados através do processo de britagem. Resultados apontam que concretos de resistências até 25,0 MPa, são mais efetivos na redução de CO_2 e pegada de carbono quando utilizado o método (b), se avaliada classes de resistências maiores, o método (a) foi o mais efetivo.

Palavras-chave: resíduos de concreto usinado, pegada de carbono, teste de campo, agregado reciclado, aditivos estabilizadores de hidratação.

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1 INTRODUCTION

Cement-based materials represent about 1/3 of the global material consumption [1] and 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 [2]. According to ERMCO [3], 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, consequently, a high mitigation potential.

The average values of raw material consumption in the production of RMCs reported in the survey by Lima [4] indicate that the annual volume of concrete produced by RMC plants in Brazil is around 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 admixture, are used annually. Much attention has been given recently to the dosage optimization for reducing the carbon footprint [5] because most of the CO_2 emissions associated with concrete are due to the cement production process and is related to the clinkerization process. To produce 1 ton of clinker around the same quantity of CO_2 is also produced [6]. However, relatively little attention was paid to the aspects related to the resource use efficiency, such as the generation and reuse of concrete waste by RMC plants.

Evaluating the impact of the concrete industry, Vieira et al. [7] estimated that approximately 3% of all concrete produced in RMC plants returns as waste. If we consider the 50 million m^3 as a Brazilian production, this represents 1.5 million m^3 of waste.

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 [8], 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.

Based on Xuan et al. [9], there are three main methods for diverting waste 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 waste 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. [10] 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. [11] concluded that the reuse of HSA-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 [12] but yields a slurry as a secondary waste. Scale tests using two different types of recyclers, carried out by Vieira and Figueiredo [13], 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 reuse of the slurry has an intrinsic difficulty associated with the need to adjust the rheology of new concrete that incorporates this waste [14]. The produced slurry can be treated using decantation systems, recovering most of the water and reducing the amount of disposable waste [15]. The other route consists of submitting the slurry to a filter-press system [16]. Therefore, this approach in general incurs an extra work to eliminate the entire waste 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 waste into new formulations [17]. Fines generated during the crushing process are usually transformed into new waste, reducing the recovering rate to ~30–50% [18]. Because higher-porosity recycled aggregates yield lower-strength concretes than regular aggregates, higher cement content may be required to compensate for this loss [19], [20]. 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 [21].

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 [22], China [23], and Turkey [24]. 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.

As stated by Damineli *et al.* [25], 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 indicators of the three main methods of concrete waste reuse, in terms of 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.

2 MATERIALS AND EXPERIMENTAL PROGRAM

This study consists of two parts. In the first one, 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, these strategies are evaluated in terms of their generated CO_2 emission. The first part of the study was performed using previously published data for individual strategies: 1) reuse of fresh concrete waste with stabilizer admixtures [26], 2) recycling of hardened concrete by crushing [27] and 3) recycling of fresh concrete by mechanical processing through washing and sieving [13]. 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). 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, it was limited to ordinary concrete only that means to those cases where ordinary raw materials are used, which corresponds to approximately 90% of concrete produced by RMC plants [13]–[27]. This is because normal concretes are more easily reusable than special concretes, such as those containing fibers, pigments, or any other addition. It 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 et al. [28], 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 [29]. Vieira et al. [7] 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 considered 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 ~3.0% of the volume of concrete produced, which corresponds to 53% of the waste (1.6% of the volume produced) owing to adhered concrete and 47% of the waste (1.4% of the volume produced) owing to leftovers [7]. Taking to account the volume of concrete produced by the RMC plants in Brazil described by Lima [4], it is estimated that nearly 420 thousand tons of cement, 2,940 thousand tons of aggregates, and 270 thousand tons of water are returned to the Brazilian RMC plants each year.

The CO_2 emission of concretes produced exclusively using raw materials and those produced using inputs from waste reuse/recycling techniques was compared for concretes in different compressive strength categories (C20, C30, C30, C35, and C40). To enable this comparison, all concretes were mix-designed according to the method traditionally used by RMC producers [30]. 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 [13], [26], [27].

