LCA of waste PET particles as a partial replacement for sand in self-compacting concrete

Robson Zulcão Mello

Federal University of Espírito Santo, Technology Centre, Department of Civil Engineering, Vitória (ES), Brazil

robsonzulcao@gmail.com

Felipe Zanellato Coelho

Federal University of Espírito Santo, Technology Centre, Department of Civil Engineering, Vitória (ES), Brazil

fcz_0019@outlook.com

João Luiz Calmon

Federal University of Espírito Santo, Technology Centre, Department of Civil Engineering-FAPES, Vitória (ES), Brazil

joao.gama@ufes.br

ABSTRACT: The waste Polyethylene Terephthalate (PET) particles combined with pozzolanic materials can be used in the production of concretes with the goal of diminish the quantity of waste in landfills and reduce the depletion of natural resources. However, little has been researched about the environmental viability of the use of wastes in the production of concrete, and no assessment regarding the use of waste PET as fine aggregate in self-compacting concretes (SCC) has been done in the literature. Thus, this paper reports a comparative life-cycle assessment (LCA) of seven SCC mixtures, aiming to verify its environmental load in a case study in a region in Brazil. The weight replacement ratio of natural fine aggregates by waste PET aggregates was 5, 10 and 15 weight percent (wt.%). For each of these replacements, the weight replacement ratio of cement by silica fume used was 0 and 10 wt.%. Moreover, a control mixture with no replacements was used for comparison. The SimaPro software along with the Ecoinvent database and Impact 2002+ impact assessment method were used to perform the LCA. The most environmentally sound mixture in the scenario analyzed was that with 5 wt.% of PET and 10 wt.% of silica fume, but no significant improvements have been noted when using and 'total impact intensity' analysis. It was concluded that waste PET particle alone does not help to reduce the overall environmental impact of concrete despite of having a lower impact than natural sand from a certain distance scenario.

Keywords *Life-Cycle Assessment (LCA), Self-compacting Concrete (SCC), Waste Polyethylene Terephthalate (PET), Silica Fume, SimaPro.*

ISBN: 978-85-92631-00-0

1. INTRODUCTION

Concrete is the most consumed artificial material in the world and sand is the second raw material more consumed in the planet after water (ANEPAC 2014, Mehta & Monteiro 2008). The sand is extracted from riverbeds, lakes, floodplains, decomposition of rocks and sandstones. Despite of its abundance in a global scale, the availability of natural fine aggregates is becoming scarce close to urban areas (MME 2009, Van den Heed & De Belie 2012), and alternatives have to be proposed. A great transport distance increases the final product economic cost, representing close to two thirds of the product final cost in the case of sand (MME 2009), additionally it increases its environmental load due to transport emissions. For the supply of the metropolitan area of the capital Vitória - Espírito Santo – Brazil (latitude: 20°19'10"S; longitude: 40°20'16"W), it started to be used sand from the city of Linhares – Espírito Santo - Brazil (latitude: 19°23'28"S; longitude: 40°04'20"W), distant 150 km from the capital. Thus, it is necessary to find best alternatives of supply for this raw material in order to reduce the transport distance and relieve the natural environment from our needs.

Another important issue in nowadays society is the correct disposal of solid residues. Waste PET bottles can contaminate natural water streams, killing aquatic animals, and it can also block urban drainage systems and contribute to urban floods if they are not properly disposed (Saikia & de Brito 2012). If it is landfilled it becomes a problem because it is not biodegradable due to its high thermal, mechanical and chemical resistance. A proper approach to this residue is recycling, as it is a 100% recyclable polymer. In 2011 it was consumed in Brazil 572 thousand tons of PET, 90% used in the production of packaging of food and beverages. The recycling rate of this material in Brazil despite being one of the biggest in the world (reaching in the referenced year 57.1% - 294 thousand tons), holds still a great growth potential (ABIPET 2013). This residue is already recycled for use in the industry of clothes manufacturing (ABIPET 2013, Nakatani et al. 2010). In the construction industry, researches have been done for its use in concrete, focusing on three main alternatives: as a resin for polymer concrete (Jo et al., 2008), as fiber for fiber-reinforced concrete (Kim et al. 2010) and as an aggregate replacement of sand for concrete (Akçaözoğlu et al. 2010, Sadrmomtazi et al. 2016).

