Master's thesis

NTNU
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Department of Manufacturing and Civil Engineering

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Comparative Life Cycle Assessment of Incorporating Recycled PET Aggregates into Concrete

Master's thesis in Sustainable Manufacturing
Supervisor: Lizhen Huang
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Abstract

Purpose

Recycling waste plastics in cementitious composites is a potential solution that can address the challenges in both concrete- and plastic industry. The purpose of this master thesis is to estimate the environmental impacts of incorporating recycled PET bottles as fine aggregate into concrete.

Method

This life cycle assessment (LCA) study follows the ISO 14040/44 methodology. The functional unit is determined as one cubic meter of concrete and the system boundary is considered as cradle to gate, limited to the production of fresh concrete and does not include the use phase and end of life disposal of concrete. The results from an existing experimental investigation are analyzed carefully to provide reliable data for the LCA work. Four different concrete mixes containing 0%, 14%, 47% and 58% of recycled PET aggregates (RPA) as fine aggregate with compressive strength equivalent to 30 MPa are considered for comparative LCA study in nine impact categories.

Results and discussion

The results of this study are discussed based on the consideration of credit from the elimination of incineration process due to using RPA in concrete. This study reveals that the main advantage of this method of using RPA in concrete when the credit from incineration is not considered, is reducing environmental impacts in the land use category, and the other selected categories have higher impacts compared to the reference concrete with 0% RPA. However, if this recycling method is considered as an alternative to incineration of waste plastics and the credit from elimination of incineration process is considered for this product, significant advantages in different impact categories will be observed.

By considering the credit, the impacts on climate change and human toxicity- non cancer effect categories are reduced considerably. Where increasing the RPA percentage to 47% and 58% will result in negative impacts. The environmental impacts on human toxicity- cancer effects, terrestrial eutrophication and land use categories decreases by increasing the portion of RPA when the credit is considered. However, there is a slight jump from 47% RPA to 58% RPA and it is due to the increase in cement content while the RPA content is not increased

considerably when compared to the difference between concrete containing 14% and 47% RPA. Considering the credit also reduced the impacts on ozone depletion, particulate matters and acidification categories, but the results show that using RPA in concrete in case of consideration of credit still had higher impacts compared to the reference concrete. Water resource depletion was the only impact category that had slightly higher impacts in the four mix designs when considering the credit and this is due to negative impact of incineration process on water resource depletion category.

Conclusion

This evaluation gives an understanding of the effect of this method of recycling. Using RPA in concrete resulted in considerable advantages in different impact categories by considering the credit from elimination of incineration process.

In order to increase environmental benefits of incorporating RPA into concrete, measures such as enhancing mechanical properties of recycled plastic aggregates, improving properties of the interface between cement and the aggregates, modification of composition of the cementitious binder as well as optimizing the washing process of waste PET bottles and natural aggregates can be taken.

Furthermore, targeting cement-based composites that do not demand high compressive strength such as separation walls, insulation boards or decorative elements as well as recycling concrete containing waste plastics into new products without re-melting the plastics would also be some approaches beneficial for the environment. The results can be a motivation for producing cement-based composites containing recycled plastic aggregates from other types of waste plastics such as mixed plastics, which are mainly incinerated in different countries including Norway.

Preface

The present work is submitted in partial fulfilment of the requirement for the master's degree at the Norwegian University of Science and Technology (NTNU). The thesis has been performed at the Faculty of Engineering, Department of Manufacturing and Civil Engineering, through the Master Program of Sustainable Manufacturing (MSUMA), between January 2019 and June 2019.

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Mohaddeseh Tahnapour Javadabdi

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Abbreviations

LCA	Life Cycle Assessment
GWP	Global Warming Potential
ODP	Ozone Depletion potential
PMP	Particulate Matter potential
LUP	Land Use potential
WRDP	Water resource depletion potential
HTP-C	Human Toxicity Potential, Cancer Effects
HTP-NC	Human Toxicity Potential, Non-cancer effects
AP	Acidification potential
TEP	Terrestrial eutrophication potential
PET	Polyethylene Terephthalate
RPA	Recycled PET Aggregate
EPS	Expanded Polystyrene
PP	Polypropylene
PVC	Polyvinyl Chloride
PS	Polystyrene
GRP	Glass fiber Reinforced Plastic
EVA	Ethylene Vinyl Acetate
PUR	Polyurethane
LDPE	Low-Density Polyethylene
HDPE	High-Density Polyethylene
W/C	Water- Cement ratio
LCI	Life Cycle Inventory
LCIA	Life-Cycle Impact Assessment
DSF	Double-Skin Facade
SRM	Steel Reinforcing Mesh
SW	Solid Wall
U.S. DOT	The U.S. Department of Transportation
U.S. EPA	The U.S. Environmental Protection Agency's
ICE	The Inventory of Carbon and Energy that as developed by the University of Bath
DEFRA/DECC	The database by the Departments of Energy and Climate Change (DECC) and the Environment, Food and Rural Affairs (DEFRA) for use within the UK.
HP-G-HyFRC	High Performance Green Hybrid Fiber-Reinforced Concrete
GFRP	Glass Fiber Reinforced Polymer
AEWRA	Air Entrainment Water Reducing Agent
RPM	Round Per Minute
SSB	Statistisk Sentralbyrå

1. Introduction

During the 20th century, using plastics increased for making various products due to their attractive properties such as, high durability, low density, high strength to weight ratio, low cost and ease of design and manufacturing. At the present time, polymer based materials (which will be referred to the commonly known phrase of “plastics” in this thesis) are extensively used in different industries such as packaging, agriculture, building and construction, automotive and electronics [1].

In 2016, world plastic production was around 335 million tons [2]. More than half of this amount was related to one-off disposable consumer products, resulting in increase in the amount of plastic waste in the world. Most types of plastics cannot be decomposed, and these polymeric products can remain for decades or even for centuries in the environment and rise the environmental issues of waste plastics [1]. Recycling waste plastics would be an important solution for reducing their environmental impacts in many areas such as pollution, global warming, waste disposal and natural resources. There are different methods for recycling wastes, however, reusing wastes and recycled plastic materials in building and construction industry would be an attractive way for managing the waste plastics without degradation in quality along its life cycle [1]. While concrete is the most consumed man-maid material in the world [3], recycling waste plastics in cement-based materials can be a potential alternative to other options for waste plastic treatment such as landfill and incineration. However, the manufactured material should satisfy requirements for essential properties of the aimed product and the environmental impacts of the product should be assessed.

Wide range of studies are conducted on the effect of using waste plastics in concrete on the fresh and hardened properties of concrete. However, limited focus has been on the life cycle assessment (LCA) of using waste plastics in concrete. Since different types of waste plastics can be used for this purpose, this LCA study is performed based on the use of recycled polyethylene terephthalate (PET) bottles in concrete production due to presence of reliable experimental results. Recycled waste PET can be used in concrete in different forms such as aggregates and fibers. The amount of fibers that can be used in concrete to keep the desired level of mechanical- and fresh state properties is low. However, using them in the form of aggregate has the potential to manage a large amount of waste in the concrete volume.

The objective of this study is to provide a comprehensive understanding of environmental benefits of addition of recycled PET aggregate (RPA) as fine aggregate in concrete production as an alternative to incineration of the waste PET. Therefore, the research questions can be defined as:

What are the benefits of incorporating RPA into concrete as fine aggregates as an alternative to incineration of the waste PET from the life cycle perspective?

What are the hotspots for reducing the environmental impacts of this product?

To explore the environmental impacts of recycling waste PET as fine aggregates in concrete, incorporation of different amounts of RPA (0%, 14%, 47% and 58%) into one cubic meter of concrete with 30 MPA compressive strength is evaluated.

This study includes a literature review in chapter 2, followed by presenting the goal and scope, boundary, assumption and inventory data of this study in chapter 3. The results of LCA work are presented and discussed in chapter 4 and chapter 5 concludes this study.

2. Literature review

A wide range of studies are conducted in using recycled plastic in concrete production. In this section, the effect of addition of recycled plastic on the mechanical and fresh state properties of concrete as well as studies on the environmental impact assessment of using plastic in concrete will be reviewed.

2.1 Recycled plastics used in concrete

There are many types of recycled plastics used in concrete production. Table 2.1 presents the most consumed types of plastics in previous studies. Furthermore, in some investigations, especially in LCA studies some virgin plastics such as expanded polystyrene (EPS) and polypropylene (PP) are considered to compare the environmental impacts of concrete containing virgin plastic and concrete containing recycled plastic.

Table 0.1. Types of plastics used in concrete and their recycling procedure

No	Types of plastics	Origin of plastics	Recycle or treating procedure
1	PET	PET bottles	- Shredding - Melted PET mix with river sand - Crushing after washing - thermal treatment
2	PP	Waste fiber	Disassembled mechanically
3	PVC (polyvinyl chloride)	PVC pipes	Grinding
4	PS (polystyrene)	PS foam plastic	Crumbling
5	GRP (glass fiber reinforced Plastic)	GRP industry waste	Grinding
6	EVA (ethylene vinyl acetate)	Waste EVA from footwear industry	Cutting
7	PUR (polyurethane)	Rigid PUR foam waste	Immersed in water for 24 h before mixing
8	EPS	Waste EPS	Crushing
9	LDPE (low-density polyethylene)	LDPE bags	Shredding
10	HDPE (High-density polyethylene)	HDPE waste	Shredding
11	Melamine	Melamine waste	Grinding

Plastics are mainly used in concrete for two purposes; first, as replacement to stone aggregates, which are called plastic aggregates and second, as fibers for reinforcing concrete, which are called plastic fibers.

2.1.1 Plastic aggregates

The plastic aggregates that were used in different studies include both coarse aggregates and fine aggregates. It is obvious that the bulk density of plastic aggregate is very low compared to the natural aggregates and because of this property, plastic aggregate is suitable for lightweight concrete. The specific gravity of plastic aggregates is between 900-1400 kg/m^3, which is much lower than natural aggregates that are used in concrete (about 2400-2900 kg/m^3). The bulk density of plastic aggregates are lower than their specific gravity because of the voids between plastic aggregate. Recycling methods for preparing plastic aggregates can result in different bulk densities, where, the mechanical recycling leads to a low bulk density and melting recycling method leads to a higher bulk density [4]. Compared to natural aggregates, plastic aggregates normally have lower bulk density, higher tensile strength, lower water absorption and much lower melting point [1].