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 impacts to transport 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 freight 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 the CO_2 emission generated in the entire production process of concrete.

The cement considered was CP II E 40, which was produced by Votorantim Cimentos at the Santa Helena factory. 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 cement, 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”. Natural sands account for ~20% of all aggregates used by the analyzed RMC producer.

The water used by RMC producers was a mixture of water from semi artesian wells, reused rainwater, and water for cleaning the mixing trucks. Concretes formulated with water-reducing plasticizer additive and HSA were analyzed, respectively classified as Type A and Type D additives according to ASTM C494.

The boundaries of the concrete production and waste reuse system (Figure 1) considered the inputs used to produce concrete in mass quantity and in volume the returned concrete. The recycled waste was considered free of the CO_2 emission, except for the emission attributed to the reuse process itself. The concrete specific weight used was 2.461 ton/m^3 (the reference concrete was C30, slump class S100), but it can change according to the compressive strength adopted.

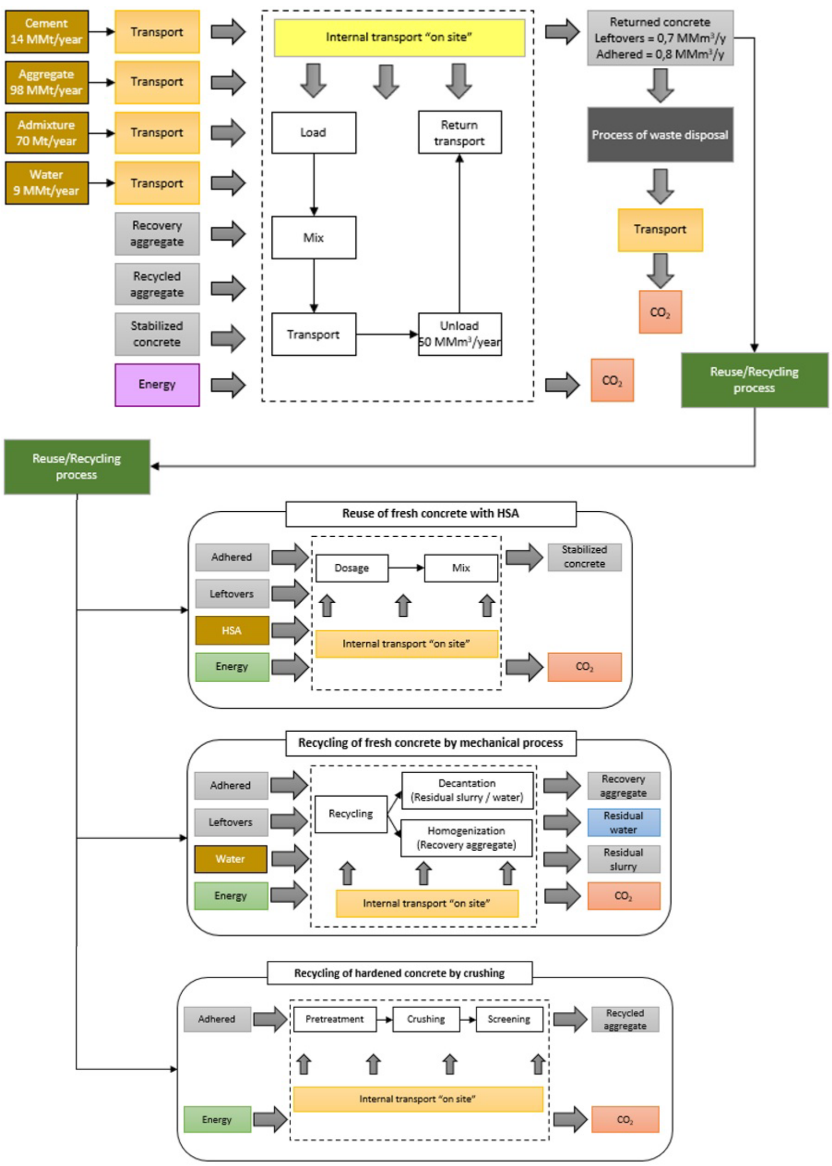

Figure 1. Boundaries of the RMC production system.