Despite of polymer concrete made with PET reduce its total cost, it is still a costly process and energy intensive (Akçaözoğlu et al. 2010, Jo et al. 2008). Fiber-reinforced concrete with waste PET used as fibers has a small volumetric capacity of absorbing waste PET – content between 0.3% and 1.5% (Akçaözoğlu et al. 2010, Kim et al. 2010). Thus, the use of waste PET as fine aggregate for concrete emerges as a possible solution for the destination of this residue, as it seems possible to absorb a greater volume of material and it yields low impact in its transformation – washing, grinding and sieving. More comprehensive reviews about the different recent researches of the utilization of waste PET and plastics, in general, in concrete are already available and can be seen in the works of Sharma & Bansal (2016), and Gu & Ozbakkaloglu (2016).

It has been reported that concrete using waste PET particles as a replacement for aggregates has a better resistance against sulfuric acid attack, showing a good advantage in its use for industrial structures and sewer pipes (Araghi et al. 2015). However, some studies have shown that the use of waste PET particles in concrete can reduce its

ISBN: 978-85-92631-00-0

mechanical strength (Gu & Ozbakkaloglu 2016). To compensate for this, the use of pozzolanic materials, such as silica fume, can be used to diminish this negative effect (Sadrmomtazi et al. 2016).

Life-cycle assessment (LCA) is a methodology that quantitatively assesses the environmental performance and the related impacts of products, processes and systems, helping to identify options for mitigating impacts. It is considered a valuable tool for identifying appropriate solutions to waste management issues (Laurent et al. 2014, Nakatani et al. 2010). Additionally, the LCA approach is increasingly used for evaluating the sustainability of construction materials, such as concrete and its composition (Marinković et al. 2010, Van den Heed & De Belie 2012, Hossain et al. 2016). Much has been said about the positives environmental impacts of using wastes in concrete, but the literature lack of comprehensive studies focused in this issue. A study has been published performing an LCA of recycled polypropylene fibres in concrete footpaths (Yin et al. 2016). Nevertheless, it was not found any study assessing the environmental impacts of using waste PET in concrete. Therefore, this methodology is used in this work to evaluate the environmental feasibility of the incorporation of waste PET as a fine aggregate into self-compacting concrete (SCC) for a case study in Brazil - metropolitan region of Vitória-ES.

2. METHODOLOGY

LCA is a tool that can elucidate how a modification in the composition of a product alters its environmental impact, and it was performed in this study by using the software SimaPro version 8.2 (SimaPro 2016). The LCA methodology and principles are described in the international standards of the International Organization for Standardization (ISO) 14040:2006 and ISO 14044:2006 (ISO 2006a, b). It consists of four steps: goal and scope definition; life-cycle inventory (LCI); life-cycle impact assessment (LCIA); and interpretation. The first three steps will be developed in the following subsections and the interpretation is an interactive step that occurs along with them and in section 3.

2.1 Goal and scope definition

The goal of this study is to compare the environmental impacts of self-compacting concrete (SCC) made with different compositions of fine aggregates: purely natural fine aggregate and waste PET aggregate as a partial substitution for sand. To achieve this goal, seven concrete mixtures were taken from the study of Sadrmomtazi et al. (2016) and analysed for the scenario of Vitória-ES. The functional unit used is 1 m^3 of concrete. The mix proportions and its compressive strength at 28 days (fck) can be seen in Table 1.

Table 1. Mix proportions (kg/m^3) and compressive strength at 28 days (MPa) of SCC.

Description	W/P	Water	Powder		PET	Sand	Gravel	SP	fck
			C	SF					
SCC (control)	0.43	195	450	-	-	850	770	6.8	36.19
NC-PET05	0.43	195	450	-	36.1	813.9	770	7.0	22.03
NC-PET10	0.43	195	450	-	72.2	777.8	770	7.4	20.25
NC-PET15	0.43	195	450	-	108.3	741.7	770	8.1	18.7
SF-PET05	0.43	195	405	45	36.1	813.9	770	6.8	33.77
SF-PET10	0.43	195	405	45	72.2	777.8	770	7.7	28.82
SF-PET15	0.43	195	405	45	108.3	741.7	770	8.3	21.44