2.1.2 Plastic fibers

Plastic fibers can be used as reinforcement instead of steel fibers in concrete. Steel is an expensive material with a high energy consumption and sensitive to corrosion, while plastic fibers are very cost effective and corrosion resistant, with lower carbon footprint. Moreover, plastic fibers almost show better elongation and better strength to weight ration compared to the steel fibers. In one study, it was shown that the strength to weight ratio and elongation of steel fibers are 192 kN m/kg and 3.2%, respectively, while for the plastic fibers these numbers are changed to 889 kN m/kg and 9.1%, respectively [5].

2.2. Basic properties of concrete containing recycled plastic

2.2.1 Effect of recycled plastic on properties of fresh concrete

In the following sub section, the effect of incorporating plastic materials on the fresh concrete properties such as slump, unit weight and air content will be presented for both plastic aggregate concrete and plastic fiber concrete.

2.2.1.1 Slump

Plastic Aggregates

The slump test measures the consistency and checks the workability of the fresh concrete [6]. The slump's results for plastic aggregate concrete are affected by the following factors; substitution level of plastic aggregates, the shape of the waste plastic and water-cement ratio (W/C) [1].

Due to the importance of the concrete slump, many studies have been done to find the effect of plastic aggregate on this property. Among these researches, two different views are recognized on the workability behavior of plastic aggregate concrete. In most of the studies, the slump value was decreased by using plastic aggregates instead of natural aggregates and it was also observed that with the increase in the amount of plastic aggregate the slump value is decreasing furtherly [7-9].

The reason for having lower slump when using plastic aggregate in concrete, are the angular particle size and sharp edge of plastic aggregate [6].

On the other hand, in a few studies were reported that the slump value will increase if the plastic aggregate replaces with the natural aggregate [10, 11]. It was claimed that, the reason for increasing slump in plastic aggregate concrete is the existence of more free water. Natural aggregate can absorb water during mixing, which is not a ability of plastic aggregate [6].

Plastic Fibers

In most researchers, it was shown that the slump of fresh concrete reduced significantly with the increase in the amount of plastic fibers used in concrete [12-14]. In one study, it was reported that, when the content of plastic fiber reach to 0.5%, there would not be a significant reduction in slump compared to the conventional concrete [15].

However, several studies also experimented that the workability of concrete can be improved just by adding small fiber. When the fiber content increased, the slump of plastic fiber aggregate declined [16, 17].

2.2.1.2 Unit weight

Plastic Aggregates

Without considering the type and size of the replacement of plastic aggregate instead of natural aggregate, the plastic composition as aggregate commonly reduces the fresh and dry densities of concrete because of the light weight of plastic [7, 8, 10, 11]

Plastic Fibers

Due to the small volume of plastic fiber used in concrete mix, reducing the density of plastic fiber concrete is not very significant compared to conventional concrete density [5, 14].

2.2.1.3 Air content

Plastic Aggregates

Few studies have been conducted on the content of air in fresh plastic aggregate concrete. Some of these studies show that the mixing of plastics as an aggregate increases the air content of concrete. This is because the plastic and natural aggregate in the concrete matrix are not sufficiently combined. Therefore, the plastic aggregate porosity increase, and as a result, the air content of the concrete has increased [4].

Plastic Fibers

There was a study on the effect of air content using plastic fiber in concrete that shows, the air content increase with the use of plastic fibers when the volume of plastic fiber is more than 0.3% and then, there is no obvious effect on the air content of fresh concrete when the amount of plastic fiber usage is below 0.3% [18].

2.2.2 Effect of recycled plastic on mechanical properties of hardened concrete

In this sub section, the effect of incorporating plastic materials on the hardened concrete properties such as compressive strength, split tensile strength, module of elasticity, flexural strength and abrasion resistance will be presented for both plastic aggregate concrete and plastic fiber concrete.

2.2.2.1 Compressive strength

Plastic Aggregates

The compressive strength of concrete is an important property which is studied in almost all research works on plastic usage in concrete. Almost, all studies reported that the combination of plastic as aggregate decrease the compressive strength of the concrete [7-11]. There was 34%, 51%, and 67% reduction in the compressive strength for concrete containing 10%, 30%, and 50% plastic aggregates.

It can be found from some researches that the reduction in 28-day compressive strength of plastic aggregate may be due to two factors; 1) A poor bond between the cement paste and the plastic aggregates. 2) The low strength which is the characteristic of plastic aggregates [18].

Plastic Fibers

Some studies stated that the compressive strength of concrete can be improved by adding plastic fiber [5, 15, 16, 19, 20]. In addition, some researchers reported that using recycled plastic fibers with a high ultimate tensile strength, like recycled polypropylene (PP) fibers, can improve the compressive strength more significant than using recycled plastic fibers with a low tensile strength such as, recycled polyethylene terephthalate (PET) fibers. It was also indicated in one study that, for polypropylene (PP) fiber volume fractions of 0.05% and 0.10%, the compressive strength ratio of the resulted concrete increased moderately by 1–3% [20].

2.2.2.2 Split tensile strength

Plastic Aggregates

Splitting tensile strength is the case for the compressive strength, therefore, the split tensile strength of plastic aggregate concrete with the same W/C, compared to the conventional concrete is commonly lower. There are lots of studies that have been done on the splitting tensile strength of the plastic aggregate concrete and the results show that, the split tensile strength of plastic aggregate concrete decrease with increase in the substitution level of plastic aggregates. It was also stated in researches that the concrete containing non-uniformly shaped plastic aggregates has more obvious reduction in the splitting tensile strength compared to the concrete with uniformly shaped plastic aggregates. Moreover, the splitting tensile strength of plastic aggregate concrete decreases with a drop in the elastic module of low modulus plastic aggregates [4, 7, 9, 10, 21]

Plastic Fibers

Most studies on the effect of plastic fiber content on the splitting tensile strength of fiber reinforced concrete reported that, by increase the addition of plastic fibers in concrete, the splitting tensile strength of concrete will be increased [16, 19, 22].

There was an experiment that has been done in one research which was stated that when splitting occurred and then continued due to loading, the plastic fibers the plastic fibers acted like a bridge and the stress was shifted to the other sections of the matrix, and therefore, could support the entire load [19]. In the other words, if the plastic fibers did not exist in concrete, the load capacity would be reduced.

However, there is another research reported that when a 0.5 % volume fraction of plastic fibers was added to the conventional concrete, the splitting tensile strength reduced by 5% [5]. Furthermore, many researches also experimented that for improving the splitting tensile strength, the content of plastic fibers added t the concrete should be small.

2.2.2.3 Module of elasticity

Plastic Aggregate

The elastic modulus of plastic aggregate concrete depends on different parameters such as substitution level of plastic aggregates, W/C, the porosity of the aggregates and the type of waste plastic. The results from the studies which have been done on the effect of amount of plastic aggregate usage in concrete on its elastic modulus show that, as module of elasticity is the case of compressive strength, the elastic modulus of plastic aggregate concrete is generally lesser than elastic modulus of conventional concrete when their W/C are the same. In addition, when the shape of plastic aggregates becomes more non-uniform or when the elastic modulus of the plastic aggregates decreases, the reduction in elastic modulus of the concrete become more noteworthy [4, 7, 10, 23]

Plastic Fibers

The studies on the effect of content of plastic fibers used in concrete on the elastic modulus of the resulted concrete, show that the elastic modulus of the plastic fiber reinforced concrete does not have very significant difference when compared to the elastic modulus of the conventional concrete [12, 17].

Commonly, elastic modulus of plastic fiber concrete is mainly affected by the elastic modulus and volume portion of each component in concrete. Plastic fibers normally have a lower elastic modulus compared to the conventional concrete, but this difference has a negligible effect on elastic modulus of the fiber reinforced concrete containing plastic fibers [1].

2.2.2.4 Flexural strength

Plastic Aggregates

In most studies on the effect of plastic aggregates on flexural strength of concrete, was reported that the flexural strength of concrete decreases when substituting plastic aggregate instead of natural aggregate.

In one report, it was concluded that by replacing 5% 10% and 15% plastic aggregate instead of fine aggregate, the flexural strength decreases with the increase in the substitution level of any types of plastic aggregate [23].

Plastic Fibers

Flexural strength of the concrete containing plastic fibers are also tested in some studies. In one report, it was stated that with the addition of plastic fibers, the flexural strength of the resulted concrete decreases. The tests show that by increasing the content of plastic fibers from 5% to15%, the flexural strength decreases from 4 MPa to 3 MPa [24].

2.2.2.5 Abrasion resistance

Plastic aggregates

Abrasion resistance is an important feature when it comes to use recycled plastic aggregate instead of natural aggregate. Most results from the exciting studies show that using plastic aggregate can help this property of concrete to work better. It was stated in the report that; the use of recycled plastic coarse aggregate and fine aggregate improved the abrasion resistance of concrete [25]. The authors believe that this improvement can be reached from the fact that plastic aggregates are harder and have higher abrasion resistance compared to the natural aggregates.

Plastic Fibers

There was just very few information is accessible on the abrasion resistance performance of concrete containing plastic fibers.

One study reported that the abrasion resistance of concrete containing plastic fibers decrease compared to the conventional concrete and the authors found the reason of reduction is incorporation of plastic fiber in concrete [26].

2.3 LCA of concrete containing plastic

The LCA methodology is an excellent management tool for calculating the environmental impacts of the products as well as comparing the environmental aspects of alternative products. The LCA consists of four phases: (1) Goal and Scope Definition; (2) Inventory Analysis; (3) Impact Assessment; (4) Interpretation [27].

The existing literature on LCA of using plastics in concrete are limited. The LCA of plastic recycling or reusing are influenced by different factors such as, plastic sources, local procedures for gathering and reprocessing plastic waste and final products. Most available literature in this subject are conducted to analyze the environmental impacts of plastic fiber concrete.

In Table 2.2, the details of each study with the classification regarding the four phases of LCA are presented. The goal and the functional unit of the studies are presented, and the material usage and boundaries of the considered system are defined. The data inventory of each study is also shown in its related column and the result part of life cycle assessment is presented with the used method and assessed impact categories in each study, which helps to have better interpretation of comparisons.