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 et al. [31]. Table 1 lists the CO_2 emission factors associated with the production of different raw materials used in this study.

Table 1. CO_2 emission factors for virgin raw materials.

Material	CO_2 emission factor (t CO_2/t)	Source
Cement	0.789*	[32]
Fine aggregate - Natural sands	0.0069	[33]
Fine aggregate - Artificial sands	0.0046	[34]
Coarse aggregate	0.0013	[35]
Admixture	-0.000855**	[36]
Water	0.0002***	[37]

* Considering that all CO_2 emitted comes from the calcination of limestone and there isn´t other source of CO_2 in the process. ** Admixture contribution is negligible and won´t be considered. The quantity of admixture in 1 m^3 is related of the quantity of cement and a ordinary C30 class concrete uses around 2,5 liters of admixture. Then the contribution in a $1m^3$ of concrete is approximately -0.000855 t CO_2. *** Water contribution is also negligible and won´t be considered.

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 RMC plant. This process also assumes that all the movement and transportation of the materials is performed at the plant, which indicates that the CO_2 emission factor of the concrete production, measured at RMC plant, is 0.0065 t CO_2 / t. 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 [38]. The numbers showed at LCA describe all the environment impacts related to the process and was showed in $CO_{2\,eq.}$

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 [39]–[41]. 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) [42].

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 [43] and Carvalho [44] accounted for the characteristics of national fuels and vehicles. The values adopted in this study for the CO_2 emission analysis were 0.00242 kg CO_2/t.km for silo and tipper trucks and 0.00584 kg CO_2/t.km for tanker and drum trucks.

3 RESULTS AND DISCUSSIONS

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 [45]. Studies by Vieira and Figueiredo [26] showed that, in Brazil, ~99% of concrete waste that 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 less special concretes [13]–[26].

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 [13] concluded that reused recovered aggregates are often used in concretes with compressive strength up to 25 MPa. However, the same tests showed that using slurries in new concrete mixtures is not economically viable, because the negatives effects in compressive strength and workability [13]. Therefore, in practice, this technique allows to reuse only the water and the aggregates that are contained in the leftover concrete that are returned to RMC plants; this method can account for ~88% of the mass amount of leftover concrete (considering the 99% less the 11%, in average, of cement [7]). Considering only ordinary concretes, this method can reuse only 36% (leftover waste represent 45% by mass [7]) 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 [46].

A study by Vieira et al. [27] 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 waste from being crushed within 48 hours. Considering that, in paper [27], the concrete reuse technique through the production of recycled aggregates was not used to eliminate adhered concrete waste, which correspond to approximately 55% of the total volume of concrete returned to Brazilian RMC plants, it is possible to deduce that this method allows the reuse about 41% (leftover waste represent 45% by mass [7]) of the total concrete waste that is currently generated by RMC producers [13].

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 [13]–[27]. 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 [26]. However, there is one important limitation, in this 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 eliminate the waste generated during the RMC plant operation (Table 2). 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 2. Waste reduction capacity of each evaluated method in terms of regular concretes produced at an RMC plant.

Method	Ability to waste reduction					Source
	Nominal		Real			
	Leftover	Adhered	Leftover	Adhered	Total	
Reuse of fresh concrete with HAS	99%	99%	89%	89%	89%	[13]–[26]
Recycling of fresh concrete by mechanical process	88%	0%	79%	0%	36%	[7]–[13]
Recycling of hardened concrete by crushing	100%	0%	90%	0%	41%	[13]–[27]

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.