Source: Adapted from Sadrmomtazi et al. 2016

ISBN: 978-85-92631-00-0

The prefix NC in mixture description refers to 'Normal concrete', concrete with no cement (C) replacement, and SF means that there is a partial replacement of cement by silica fume (SF). The water/powder ratio (W/P) was fixed in 0.43. The waste PET replacement of sand was of 5, 10 and 15% by weight. An addition of 10% of silica fume was considered in three mixtures to decrease the negative effect that waste PET has on the compressive strength of concrete. Additionally, a control mixture with no waste or silica fume was used (SCC control). A polycarboxylic superplasticizer (SP) was used to achieve the desirable workability of the mixtures. It can be seen in Table 1 that despite of its high cement content, the SCC control mix has a low compressive strength. The explanation for that may lie in the fact that in the mixtures analysed in the original study of Sadrmomtazi et al. (2016), the aggregates used in the mixes had high porosity, with water absorption of 3.26% and 3.2% for fine and coarse aggregate, respectively.

The goal establishes the system boundaries of the study, which in this case, is considered a cradle-to-gate LCA. The construction, service phase, demolition phase and end-of-life scenario are not included in the boundaries of the study. These phases are expected to be similar for the concrete types analysed in this study, thus they will not be taken into account in the comparative analysis.

Thus, the analysis encompasses the following steps: extraction, production and transport of cement and its raw materials; extraction, processing and transport of natural aggregates (sand and gravel); processing and transport of waste PET aggregate; production and transport of superplasticizer; processing and transport of silica fume. It was not considered the infrastructure items of the processes in the assessment. The system analysed can be seen schematically in Figure 1, and it will be explained further in the next subsection. Additionally, a comparative assessment of 1 kg of sand and 1 kg of waste PET was performed for 2 different transport scenarios (Sc1 and Sc2).

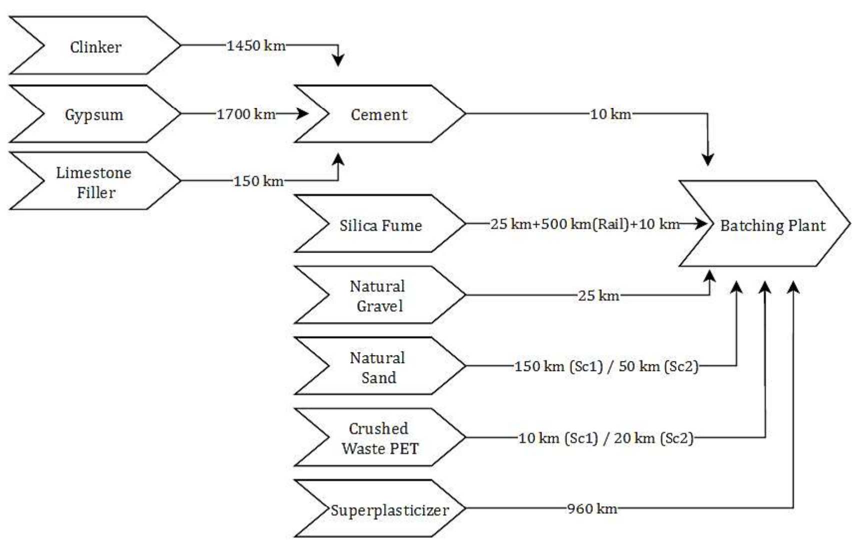

Figure 1. Flowchart of the concrete production
Note: Sc1 and Sc2 - transport scenario 1 and 2, respectively.

ISBN: 978-85-92631-00-0

2.2 Life-Cycle Inventory (LCI)

In this step of the LCA, a comprehensive data collection is realized. All data regarding relevant inputs and outputs of energy and mass, comprising the emissions to air, land and water, must be collected. In this work, the processes are adapted from the Ecoinvent 3.2 database to the Brazilian context.

In Figure 1, it can be seen the transport distances used in the assessment of the system. The transportations are made by road (truck, unspecified), unless when otherwise stated. To assess the sensibility of transport in the LCA, in the comparative assessment of the fine aggregates sand and waste PET, two different scenarios are considered. In the scenario 1 (Sc1), it is considered the best case for waste PET, the sand from Linhares-ES (150 km) and the waste PET at a shorter distance (10 km). In the scenario 2 (Sc2), the sand is considered from a closer quarry (50 km), and the waste PET from a farther recycling plant (20 km). For the concrete mixtures analysis, only the scenario 1 was used, due to being the best case for waste PET and now also a usual procedure in the region.