Table 0.2. The details of the LCA studies regarding plastic concrete

REF	Goal	Functional unit	Materials	System boundary	LCI / Data Sources	LCIA					
						Method	Impact categories				
							Global warming (kg CO_2 eq)	Eutrophication (kg PO4 eq)	Fossil fuels (kg oil eq)	Water use (m3)	Energy (MJ)
[30]	Assessing the environmental impacts of four concrete reinforcing options	Reinforcing 100 m2 of concrete (10m×10m)	1)Producing SRM	Include all steps from the extraction, transportation of raw materials, fuels and conversion steps	SimaPro 8.0 Australian LCA databases, data from different companies and scientific publications	Australian Indicator Set V3.00	1250	1.09	245	20.9	
			2)Producing virgin PP				137	0.085	91.3	0.24	
			3)Recycling industrial PP waste	Begin with industrial and domestic PP waste products until they become fit for the purpose of recycled pp fibers			81.7	0.033	21.3	0.2	
			4)Recycling Domestic PP waste				109	0.069	32.1	0.99	
[31]	Comparing the carbon footprint of PP fibers reinforced concrete with steel reinforced concrete	Reinforcing 150,000 ft2 floor (13935.456 m2)	1) PP fibers reinforced concrete	manufacture, fabrication and site phases with the linked transportation	DEFRA/ DECC database ICE database, U.S. DOT, U.S. EPA and scientific publications	----	20550				
			2) steel reinforced concrete				46800				
[32]	Life cycle assessment DSF system with fiber reinforced concrete	Reinforcing 16 m2 of façade	SW, reinforced by steel rebar	Raw materials extraction, transportation, concrete production and system usage	Green Concrete LCA application, European studies	COMFEN Version 5	470				2726
			DSF from HP-G HyFRC				399				3758
			DSF + EPS				419				4200

Since, CO_2 emission within the concrete industry is a very wide practical, technical, political, and social challenge, many studies have concentrated in the possible ways of reducing the amount of CO_2 to find sustainable alternatives [33].

As can be seen from Table 2.2, the LCA results show that in general, using plastic fibers in concrete instead of steel rebars can have a significant impact in reducing the amount of carbon dioxide equivalent (CO_2 eq) and associated global warming potential (GWP). In the first study that was done by [30]. all three types of plastic fibers concrete have less CO_2 eq emissions compared to the steel reinforced concrete. Among these three types, comparing the best performing pp fibers to SRM, industrial pp fibers production emits CO_2 eq 15 times less than SRM production which can lead to 93% reduction in CO_2 eq. However, comparing virgin pp fibers with recycled pp fibers shows that in general in all impact categories except from water usage (producing domestic pp fibers use more water than the two other types of pp fibers), virgin PP fibers has higher environmental impacts than the recycled ones. However, the industrial recycled pp fibers produce 81.7 kg of CO_2 eq and use 23.1 kg oil where, the domestic pp fibers produce more CO_2 eq (109 kg) and 32.1 kg oil. These differences can be sourced from the more complex and energy intensive processes for domestic pp wastes that makes the recycled industrial pp fibers to be more sustainable choice [30].

The second study in Table 2.2 [31], Analyze the carbon foot print CO_2 eq of pp fiber reinforced concrete floor and steel reinforced concrete to use for 15 ft2 of floor. The LCA results determine that again, pp fiber has more superior in terms of less environmental impact from the CO_2 eq emissions side compared to the steel rebar. The CO_2 eq from producing pp fibers is 20550 kg where the amount of CO_2 eq related to the production of steel rebar is 46800 kg which is almost 56% higher than CO_2 eq from pp fibers production.

In the last study [32], where the three types of reinforcing the concrete façade are presented, the results indicate that, CO_2 eq of DSF are approximately 15 % less than that in the SW. This is related to the combined effects of using less material for the production of the DSF system, the relatively low CO_2 eq of PP fibers and glass fiber reinforced polymer (GFRP) fibers relative to their energy intensity, and the intensity of CO_2 eq of slag and fly ash as a replacement for cement in HP-G-HyFRC. However, the embodied energy in the production of DFS are nearly 38% greater than the energy usage in the production of SW and it can be due to the presence of fibers and high binder content in the HPG-HyFRC composite. In addition, comparing DSF containing air gap, with the DFS containing EPS as a filler material increase both embodied energy and embodied CO_2 eq by 11.7% and 5%, respectively.

2.4 Overall findings from the previous works

Many studies are conducted on the effect of using recycled plastic on concrete properties for both plastic aggregates and plastic fibers. However, there are a few studies that assess the environmental impacts of concrete containing recycled plastic materials.

A brief overview of the common changes in fresh state- and mechanical properties of concrete by inclusion of plastic is given in Tables 2.3 and 2.4, respectively. This overview is the overall expectation and can be different in specific experimental conditions. The results show that in most cases concrete containing plastic aggregates or plastic fibers has lower slump compared to the conventional concrete. The slump value is an important property of the fresh concrete and the demanded value may vary from case to case. Although reduction in slump can be challenging for many cases, this challenge can usually be overcome by using admixtures such as superplasticizers. These admixtures are basically water-based solutions, which are usually used in a very low amount. For example, the dry matter of the consumed solution can be lower than 0.02% of the concrete weight, so they will usually not have a considerable negative impact on environmental assessment of the concrete. However, they can improve the concrete properties, which may be even positive for the environment.

Concerning the density, this is a fact that plastic aggregates are lighter than natural aggregates and therefore, the plastic aggregate concrete have lower density than conventional concrete. Furthermore, it is observed that plastic fibers do not usually have a visible impact on the density of concrete due to low volumetric consumption compared to using plastics as aggregate.

Due to the lower density of plastic aggregates compared to the other major particles in concrete, more air bubbles may be produced during mixing of concrete containing plastic aggregates, which leads to higher air content compared to the conventional concrete. If the volumetric content of plastic fibers is low (for example less than 0.3 vol%), it may not have a significant impact on the air content of concrete. However higher volumetric amount of plastic fibers can increase the air content compared to conventional concrete. Higher air content can be desirable for thermal insulating concrete or for increasing the ability to tolerate freeze and thaw cycles. On the other hand, higher air content can reduce compressive strength, which may be challenging for some applications. Similar to the case of using superplasticizers for adjusting the slump, air detraining admixtures can also be used in low amount to reduce air content.

It can be found from the Table 2.4 that, the compressive strength, split tensile strength, elastic modulus and flexural strength of concrete containing plastic aggregates will usually decrease with the increase in the substitution level of plastic aggregates. The reason can be the lower elastic modulus of plastic aggregates compared to natural aggregates and low relative strength in the interface between the cement paste and the plastic aggregates. Due to hydrophobic nature of plastic aggregate, the surface between plastic aggregate and hardened cement is the weak part of the composite because of low amount of water accessible to cement and thus low hydration degree in this zone. Functionalization of the surface of plastic aggregates can be a solution for this challenge, which can be mentioned as the future research potential.

On the other hand, concrete containing plastic fibers have shown higher compressive strength, splitting tensile strength and flexural strengths compared to conventional concrete, when concrete contains a small amount of fibers (for example less than 1 vol%). Increasing the plastic fiber content has mainly led to decrease the mechanical properties of concrete. Moreover, the elastic modulus of concrete containing plastic fibers does not have a significant difference compared to that in conventional concrete.

Table 0.3. Prevailing changes in the properties of fresh concrete containing plastic compared to conventional concrete

Concrete Properties	**Slump**	**Density**	**Air content**
Plastic aggregates	Lower	Lower	Higher
Plastic fibers	Lower	No significant difference	High amount: Higher Low amount (f.ex.< 0.3 vol%): No significant difference

Table 0.4. Prevailing changes in the properties of hardened concrete containing plastic compared to conventional concrete

Concrete Properties	**Compressive strength**	**Split tensile strength**	**Elastic modulus**	**Flexural strength**	**Abrasion resistance**
Plastic aggregates	Lower	Lower	Lower	Lower	Higher
Plastic fibers	Can be higher	Usually higher	No significant difference	Usually higher	Lower

The overall results in the reviewed literature reveals that, using low amount of recycled plastic fibers in concrete can improve the mechanical properties of conventional concrete. On the other hand, recycled plastic aggregates have weaker mechanical properties. This type of concrete can be compared to lightweight concrete, where the mechanical properties are usually weaker than normal concrete, but they have different structural and non-structural applications taking the advantage of their low density. When considering the structural applications, it is noteworthy that, since the concrete containing plastic aggregates has lower weight compared to the conventional concrete, the forces applied on the structural elements (like own weight, wind and earthquake forces), are also lower compared to structures containing conventional concrete, which can be a compensation for the weaker mechanical properties. On the other hand, combination of lightweight concrete with conventional concrete in one structural element (layered element) can be the other solution, because the stresses in structural elements are not constant. The conventional concrete can be used where there is higher stress and lightweight concrete can be used where there is lower stress. This can result in a more efficient material consumption compared to using one type of material in the structural element.

Furthermore, the mechanical properties are not the dominating property when using concrete for non-structural applications (such as flooring or insulation), which can be suitable application areas for using recycled plastic in concrete. The fresh properties such as air content and slump are also the properties that are adjustable by using different admixtures and additives. For example, in the case of concrete casting for industrial floors, if self-consolidating concrete is demanded, using more superplasticizer and fine particles could compensate the low slump value as well as separation risk. Thus, the challenges with fresh properties are possible to overcome using the concrete technology knowledge.

On the other hand, when it comes to the environmental aspects, plastic concrete plays a more significant role for decision making. As can be seen in Table 2.2, using recycled plastic fibers as a reinforcement option, is beneficial for the environment compared to using steel. In addition, a comparison between industrial recycled plastic fibers and domestic recycled plastic fiber shows that industrial fibers have priority to be uses by considering environmental issues. It is noteworthy that the greenhouse gas emissions within concrete industry is a serious challenge and using alternative materials can help overcoming this challenge. Furthermore, recycling plastic can make a significant effect on increasing sustainability of plastic industry.

Since plastic aggregates are used in a much higher volume compared to plastic fibers in concrete, the possible environmental benefits of are also expected to be more significant than the case of using plastic fibers. However, proper and reliable LCA study on the effect of incorporating plastic aggregates into concrete as an alternative to waste treatment methods such as landfill and incineration was not observed during this review process. Therefore, this master thesis, addresses LCA of concrete containing different amounts of RPA as an alternative for waste plastic treatment.