3.2 CO_2 Emission Analysis

Figure 2 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 [26]; Recovery - D and Recovery - R [13]; Recycle - C [27].

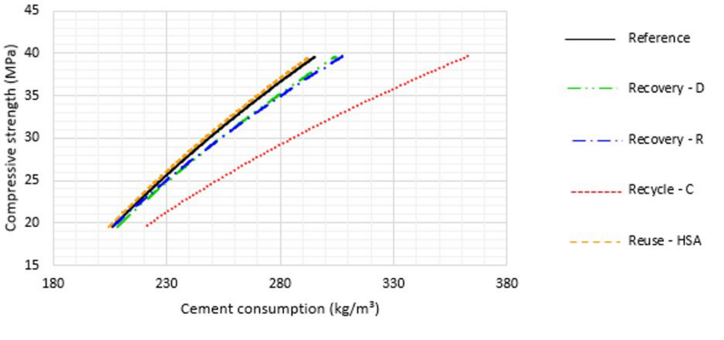

Figure 2. Concrete mixing design curves.

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 this 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, were based on the equipment producer information [39]–[41] and calculated using the concrete specific weight as 2.461 ton/m^3 (the reference concrete was C30, slump class S100) [7].

- The spiral recycler (Liebherr LRS 806) has the capacity of 12 m^3/ h, power of 11.0 kw, and energy consumption of 0.36 kwh/t.
- The rotary-type equipment (Schwing-Stetter RA 12) has the capacity of 12 m^3/ h, power considered of 22.5 kw, and energy consumption of 0.76 kwh/t.
- The jaw crusher (Nordberg® C80) used in the production of recycled aggregate has the capacity of 25 m^3/ h, power of 75 kw, and energy consumption of 1.22 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 3.

Table 3. CO_2 emission factors for reused raw materials.

Material	CO_2 emission factor (t CO_2/t)
Reuse – HSA concrete	3x10^{-4}
Recycle aggregate (C)	4x10^{-4}
Recovery aggregate (D)	5x10^{-4}
Recovery aggregate (R)	5x10^{-4}

CO_2 emission analysis (Figure 3) 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 for compressive strength C30 class concrete, 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). That is possible, because the consumption of cement, the most responsible for CO_2 emission, is almost the same in those tests (Reference, Recovery-D, Recovery-R and Reuse-HSA). The emission associated with the concrete produced from recycled aggregates obtained from crushed hardened concrete (Recycling - C) is 13% higher than the reference case.

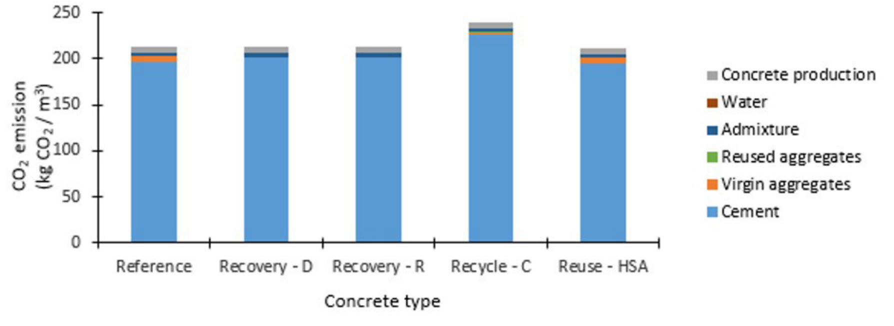

Figure 3. CO_2 emission levels for compressive strength class C30 concretes.

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 4. The CO_2 emission factor increases with increasing the compressive strength, confirming the conclusions of Flower and Sanjayan [47] and Oliveira et al. [48].

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 that is used in concrete will 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. [49].