In the study of Sadrmomtazi et al. (2016), the cement used was an ordinary Portland cement (OPC) produced in Iran, the Portland cement type II, which is similar in its chemical and mineralogical composition to the European CEM I. Its correspondents in the Brazilian context are the CPI and CPV-ARI. The best equivalent commercially available for this scenario is the CPV-ARI, since the OPC called CPI is only available on production demand. The inventory data adaptation is made similar to the study of Mello (2015), who considered the scenario of the same region. Its adapted processes and emissions at the batching plant, and the supply and production (taken from a European inventory) of the superplasticizer were also used. The sand and gravel production data were adapted using the data of the study of Castro et al. (2015), which analysed the feasibility of adapting the inventory data to the Brazilian context using their own collected data, estimates, and other national inventory studies. However, their estimate for the emission of particulates (<2.5 μm) of the gravel production was not considered, due to the lack of data reliability.

The silica fume considered was taken from the Ecoinvent database, without bearing environmental load from the ferrosilicon production, as it is a byproduct, and only accounting for the transport. For the waste PET, only the mechanical recycling process and transport were considered. The crushing/grinding energy consumption was estimated by commercially available large granulators (throughput higher than 2000 kg/h) as being 0.085 kWh/kg PET (PROSINO, 2016), due to the high volume of aggregates consumed by the construction industry. The waste collection of PET and transport to the recycling plant was not considered, neither the difference of impacts of alternative final destinations of the waste because of the scope of this study.

2.3 Life-Cycle Impact Assessment (LCIA)

In this stage, the potential environmental impacts are calculated based on the inventory. It consists of three mandatory steps: selection of the impact categories; the classification of the impacts, that matches the LCI data with the chosen impact categories; and characterization, that aggregates the LCI results into the indicators results, which integrates the inventory into a common unit (e.g. kg CO_{2}-$_{eq}$). Additional optional steps can also be used, such as normalization, grouping, weighting and single score (also known as

ISBN: 978-85-92631-00-0

eco-point). The Impact2002+ impact assessment method was chosen to be used in this study; it encompasses both problem-oriented (midpoints) and damage (endpoints) approaches for the analysis (Jolliet et al. 2003).

For this study, it was considered the midpoint approach and the impact categories of respiratory inorganics, global warming and non-renewable energy for the comparison of waste PET (1 kg) and sand (1 kg) in the characterization step, due to being the three most important impacts of both products. For the comparison of waste PET and sand incorporated into self-compacting concrete (unit of m^3), it was considered both midpoints and endpoints approach. The analysis encompassed the impact categories of global warming, respiratory inorganics and non-renewable energy (midpoints) in the characterization step, due to being the most significant impacts of overall concrete production. Additionally, human health, ecosystem quality, climate change and resources (endpoints) in the single score stage were analysed.

3. RESULTS AND DISCUSSION

As can be seen in Table 2 and Figure 2, the indicators analysed show that waste PET particle has a lower environmental impact for the scenario 1, the most favorable to waste PET, with the impact reduction ranging from to 40-45% approximately. Table 2 shows that the most famous impact, global warming, can be reduced significantly, being 13.5 g $CO_{2\text{-}eq}$ for 1 kg of waste PET, in contrast to 22.2 g $CO_{2\text{-}eq}$ for 1 kg of sand. The respiratory inorganics, represented by the 2.5 µm particulates equivalent ($PM2.5_{\text{-}eq}$) unit, can also be reduced from 3.65E-05 $PM2.5_{\text{-}eq}$ to 2.03E-05 $PM2.5_{\text{-}eq}$.

Table 2. Indicator results for 1 kg of waste PET and 1 kg of sand in both scenarios.