3. Methodology

An LCA methodology is conducted for this thesis to evaluate the environmental impacts of concrete containing RPA. According to ISO:14040 /44 [27, 29], LCA is a tool for assessing the environmental aspects and potential environmental impacts of a product or a process throughout its life cycle from the acquisition of raw material, production phase, use phase and end of life treatment. The most important applications within an LCA study can be the improvements in products or processes from the environmental perspective or can be a comparison between products to identify the appropriate choice.

As it is shown in Fig. 3.1, an LCA study's framework consists of four following stages [27]:

Step 1: Goal and scope definition: In this step, the purpose of the study along with the intended application and the intended audience are defined. The scope of the study will also describe determining the functional unit and system boundary under the study.

Step 2: LCI analysis: Inventory analysis gives a description of all input/output data for a given product system or a single process throughout its life cycle. The LCI includes compilation and quantification of the data align with the goal and scope criteria.

Step 3: LCIA: The Life Cycle Impact Assessment classify and evaluates the number of environmental impacts arising from the LCI. The LCI data are first assigned to impact categories, and their potential impacts then measured based on the characterization factors.

Step 4: Interpretation: The interpretation phase is the final step, where the results are checked and evaluated to be sure that they satisfy the requirements of the goal and scope. A critical review then provides the basis for decision making and recommendations.

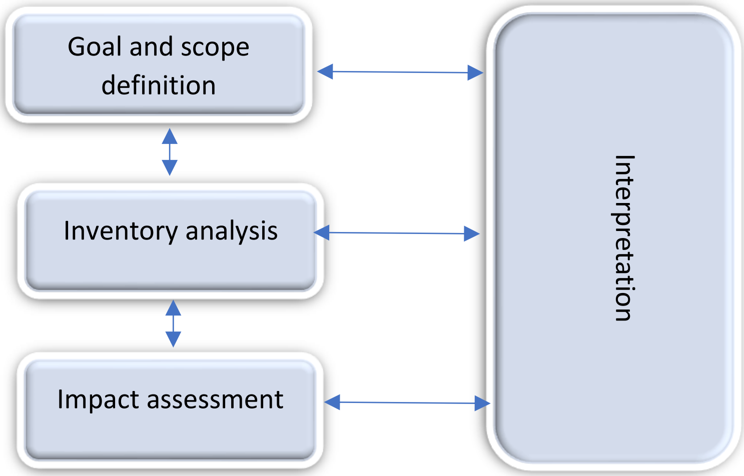

Fig. 0.1. LCA framework according to ISO:14040

3.1 Goal and Scope

The goal of this study is to identify the environmental impacts of concrete containing recycled PET bottles as fine aggregate by incorporation of different amounts of RPA while having same compressive strength (30 MPa). Concrete proportioning or mix design is the determination of the amount of each component of the mix in order to achieve specific material property, which is mainly compressive strength when dealing with mechanical properties. Since concrete is made of various components, each designer may end up with a different amount of component to achieve the targeted compressive strength. While concrete is one of the most consumed building materials in the world and has a significant contribution to the greenhouse gas emissions making even small changes in the design phase can make a considerable change on environmental impacts globally.

The results of the study can be used by the plastic recycling industry, concrete mix designers, contractors, environmental advisors as well as owners and clients.

3.1.1 Functional unit

The function of the product is to use the concrete containing RPA for flooring purposes as a non-structural application. The focus will be on the effect of changes in the portion of RPA on the environmental impacts for making one cubic meter of concrete with a compressive strength of 30 MPa.

3.1.2 System boundary

The scope of this cradle to gate LCA study is limited to the production of fresh concrete and therefore, does not include the environmental impacts of use phase and end-of-life disposal of the concrete.

The process involved in this system boundary starts from the transportation of waste PET bottles to the plastic recycling factory. After washing and shredding steps in the recycling factory, the shredded PETs are then mixed with the powder of river sand to be formed as plastic aggregates. The ready RPA as well as other concrete components (like cement, sand and gravel) are transported to the concrete production to produce concrete containing RPA (See Fig. 3.2). European condition is considered as the geographical boundary for providing raw materials as well as concrete production.

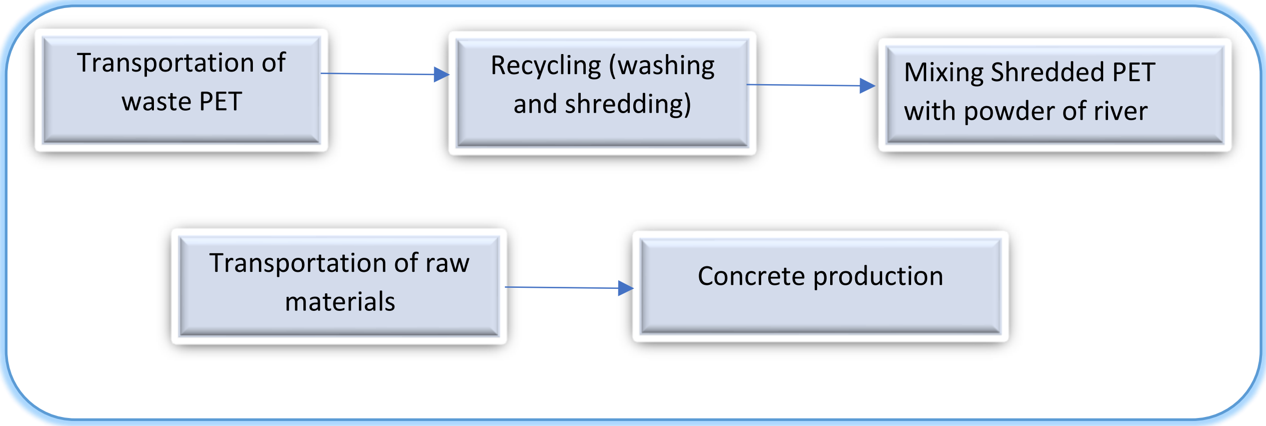

Fig. 0.2. System boundary of the study

3.1.3 Assumptions and limitations

- The Euro 6 lorry with capacity more than 32 metrics ton is considered for transportation of waste PET bottles from the waste reception gate to the recycling factory with the average distance of 100 Km.
- The Euro 6 lorry with capacity between 16-32 metrics ton is considered for transportation of RPA from the recycling factory to the concrete production factory with the average distance of 100 Km.

- The Euro 6 lorry with capacity between 16-32 metrics ton is considered for transportation of cement, sand and gravel to the concrete production factory with the average distance of 100 Km.
- It was assumed that, the mixing facility is situated close to the recycling facilities and therefore, there is no need for extra transportation.

3.2 Inventory analysis

This LCA study follows the ISO 14040/44 methodology. The LCA modelling is carried out in SimaPro V.8.5.2.0. The method used for estimating the environmental impact is ILCD 2011 Midpoint+ and main database is Ecoinvent 3. The LCI data have been taken from the European data**.** The inventory analysis for this study is divided into two parts; Concrete mix design and Unit processes.

3.2.1 Concrete mix design

In order to compare concrete mixes containing different amount of RPA, it is necessary to obtain reliable experimental data. Concrete samples are usually cured in water for 28 days to allow the cement to harden. The samples are then tested for compressive strength. To find a mix composition, which results in an exact value of compressive strength, one approach is to modify the mix design based on the result of compressive strength test and repeat the experiment to find the intended value. This process can be time consuming because each modification step needs 28 days of waiting for curing. The other approach is to cast different mixes at the same time and find the intended value by interpolating the results. This approach is common in testing concrete and for example cement producers extract curves for compressive strength of their products at different ages and different W/C ratio to deliver as datasheet to their customers. Changing the amount of RPA in concrete can change the compressive strength and in order to keep the compressive strength constant, W/C can be adjusted (and vice versa). Having a wide range of experimental results can facilitate extracting data for the intended compressive strength.

Preparing PRA from waste plastics as well as preparing and testing concrete samples needs proper time and specific laboratory facilities. Moreover, possible post measurement experiments due to unexpected laboratory results can lead to a high risk for time management of this Master thesis, thus, the results from an existing experimental investigation will be considered to provide the data for LCA study. To provide reliable data, existing literature from well-known authors in highly ranked peer-reviewed journals were evaluated and one of the extensive experiments by Choi et al. [10], who has conducted different relevant studies was selected as the basis for LCA work. Reliable reports from experimental investigations are considered to be repeatable and it is expected that repeating the experiment in the other laboratories under the reported condition would give similar results.

The selected experimental work has investigated three types of concrete with different W/C which include different portions of RPA as replacement for fine aggregates (0%, 25%, 50%, 75%) resulting in different measured compressive strengths. To have a fair environmental impacts comparison between different types of concrete mixes containing RPA, one cubic meter of each type of concrete having compressive strength of 30 MPa are considered as an evaluation basis in the present study.

The materials used in the experiments were cement, crushed stone (as gravel), sand, RPA and an air entrainment water reducing agent (AEWRA). The chosen cement is ordinary Portland cement, with the density of 3150 kg/m^3. The coarse aggregates were crushed stone, with the density of 2690 kg/m^3. The density of sand and RPA were 2600 kg/m^3 and 1390 kg/m^3, respectively. An AEWRA with a 1.2 ± 0.02 g/cm^3 density and pH 7.0 ± 1.0 was also used in the mixes.

To have a better understanding of how the mix designs of the studied concrete mixes have been analysed from the reference study [10], the steps for extracting intended mix designs are described below:

1. In the first step, the compressive strength of each concrete mix is extracted from the reference article [10] and presented in Tables 3.1 to 3.3.

Table 0.1. Compressive strength of mixes containing different portions of RPA with W/C= 0.53 [10]

W/C	RPA (%)	Compressive strength (MPa)
0.53	0	31.5
	25	28.5
	50	26
	75	22

Table 0.2. Compressive strength of mixes containing different portions of RPA with W/C= 0.49 [10]

W/C	RPA (%)	Compressive strength (MPa)
0.49	0	34.5
	25	33.5
	50	29
	75	23.5

Table 0.3. Compressive strength of mixes containing different portions of RPA with W/C= 0.45 [10]

W/C	RPA (%)	Compressive strength (MPa)
0.45	0	37.5
	25	34
	50	32
	75	27

2. The second step is drawing the diagram of compressive strength against the portion of RPA for each W/C, which is shown in Figs. 3.3 to 3.5.