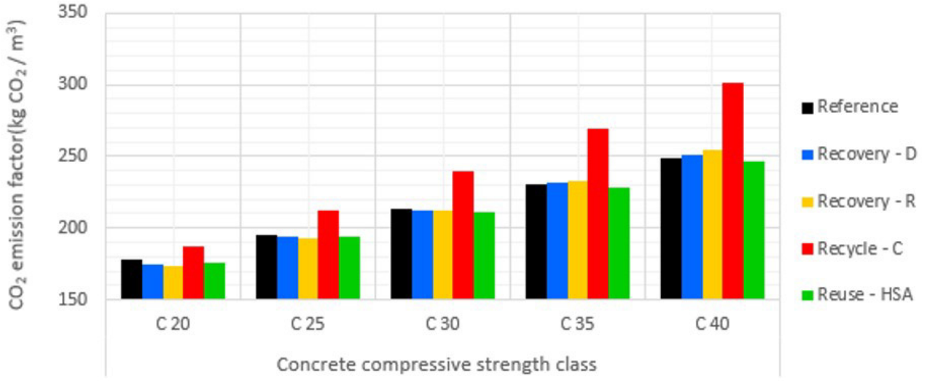

Figure 4. CO_2 emission of 1 m^3 of concrete with 100 mm slump, for different concrete types.

From the observed results (Figure 5), it is possible to state that the waste reuse strategy that uses HSA (Reuse - HSA) is more efficient with respect to the CO_2 emission 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 CO_2 emission. For C25 compressive strength concretes, recycling of fresh concrete by mechanical processing and reusing fresh concrete with HSA yielded the same CO_2 emission. For the concrete compressive strength C30, the reference concrete had the same CO_2 emission 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 CO_2 footprint.

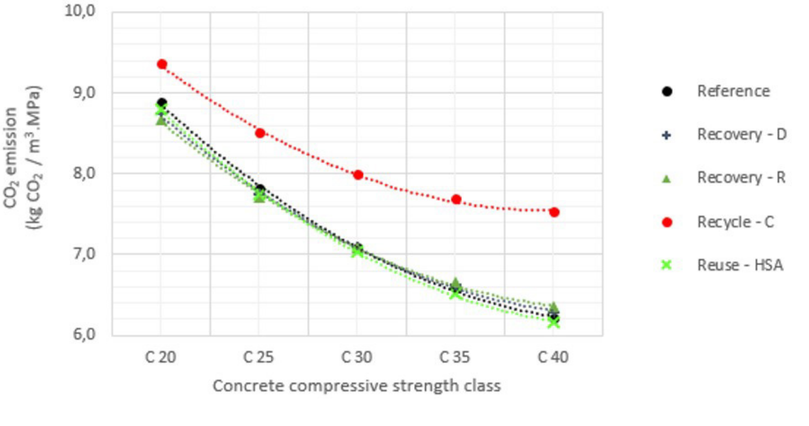

Figure 5. CO_2 emission per MPa of 1 m^3 of concrete with 100 mm slump, vs. concrete compressive strength.

4 CONCLUSIONS

Despite being within the world average, the RMC industrial sector in Brazil generates a significant amount of waste, approximately 45-79 million tons and most of this waste is sent to landfills (79%) [6]. Vieira et al. [7] also mentioned that approximately 3% of all concrete produced in a RMC plant is returned as waste, representing something around 1,5 million m^3 per year [4]. This creates significant problems and incurs a high cost on the transportation and proper disposal of this waste.

When the problem is evaluated globally, the RMC industry produces 14 billion m^3 of concrete [50] and keeping the same percentage of 3% as a reference, the volume of waste generated would be approximated 420 million m^3, which highlights the high potential for greater investments in the management of construction waste to reduce CO_2.

The method that reuses fresh concrete with HSA is capable of reusing leftover 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 [13] 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 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 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 reaction 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.

Another line of research is the reduction of the cement clinker factor through the addition of reactive or non-reactive materials. In Brazil, several materials are added: blast furnace slag, pozzolan, carbonate material, etc. Oliveira et al. [6] studied the addition of the fine fraction of concrete waste as an addition to cement replacing part of clinker. This would reduce not only construction waste but also the cement clinker factor.

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