Impact category	Unit	Waste PET Sc1 (10 km)	Sand Sc1 (150 km)	Waste PET Sc2 (20 km)	Sand Sc2 (50 km)
Respiratory inorganics	kg $PM2.5_{\text{-}eq}$	2.03E-05	3.65E-05	2.16E-05	2.43E-05
Global warming	kg $CO_{2\text{-}eq}$	0.013482	0.022225	0.014538	0.011665
Non-renewable energy	MJ primary	0.19107	0.34713	0.20741	0.18379

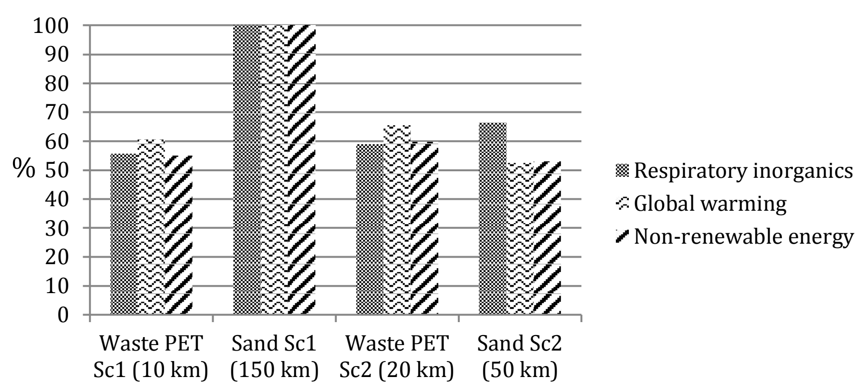

Figure 2. Characterization results for 1 kg of waste PET and 1 kg of sand in both scenarios.

Figure 2 presents the characterization results, and the % represents the product equivalent impacts to the most impacting product, the sand in the scenario 1. However, in

ISBN: 978-85-92631-00-0

the scenario 2, the global warming and non-renewable energy impacts are higher for waste PET, despite of reducing the impact of respiratory inorganics. This shows the significance of the transport distance for the LCA analysis, especially in products where the highest emissions and energy consumption originate from its logistics, as it is the case of sand. In this initial result analysis, it seems tempting to conclude that the waste PET particle is a better alternative from an environmental point of view in this scenario where it is much closer the supply of the waste PET than the natural sand. Nonetheless, a further analysis is required to assess the influence of this substitution in the concrete mixture.

To complement the environmental analysis, the full final product must be assessed. Thus the indicator results for 1 m^3 of different mixtures of self-compacting concrete are presented in Table 3 and Figure 3. As can be observed, the actual overall impact of the concrete mixture did not reduced significantly solely with the incorporation of waste PET, and it actually slightly increased for some impact categories, for example, in the case of all impact categories analysed in the mix NC–PET15. This can be explained by the highest amount of superplasticizer needed in the mixes with the increasing waste PET incorporation to compensate for the loss of workability of the concrete. The highest dosage of superplasticizer required eliminated the potential small environmental benefit of incorporating the waste PET into the matrix.

Table 3. Indicator results for 1 m^3 of different concrete mixtures.

Impact category	Unit	SCC control	NC-PET05	NC-PET10	NC-PET15	SF-PET05	SF-PET10	SF-PET15
Respiratory inorganics	kg $PM2.5_{-eq}$	0.31962	0.31930	0.31946	0.32036	0.29679	0.29818	0.29883
Global warming	kg CO_{2-eq}	487.39	487.26	487.44	488.08	443.54	444.49	444.97
Non-renewable energy	MJ primary	2534.93	2532.19	2534.93	2545.91	2359.12	2375.59	2383.82