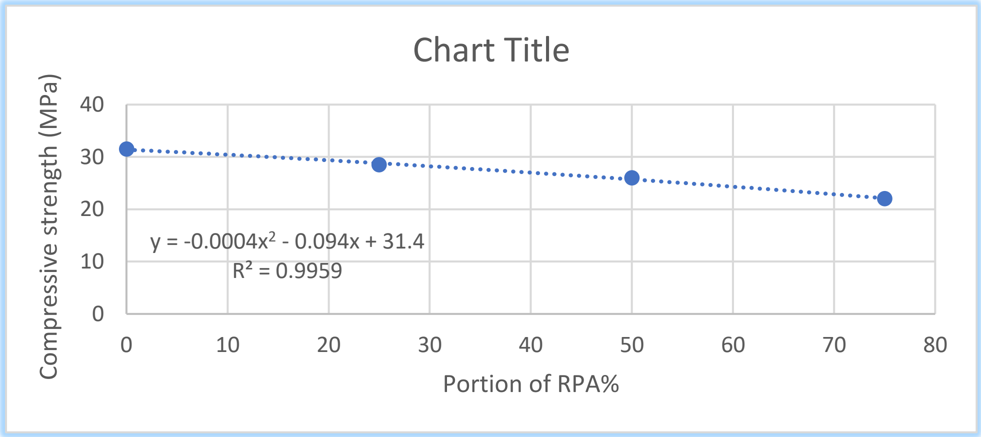

Fig. 0.3. Compressive strength of concrete with different portion of RPA and W/C= 0.53

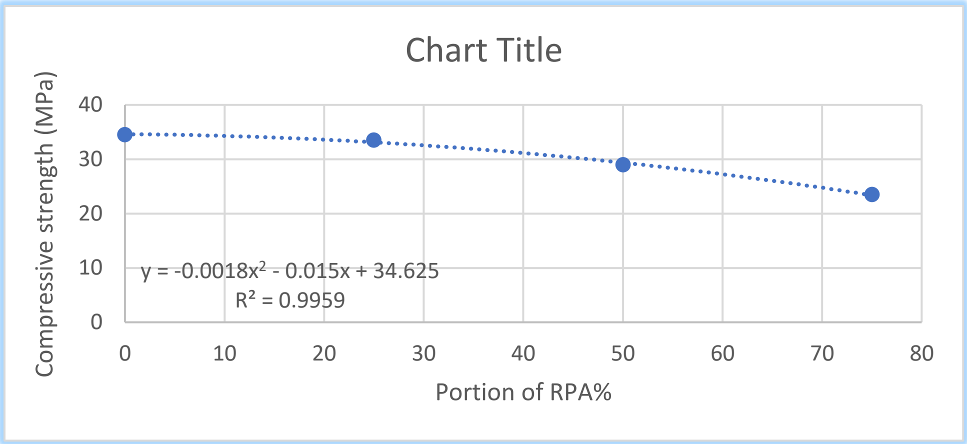

Fig. 0.4. Compressive strength of concrete with different portion of RPA and W/C= 0.49

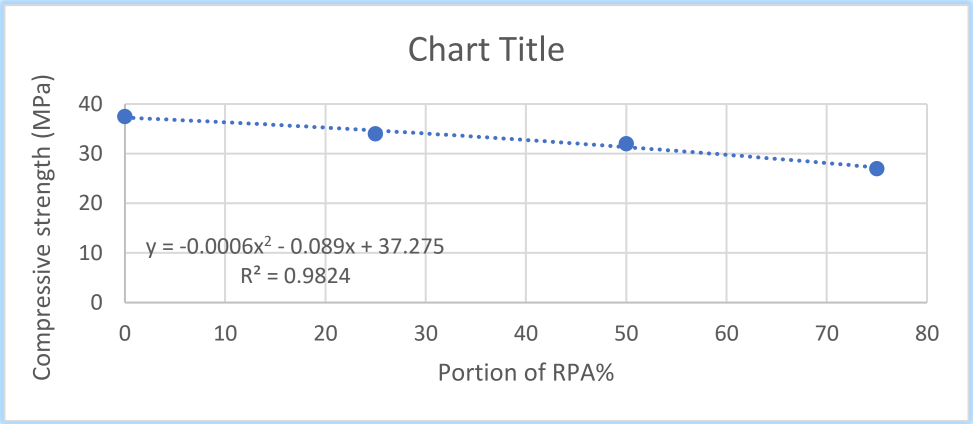

Fig. 0.5. Compressive strength of concrete with different portion of RPA and W/C= 0.45

3. Since Figs. 3.3 to 3.5, all cover the 30MPa compressive strength, the equivalent portion of RPA for compressive strength of 30MPa, can be interpolated from these figures (see Table 3.4).

Table 0.4. Portions of the RPA with different W/C corresponding to 30MPa compressive strength

Compressive strength (MPa)	**W/C**	**RPA (%)**
30	0.53	14
	0.49	47
	0.45	58

4. Determination of the weight portion of each component in the mixes for the LCA study is the next step. The mix design is conducted based on the particle-matrix model, which is a common approach for concrete proportioning and is in alignment of the existing data for the selected experimental work. (NB: Detailed analysis for the case of W/C= 0.53 and RPA 14% will be described in detail followed by the final results for the other two concrete mixes i.e. W/C=0.49 and W/C=0.45)

4.1. To calculate the amount of coarse aggregates, the diagram of the mass of coarse aggregate to the portion of RPA in fine aggregate is drawn based on the data in Table 3.5 from the reference article [10].

Table 0.5. The amount of coarse aggregate for different portion of RPA and W/C= 0.53 [10]

W/C	RPA (%)	Gravel (kg)
0.53	0	930
	25	885
	50	840
	75	786

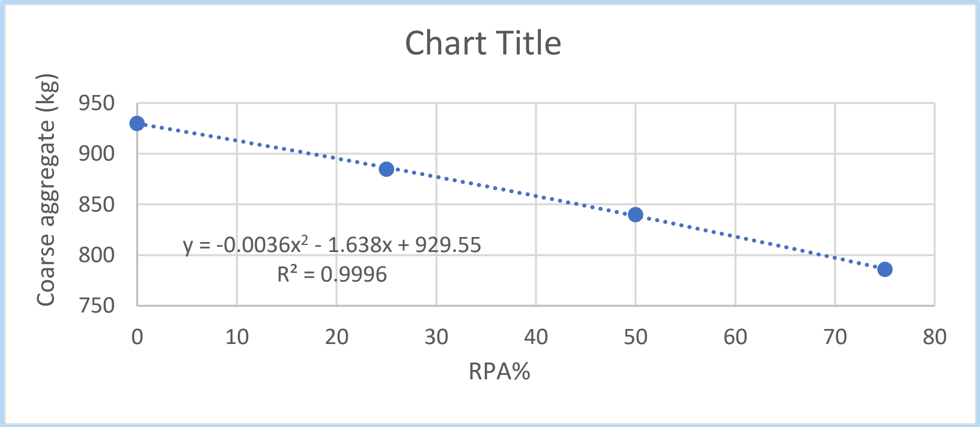

Fig. 0.6. The amount of coarse aggregate for concrete mixes with W/C=0.53

As illustrated in Fig. 3.6, for W/C= 0.53 (RPA= 14%), the amount of coarse aggregates is 905.91 kg and giving a volume of: 905.91 (kg) / 2690 (kg/m^3) = 0.3367 m^3

4.2. In order to find the mass of fine aggregates, the volume of fine aggregates needs to be calculated. Summing up the volume (Total volume: Mass(Sand)/2600+ Mass(RPA)/1390+ Mass(Gravel)/2690) of both fine aggregate and coarse aggregate for each concrete present nearly similar results, therefore, 0.67 m^3 of the total volume of concrete is selected for the aggregate volume (See Table 3.6).

Table 0.6. Total volume of aggregate used for concrete mixes with W/C= 0.53 [10]

Sand (kg)	RPA (kg)	Gravel(kg)	Total volume (m^3)
844	0 (0 %)	930	0.6703
665	119 (25%)	885	0.6704
465	249 (50%)	840	0.6703
246	394 (75%)	786	0.6703
		selected	0.6703

Based on the selected total volume and the volume of gravel for 14% RPA, the volume of fine aggregate can be calculated (accurate calculation with more decimals are carried out in Excel):

$$0.6703\ m^3 - 0.33676\ m^3 = 0.33354\ m^3$$

While 14% of the volume of fine aggregate is RPA, therefore, the volume of RPA is equal to:

$$14\% * 0.33354\ m^3 = 0.04669\ m^3$$

Consequently, the volume of sand would be:

$$0.33354\ m^3 - 0.04669\ m^3 = 0.2868\ m^3$$

By multiplying the volume of RPA and sand to their density, the following amount of RPA and sand are determined.

Mass of RPA for concrete mixes with W/C= 0.53:

$$0.04669\ m^3 * 1390\ kg/m^3 = 64.9\ kg$$

Mass of Sand for concrete mixes with W/C= 0.53:

$$0.2868\ m^3 * 2600\ kg/m^3 = 745.7\ kg$$

The same trend is then performed for the two other concrete mixes, and the results are given in the following.

Table 0.7. The amount of coarse aggregate for different portion of RPA and W/C= 0.49 [10]

W/C	RPA (%)	Gravel (kg)
0.49	0	939
	25	895
	50	850
	75	797

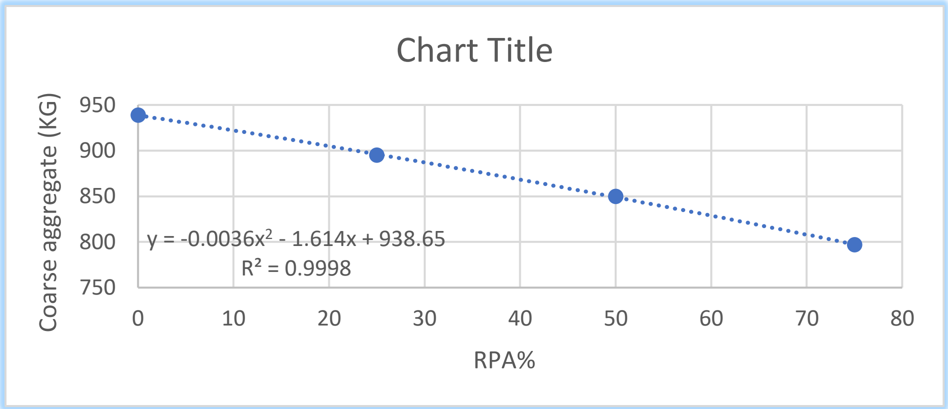

Fig. 0.7. The amount of coarse aggregate for concrete mixes with W/C=0.49

Mass of Gravel for concrete mixes with W/C 0.49= 855.04 kg

Mass of RPA for concrete mixes with W/C 0.49= 222.54 kg

Mass of Sand for concrete mixes with W/C 0.49= 469.40 kg

Table 0.8. The amount of coarse aggregate for different portion of RPA and W/C= 0.45 [10]

W/C	RPA (%)	Gravel (kg)
0.45	0	941
	25	906
	50	854
	75	802

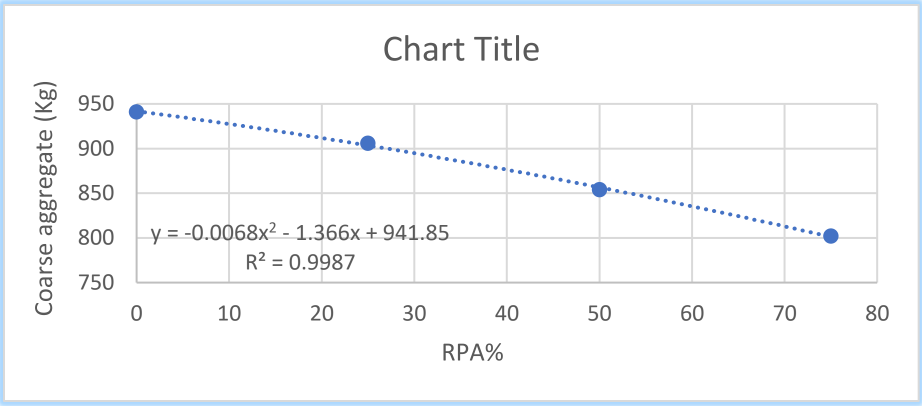

Fig. 0.8. The amount of coarse aggregate for concrete mixes with W/C=0.45

Mass of Gravel for concrete mixes with W/C 0.45= 836.75 kg

Mass of RPA for concrete mixes with W/C 0.45= 270.43 kg

Mass of Sand for concrete mixes with W/C 0.45 = 366.30 kg

5. The next step is mix design of the reference concrete

5.1. In order to design the new reference concrete with 0% RPA, the diagram of W/C to the compressive strength is drawn, and the corresponding value of W/C for compressive strength of 30 MPa is determined as 55 (W/C= 0.55). (See Table 3.9 & Fig. 3.9)

Table 0.9. Compressive strength of the reference concrete with the different W/C [10]

W/C	Compressive strength (MPa)
0.53	31.5
0.49	34.5
0.45	37.5

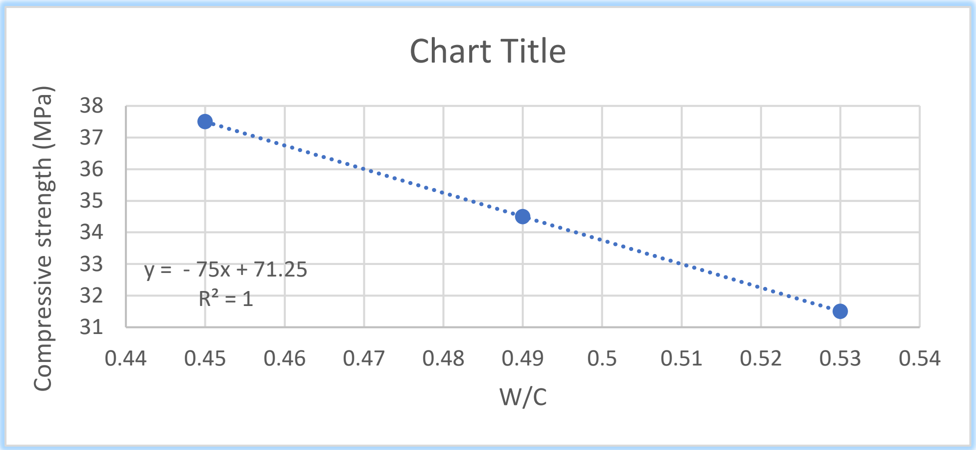

Fig. 0.9. Compressive strength of the reference concrete for different W/C

5.2. In the next step, the matrix volume for the new reference concrete needs to be calculated. First, from the data for mass and density of water and cement in the reference article [10], the matrix volume of each concrete type was calculated (See Table 3.10). Then the diagram of matrix volume to the W/C was drawn (See Fig. 3.10). The corresponding matrix volume of W/C= 0.55 is found to be equal to 0.279 m^3. Therefore, the amount of water and cement for the new reference concrete can be calculated as 176.9 kg and 321.6 kg, respectively. The amount of AEWRA is equal to 0.003 of cement mass; hence, it would be equal to 0.965 kg.

Table 0.10. The matrix volume data for the reference concretes

W/C	**Cement mass (kg)**	**Water mass (kg)**	**Matrix volume (m^3)**
0.53	336	178	0.285
0.49	367	180	0.297
0.45	492	181	0.309

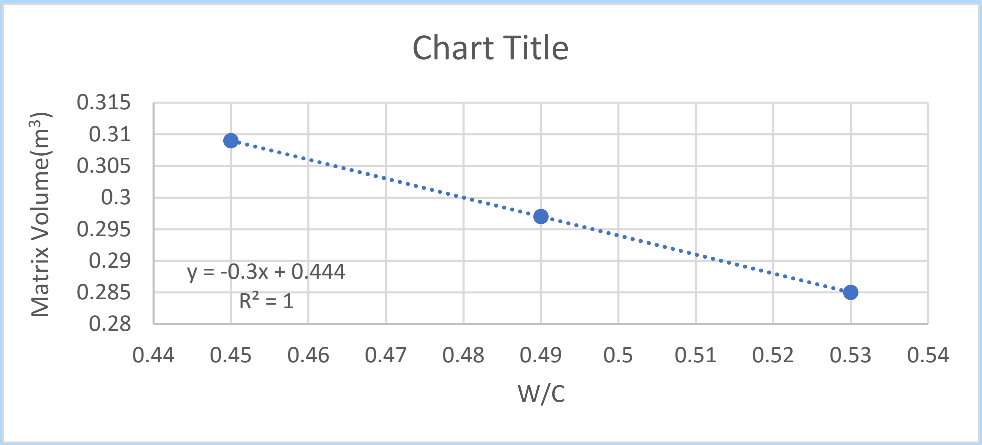

Fig. 0.10. The matrix volume of the concretes with different W/C

5.3. In the next part, the ratio of sand mass to the gravel mass was calculated for each reference concrete in the article and the diagram of the sand mass/gravel mass against the W/C was drawn (See Table 3.11 & Fig. 3.11). Therefore, from Fig. 3.11, the ratio sand mass/gravel mass for the W/C= 0.55 is 0.9854 and the mass of sand and gravel for the reference concrete with compressive strength of 30MPa is determined as 887.3 kg and 900.4 kg respectively

Table 0.11. The ratio of sand mass to gravel mass for each reference concrete

W/C	Sand mass (kg)	Gravel mass (kg)	Sand mass/ Gravel mass
0.53	844	930	0.907527
0.49	805	939	0.857295
0.45	771	941	0.819341

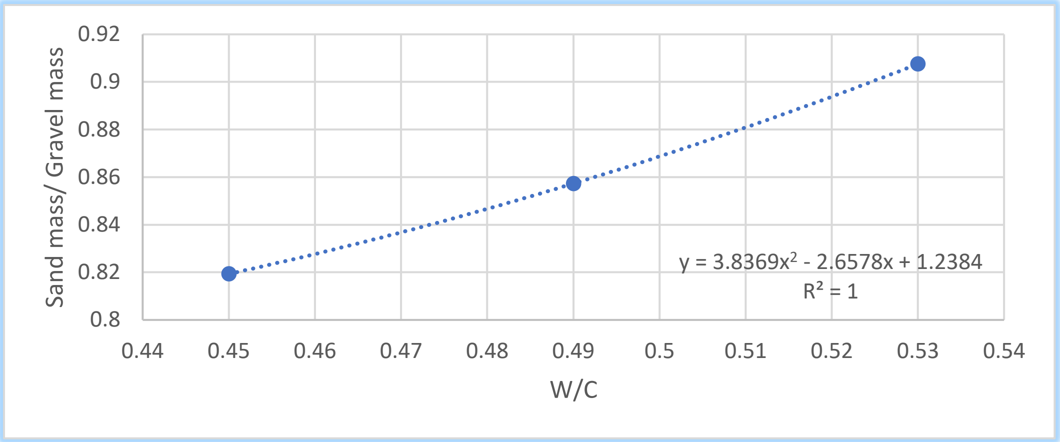

Fig. 0.11. The mass ratio of sand to gravel for different W/C

6. The amounts of water and cement are the same as experimental series in the concrete mixes containing RPA with compressive strength of 30MPa and this data is calculated for the reference concrete. The table below shows the mix design of the concrete mixes for LCA study.

Table 0.12. The mix design data for the four types of concrete mixes for LCA study

Mix label	**W/C**	**RPA/ (RPA+ Sand) (%)**	**Unit weight (kg/m³)**					
			water	cement	Sand	RPA	Gravel	AEWRA
Reference	0.55	0	176.9	321.6	887.3	0	900.4	0.965
Type 1	0.53	14	178	336	745.77	64.90	905.91	1.008
Type 2	0.49	47	180	367	469.40	222.54	855.04	1.101
Type 3	0.45	58	181	402	366.30	270.43	836.74	1.206

3.2.2 Unit processes

The system under the study consists of three different unit processes, recycling, mixing and concrete production. The following Figures show the inputs and outputs for each unit process.