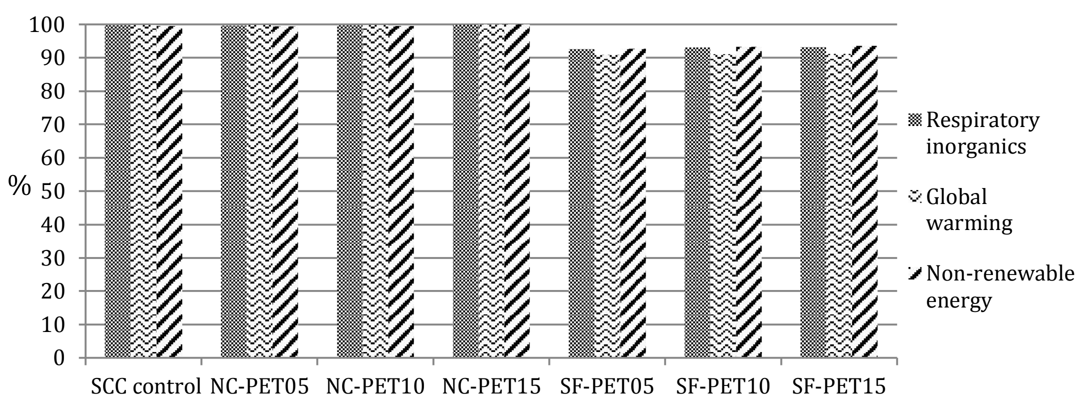

Figure 3. Characterization results for 1 m^3 of different concrete mixtures.

On the other side, the mixtures with silica fume (at 10 wt.% of cement) presented a more significant lower impact in the selected categories, as noted in Figure 3 (SF-PET05/10/15), reducing nearly 9% the global warming impact. This can be explained by its neutral impact production – it is a byproduct from the ferrosilicon production. On the other hand, cement production has intense energy consumption and gases emissions. Moreover, the cement logistics in this scenario is more environmentally harmful due to the high

ISBN: 978-85-92631-00-0

transport distance by road, and the silica is supplied at a shorter distance and with a transport mode that impacts less, the rail.

The eco-points results for the mixtures can be seen in the Table 4 and Figure 4. Here, the problem-oriented results are transformed into damage results. They are presented as dimensionless figures called millipoints (mPt), which represent the potential population affected by the environmental impacts in a period of one year, and have the sole purpose of compare the difference between products, in this case, the seven concrete mixtures. The results of the previous stage were normalized according to the impact assessment method and then grouped together. It can be noted that the three most relevant damage impacts for the concrete mixes are climate change, human health and resources. They represent approximately 45%, 32% and 15% of the total environmental impact of concrete, respectively, while the impact on ecosystem quality represents approximately 8%.

Table 4. Single Score and 'total impact intensity' for 1 m^3 of different concrete mixtures.

Damage category	Unit	SCC control	NC - PET05	NC - PET10	NC - PET15	SF - PET05	SF - PET10	SF - PET15
Total	mPt	110.1723	110.1882	110.3510	110.7341	101.5290	102.0590	102.3687
Human health	mPt	35.0467	35.1041	35.2324	35.4668	32.6583	32.9635	33.1625
Ecosystem quality	mPt	9.1964	9.1853	9.1834	9.1953	8.5274	8.5485	8.5557
Climate change	mPt	49.2259	49.2135	49.2319	49.2964	44.7979	44.8932	44.9423
Resources	mPt	16.7033	16.6853	16.7033	16.7757	15.5454	15.6539	15.7081
Total impact intensity	$\frac{mPt}{fck}$	3.04	5.00	5.45	5.92	3.01	3.54	4.77

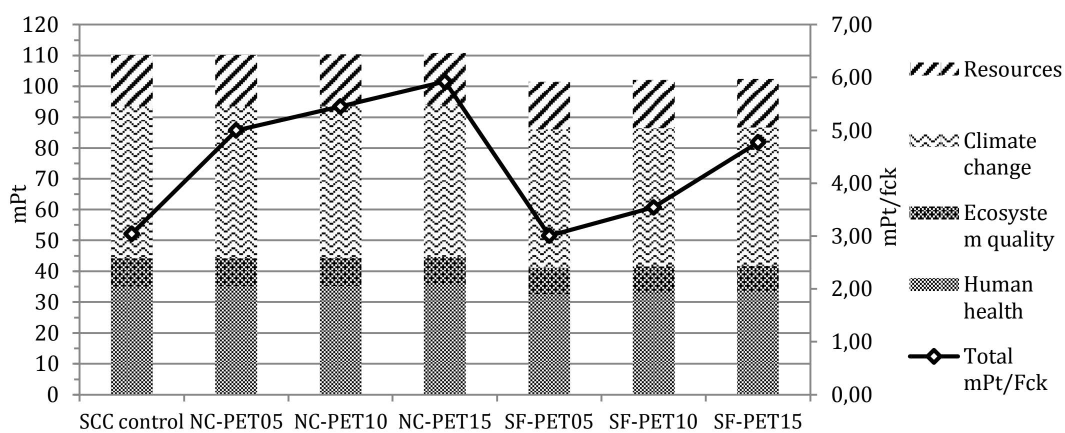

Figure 4. Single Score results for 1 m^3 of different concrete mixtures and Total mPt/fck.