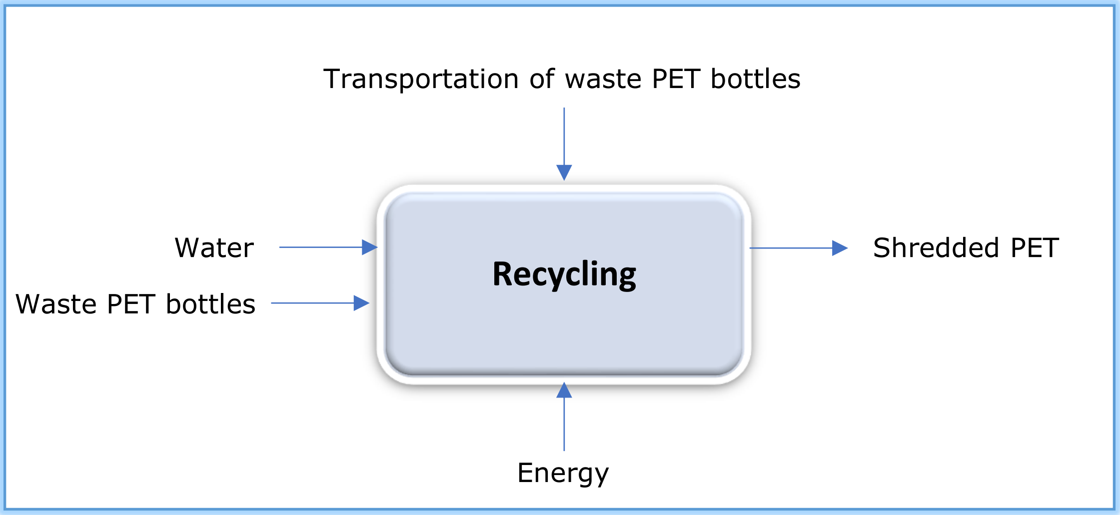

Fig. 0.12. The inputs and outputs for recycling process

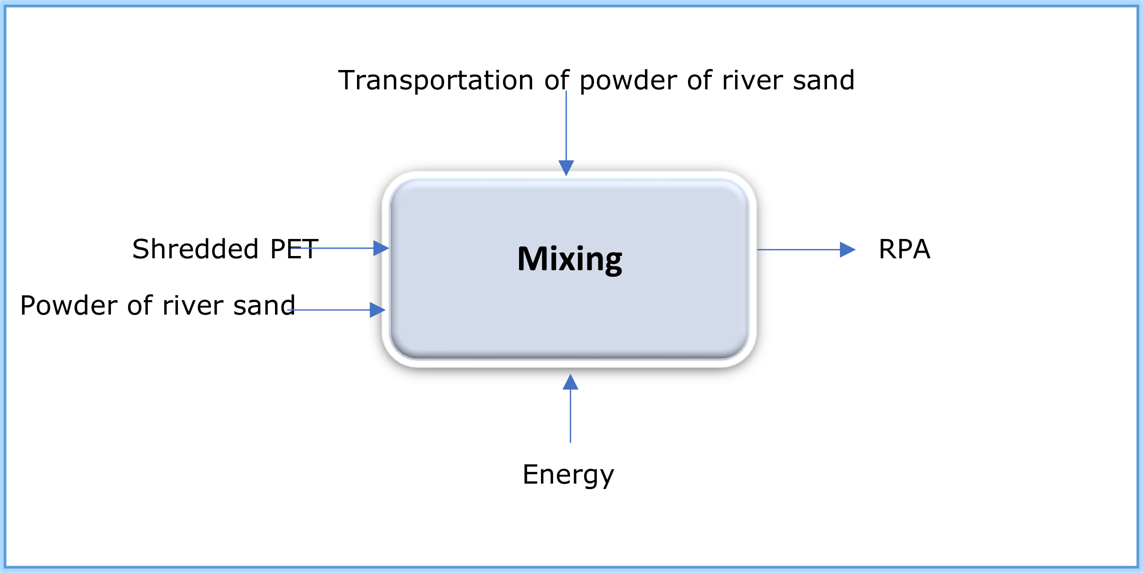

Fig. 0.13. The inputs and outputs for mixing process

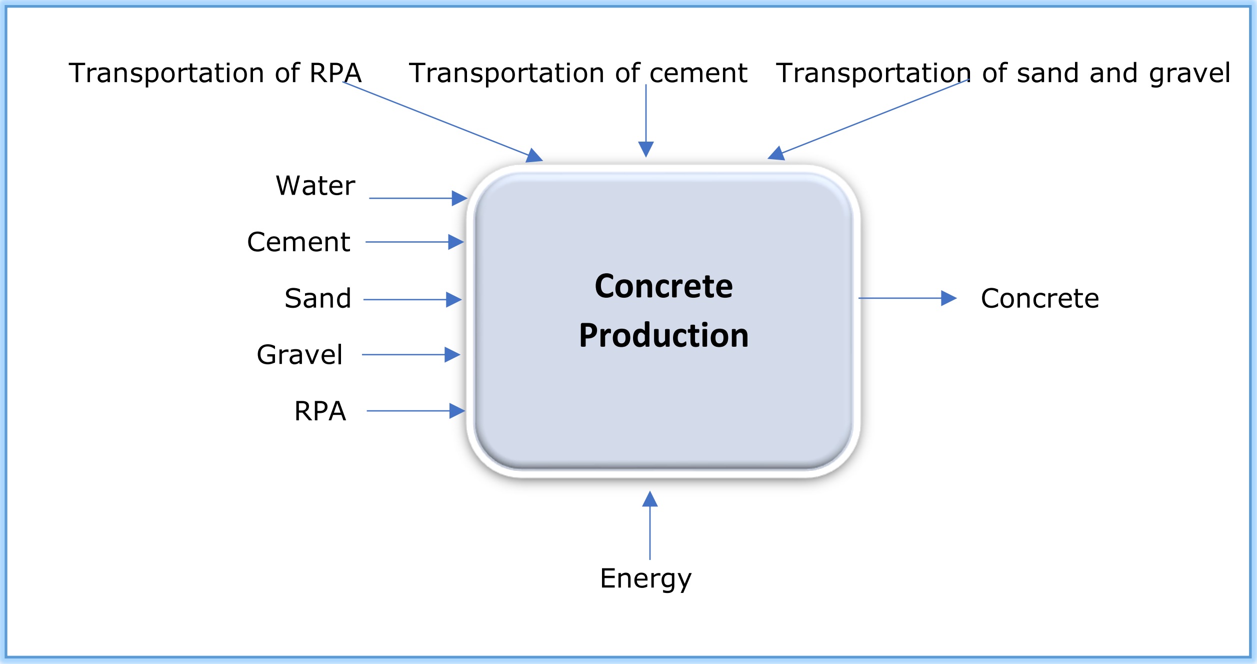

Fig. 0.14. The inputs and outputs for concrete production process

Considering the above unit processes, waste PET bottles were transported from the waste reception gate to the recycling factory. After washing and shredding in the recycling machine, the shredded PET was sent to the mixing sector for coating with river sand powder (to improve the quality of aggregate and especially its fire resistant) and being prepared for use as aggregate in concrete. Then, the ready RPA were sent to the concrete production factory, where the specific amount of each concrete component based on the different mix designs, were added to the mixer and after a determined mixing time, the final product (1 m^3 of concrete) is ready.

Before starting the description of unit processes, the amount of required waste PET bottles needs to be calculated for the three concrete mixes. 15% of ready RPA is powder of river sand[10], and therefore, the amount of RPA without river sand powder is 0.85% of the mas of RPA, which is equal to the amount of shredded waste PET. Moreover, during the recycling process, 7% scrapes are produced from the washing and shredding stages [34].

3.2.2.1 Recycling

The recycling system selected for this experiment combines both washing and shredding processes into one recycling machine. A PET washing recycling machine from BOGDA company with 1000 kg/h capacity, is considered for calculating energy and water consumption. The power consumption of the machine is 200 KW, and the consumption water is around 5.5 tons/h. The machine can cut the waste PET into quadrilateral shapes approximately 5-15 mm in size. The information concerning technical details for this machine is given in Appendix A.

Waste PET bottles are considered as waste; therefore, the environmental impacts of this material are considered to be zero for incorporation into concrete. Tables 3.13 to 3.15 present the inventory data for the recycling process to produce 56.439, 193.5134, 235.159 kg of Shredded PET respectively for the concrete type 1 to type 3.

Table 0.13. The inventory data for recycling process to produce 56.44 kg of shredded PET for concrete type 1

	Data	Assumptions and data sources	Input in Simapro
Processes	333.779 kg water	The recycling machine from BOGDA company (Appendix A)	Tap water (Europe without Switzerland) | market for | Alloc Rec, U
	12.137 kwh electricity	The recycling machine from BOGDA company (Appendix A)	Electricity, medium voltage (Europe without Switzerland) | market group for | Alloc Rec, U
	6068.7 Kgkm of waste PET transport	Assumption of the average distance. Transporting facility based on the literature [35]	Transport, freight, lorry >32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
Waste treatment	4.25 kg scrapes	Estimated based on the literature [34]	Waste polyethylene terephthalate (RoW)| market for waste polyethylene terephthalate | Alloc Rec, U

Table 0.14. The inventory data for recycling process to produce 193.61 kg of shredded PET for concrete type 2

	Data	Assumptions and data sources	Input in Simapro
Processes	1144.437 kg water	The recycling machine from BOGDA company (Appendix A)	Tap water (Europe without Switzerland) | market for | Alloc Rec, U
	41.616 kwh electricity	The recycling machine from BOGDA company (Appendix A)	Electricity, medium voltage (Europe without Switzerland) | market group for | Alloc Rec, U
	20807.9 Kgkm of waste PET transport	Assumption of the average distance. Transporting facility based on the literature [35]	Transport, freight, lorry >32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
Waste treatment	14.565 kg scrapes	Estimated based on the literature [34]	Waste polyethylene terephthalate (RoW)| market for waste polyethylene terephthalate | Alloc Rec, U

Table 0.15. The inventory data for recycling process to produce 234.52 kg of shredded PET3 for concrete type 3

	Data	Assumptions and data sources	Input in Simapro
Processes	1390.727 kg water	The recycling machine from BOGDA company (Appendix A)	Tap water (Europe without Switzerland) | market for | Alloc Rec, U
	50.572 kwh electricity	The recycling machine from BOGDA company (Appendix A)	Electricity, medium voltage (Europe without Switzerland) | market group for | Alloc Rec, U
	25286 Kgkm of waste PET transport	Assumption of the average distance. Transporting facility based on the literature [35]	Transport, freight, lorry >32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
Waste treatment	17.700 kg scrapes	Estimated based on the literature [34]	Waste polyethylene terephthalate (RoW)| market for waste polyethylene terephthalate | Alloc Rec, U

3.2.2.2 Mixing

A laboratory mixer machine called Bitumix, was selected for mixing the river sand powder and shredded PET. The selected machine is an automatic laboratory mixer with 30-litre capacity and adjustable mixing speed from 5 to 35 round per minutes (rpm) which can increase the mixing temperature up to 250 °C. The information concerning technical details for this machine is given in Appendix A.