Figure 4 shows the single score results and gives a good overall view of the impacts of the mixes. The control and the NC mixes presented a similar environmental load. The total impact is reduced by a little more than 7% for the SF mixes compared to the control mix. An additional analysis has been performed, to assess the 'total impact intensity' of the incorporation of waste PET into SCC. It was defined as the Total mPt results divided by the compressive strength (fck) of the concrete. The lower the value, the lower is the environmental impact, and more eco-efficient is considered the mix. It can be noted that the 'total impact intensity' is abruptly increased for the NC mixes, and it is then reduced for the SF mixes. Additionally, it can be noted that only the SF–PET 05 mixture is more

ISBN: 978-85-92631-00-0

eco-efficient than the SCC control mixture, but not significantly. This analysis is important because the incorporation of wastes and byproducts can influence much negatively some the properties of concrete, and this should be considered in an environmental analysis as well. In this case, only the compressive strength has been examined, due to be considered the most important characteristic of the final product. However, for a full detailed analysis, it is advisable that the durability properties are also considered.

Thus, it can be seen that the potential environmental benefits of incorporating waste PET into concrete are depreciated by its poor combination with the cement matrix, reducing the workability and compressive strength. Sadrmomtazi et al. (2016) reported that this is due to the fact that, when compared with natural sand, waste PET particles have more specific surface area due to their plane shape, what causes an increase in the amount of water in the transition interfacial zone. Thus, the porosity increases weakening the microstructure and decreasing the compressive strength. Despite of this, the authors stated that its incorporation has several advantages, such as no effect on electrical resistance and in reducing brittleness of concrete, including improvements in the environmental aspect, without evaluating it properly, as by LCA means. In this study, it was found through the LCA methodology that the environmental aspect can be enhanced only when waste PET is combined with silica fume.

4. CONCLUSIONS

The waste PET as an aggregate has a reduced environmental load when compared with natural sand in the studied scenario. However, when the whole supply chain in analysed, this environmental improvement does not have much significance, since the biggest impacts are located in the cement production and supply chain. Thus, the initial expected environmental improvements obtained by the sole incorporation of waste PET into the self-compacting concrete were not found. However, it presented an improved environmental performance when combined with silica fume.

There is actually a lot of fuss about the benefits of incorporating some wastes into concrete, and it has been shown in this article that using waste PET into concrete as a partial substitution for sand is not as environmentally favorable as previously thought. Furthermore, there is no proof that this concrete is equivalent in term of mechanical properties and durability traditional concrete, and many studies findings state otherwise (Sharma & Bansal 2016, Gu & Ozbakkaloglu 2016).

However, the civil construction sector might still hold a good option for waste PET use, and alternatives should be analysed properly by using the adequate methodology. A LCA of non-structural lightweight concrete blocks or a comparative LCA of recycled waste PET resin for polymer concrete, for example, is advisable for future studies.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of FAPES (Fundação de Amparo à Pesquisa e Inovação do ES).

ISBN: 978-85-92631-00-0

REFERENCES

ABIPET (Associção Brasileira da Indústria do PET) 2013. Panorama 2013 – *Indústria do PET no Brasil*. Available in http://www.abipet.org.br. Accessed 15 may 2016.
ANEPAC (Associação Nacional das Entidades de Produtores de Agregados para a Construção Civil) 2014. Construindo o Futuro – Sustentabilidade na Mineração de Agregados. Areia e Brita. São Paulo.
Akçaözoğlu, S., Atiş, C., & Akçaözoğlu, K. 2010. An investigation on the use of shredded waste PET bottles as aggregate in lightweight concrete. Waste Manag. 30(2):285-290.
Araghi, H.J., Nikbin, I.M., Reskati, S.R., Rahmani, E. & Allahyari, H. 2015. An experimental investigation on the erosion resistance of concrete containing various PET particles percentages against sulfuric acid attack. *Constr. Build. Mater*. 77: 461-471.
Castro A.L., Silva F.B., Arduin R.H., Oliveira L.A. & Becere O.H. 2015. Análise da viabilidade técnica da adaptação de dados internacionais de inventário de ciclo de vida para o contexto brasileiro: um estudo de caso do concreto para paredes moldadas no local. *Congresso Brasileiro do Concreto; Event proceedings*. Bonito-MS, October 2015.
Gu, L. & Ozbakkaloglu, T. 2016. Use of recycled plastics in concrete: A critical review. *Waste Manag*. 51:19-42.
Hossain, M., Poon, C., Lo, I., & Cheng, J. 2016. Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *Resour. Conserv. Recycl.* 109:67-77.
ISO (International Organization for Standardization) 2006a. *Environmental management - life cycle assessment - principles and framework*. ISO 14040
ISO (International Organization for Standardization) 2006b. *Environmental management - life cycle assessment - requirements and guidelines*. ISO 14044
Jo, B.-W., Park, S.-K. & Park, J.-C. 2008. Mechanical properties of polymer concrete made with recycled PET and recycled concrete aggregates. *Constr. Build. Mater*. 22:2281-2291.
Jolliet O., Margni M., Charles R., Humbert S., Payet J., Rebitzer G. & Rosenbaum R. 2003. IMPACT 2002+: a new life cycle impact assessment methodology. *Int. J. Life Cycle Assess*. 8(6): 324-330.
Kim S.B., Yi N.H., Kim H.Y., Kim J.H.J. & Song Y.C. 2010. Material and structural performance evaluation of recycled PET fibre reinforced concrete. *Cem. Concr. Compos*. 32:232–40.
Laurent A., Bakas I., Clavreul J., Bernstad A., Niero M., Gentil E., Hauschild M.Z. & Christensen TH. 2014. Review of LCA studies of solid waste management systems - Part I: Lessons learned and perspectives. *Waste Manag*. 34:573-588.
Marinković, S., Radonjanin, V., Malešev, M. & Ignjatović, I. 2010, Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Manag*. 30(11):2255-2264.
Mehta P.K. & Monteiro P.J.M. 2008. *CONCRETO. Microestrutura, propriedades e materiais*. tradução de cristina borba, 3rd ed. IBRACON, São Paulo.
Mello, R. Z. 2015. *Avaliação do ciclo de vida de concreto auto adensável: comparação com diferentes teores de adição de escória de alto-forno*. Projeto de Graduação – Departamento de Engenharia Civil, Universidade Federal do Espírito Santo. Vitória-ES, 108 p.
MME (Ministério de Minas e Energia) 2009. *Relatório Técnico 31 - Perfil de areia para construção civil*. Secretaria de Geologia, mineração e transformação mineral – SGM.
Nakatani J., Fujii M., Moriguchi Y. & Hirao M. 2010. Life-cycle assessment of domestic and transboundary recycling of post-consumer PET bottles. *Int. J. Life Cycle Assess*. 15:590-597.
PROSINO. 2016. *Medium and Large Granulator*. Available in http://www.sinoshredder.com/shredders/medium-and-large-granulator-for-sale/. Accessed 18 may 2016.
Sadrmomtazi, A., Dolati-Milehsara, S., Lotfi-Omran, O. & Sadeghi-Nik, A. 2016. The combined effects of waste Polyethylene Terephthalate (PET) particles and pozzolanic materials on the properties of self-compacting concrete. *J. Clean. Prod*. 112:2363-2373.
Saikia, N. & de Brito, J. 2012. Use of plastic waste as aggregate in cement mortar and concrete preparation: A review. *Constr. Build. Mater*. 34:385-401.
Sharma, R. & Bansal, P.P. 2016. Use of different forms of waste plastic in concrete - a review. *J. Clean. Prod*. 112:473-482.
SimaPro Faculty (2016) *Version 8.2.0.0*. Developed by PRéConsultants.
Van den Heede, P. & De Belie N. 2012. Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: literature review and theoretical calculations. *Cem. Concr. Composites* 34:431–442.
Yin, S., Tuladhar, R., Sheehan, M., Combe, M., & Collister, T. 2016. A life cycle assessment of recycled polypropylene fibre in concrete footpaths. *J. Clean. Prod*., 112:2231-2242.