In the mixing process, powder of river sand (the pass in the 0.15 mm sieve were designated as river sand powder [10] was put into the mixer and rotated at around 30 rpm while heated to 250 °C. The shredded PET then were added into the mixer and rotated more than 5 minutes at around 30 rpm [10]. The total mixing time is considered 12 minutes. The following Tables (3.16, 3.17 and 3.18) present the data for the mixing process.

Table 0.16. The inventory data for the mixing process to produce 64.90 kg of RPA for concrete type 1

	Data	**Assumptions and data sources**	**Input in Simapro**
Processes	8. 466 kg river sand powder	Calculated based on the reference article [10]	Sand (GLO)| market for | Alloc Rec, U
	56.439 kg of Shredded PET produced for concrete type 1	Calculated based on the reference article [10]	Shredded PET produced for concrete type 1
	1.693 kwh electricity	Bitumax automatic mixer (Appendix A)	Electricity, medium voltage (Europe without Switzerland) | market group for | Alloc Rec, U
	169 kgkm transportation of river sand powder	Assumption of the average distance and transport facility.	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 (GLO)| market for | Alloc Rec, U

Table 0.17. The inventory data for mixing process to produce 222.655 kg RPA for Concrete type 2

	Data	**Assumptions and data sources**	**Input in Simapro**
Processes	29.027 kg river sand powder	Calculated based on the reference article [10]	Sand (GLO)| market for | Alloc Rec, U
	193.613 Kg of Shredded PET produced for concrete type 2	Calculated based on the reference article [10]	Shredded PET produced for concrete type 2
	5.805 kwh electricity	Bitumax automatic mixer (Appendix A)	Electricity, medium voltage (Europe without Switzerland) | market group for | Alloc Rec, U
	581 kgkm transportation of river sand powder	Assumption of the average distance and transport facility.	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 (GLO)| market for | Alloc Rec, U

Table 0.18. The inventory data for mixing process to produce 269.695 kg of RPA for concrete type 3

	Data	Assumptions and data sources	Input in Simapro
Processes	35.274 kg river sand powder	Calculated based on the reference article [10]	Sand (GLO)| market for | Alloc Rec, U
	234.517 Kg of Shredded PET produced for concrete type 3	Calculated based on the reference article [10]	Shredded PET produced for concrete type 3
	7.058 kwh electricity	Bitumax automatic mixer (Appendix A)	Electricity, medium voltage (Europe without Switzerland) | market group for | Alloc Rec, U
	704 kgkm transportation of river sand powder	Assumption of the average distance and transport facility.	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 (GLO)| market for | Alloc Rec, U

3.2.2.3 Concrete production

The key materials in the concrete mixes were water, cement, gravel, sand, RPA (transported from recycling factory to the concrete production factory), crushed stone and an AEWRA. The water source was tap water and the cement was ordinary Portland cement. The coarse aggregates were crushed stone and the fine aggregates were sand as well as RPA. A commercial AEWRA was also used in the mix design.

For mixing concrete, Zyklos Rotating Pan Mixer with 500-litres capacity is selected to evaluate the energy. The electricity consumption of the mixer is 5.5 kWh. The information concerning technical details for this machine is given in Appendix A.

The mixing process consists of the following steps:

1. Dry materials such as cement and aggregate are mixed for 1 minute
2. Water and liquid admixtures such as superplasticizer are added in an interval of 30 seconds and then mixing continues for 2 minutes
3. Rest for 2 minutes
4. Mixing for 1.5 minutes

This process results in a mixing duration of 5 minutes. Thus, the total energy for mixing 1 m3 of concrete is calculated as:

$5.5\ (kW) \times 2 \times (5/60)\ (h) = 0.916\ kWh$

Table 3.19- 3.22 show which data resources have been used in the concrete production for four different concrete mixes. Since the amount of AEWRA in these four concrete mixes is

much lower than 5% (the cut off criteria of the study), the environmental impacts of this material are disregarded.

Table 0.19. Inventory data for concrete production process for producing 1 m^3 of reference concrete

	Data	**Assumptions and data sources**	**Input in Simapro**
Processes	176.9 kg of water	Selected from the literature [10]	Tap water (Europe without Switzerland) | market for | Alloc Rec, U
	321.6 kg cement	Selected from the literature [10]	Cement, Portland (Europe without Switzerland) | market for | Alloc Rec, U
	887.3 Kg sand	Calculated based on the reference article [10]	Sand (GLO)| market for | Alloc Rec, U
	0 Kg RPA	Calculated based on the reference article [10]	______
	900.4 Kg gravel	Calculated based on the reference article [10]	Gravel, round (RoW)| market for gravel, round | Alloc Rec, U
	0 Kgkm of RPA transport	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	3.22E4 Kgkm of cement transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	8.87E4 Kgkm of sand transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	9E4s Kgkm of gravel transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	0.916 kwh electricity	Zyklos Rotating Pan Mixer (Appendix A)	Electricity, medium voltage (Europe without Switzerland)| market group for | Alloc Rec, U

Table 0.20. Inventory data for concrete production process for producing 1 m^3 of concrete type 1

	Data	Data sources	Input in Simapro
Processes	178 kg of water	Selected from the literature [10]	Tap water (Europe without Switzerland) | market for | Alloc Rec, U
	336 kg cement	Selected from the literature [10]	Cement, Portland (Europe without Switzerland) | market for | Alloc Rec, U
	745.7722 Kg sand	Calculated based on the reference article [10]	Sand (GLO)| market for | Alloc Rec, U
	64.905 Kg RPA produced for concrete type 1	Calculated based on the reference article [10]	RPA produced for concrete type 1
	905.912 Kg gravel	Calculated based on the reference article [10]	Gravel, round (RoW)| market for gravel, round | Alloc Rec, U
	6.49E3 Kgkm of RPA transport	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	3.36E4 Kgkm of cement transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	7.46E4 Kgkm of sand transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO) | market for | Alloc Rec, U
	9.06E4 Kgkm of gravel transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	0.916 kwh electricity	Zyklos Rotating Pan Mixer (Appendix A)	Electricity, medium voltage (Europe without Switzerland)| market group for | Alloc Rec, U

Table 0.21. Inventory data for concrete production process for producing 1 m^3 of concrete type 2

	Data	Data sources	Input in Simapro
Processes	180 kg of water	Selected from the literature [10]	Tap water (Europe without Switzerland) | market for | Alloc Rec, U
	367 kg cement	Selected from the literature [10]	Cement, Portland (Europe without Switzerland) | market for | Alloc Rec, U
	469.404 Kg sand	Calculated based on the reference article [10]	Sand (GLO)| market for | Alloc Rec, U
	222.655 Kg RPA produced for concrete type 2	Calculated based on the reference article [10]	RPA produced for concrete type 2
	855.04 Kg gravel	Calculated based on the reference article [10]	Gravel, round (RoW)| market for gravel, round | Alloc Rec, U
	2.23E4 Kgkm of RPA transport	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	3.67E4 Kgkm of cement transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	4.7E4 Kgkm of sand transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	8.55E4 Kgkm of gravel transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	0.916 kwh electricity	Zyklos Rotating Pan Mixer (Appendix A)	Electricity, medium voltage (Europe without Switzerland) | market group for | Alloc Rec, U

Table 0.22. Inventory data for concrete production process for producing 1 m^3 of concrete type 3

	Data	**Data sources**	**Input in Simapro**
Processes	181 kg of water	Selected from the literature [10]	Tap water (Europe without Switzerland) | market for | Alloc Rec, U
	402 kg cement	Selected from the literature [10]	Cement, Portland (Europe without Switzerland) | market for | Alloc Rec, U
	366.302Kg sand	Calculated based on the reference article [10]	Sand (GLO)| market for | Alloc Rec, U
	269.695 Kg RPA produced for concrete type 3	Calculated based on the reference article [10]	RPA produced for concrete type 3
	836.747 Kg gravel	Calculated based on the reference article [10]	Gravel, round (RoW)| market for gravel, round | Alloc Rec, U
	2.7E4 Kgkm of RPA transport	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	4.02E4 Kgkm of cement transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	3.65E4 Kgkm of sand transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	8.4E4 Kgkm of gravel transportation	Assumption of the average distance. Transporting facility based on the literature [36]	Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U
	0.916 kwh electricity	Zyklos Rotating Pan Mixer (Appendix A)	Electricity, medium voltage (Europe without Switzerland) | market group for | Alloc Rec, U

3.3 Life cycle impact assessment

This LCA study follows the ISO 14040/44 [27, 29] methodology. The LCA modelling is carried out in SimaPro V.8.5.2.0 (Faculty NTNU). The method used for estimating the environmental impact is ILCD 2011 Midpoint+ and main database is Ecoinvent 3.

According to the relevant studies on the topics in the fields of construction and plastic recycling [30, 34, 35, 37], nine following impact categories are selected for this assessment:

- Climate change (GWP)
- Ozone depletion (ODP)
- Human toxicity, cancer effects (HTP-C)
- Human toxicity, non-cancer effects (HTP-NC)
- Particulate matter (PMP)
- Acidification (AP)
- Terrestrial eutrophication (TEP)
- Land use (LUP)
- Water resource (WRDP)

4. Results and Discussion

The environmental impacts of each impact category of the four concrete mixes containing different amounts of RPA as fine aggregate but the same compressive strength, are shown in Table 4.1. It is noteworthy that study is a cradle to gate analysis; hence, the results show the environmental impacts from the collection of waste PET bottles from the waste reception gate to the concrete production factory for producing one cubic meter of concrete. Therefore, the environmental impacts of the use phase and the end of life phase disposal of concrete are not calculated in this study. The details of the LCA results of each mix design are provided in Appendix B. The results of this study will further be discussed based on the consideration of credit from the elimination of incineration process due to using RPA in concrete.

Table 0.1. The environmental impacts of the four types of concrete mixes (without considering credit on elimination of incineration)

Impact category	Unit	Reference concrete (0% RPA)	Concrete type 1 (14% RPA)	Concrete type 2 (47% RPA)	Concrete type 3 (58% RPA)
GWP	kg CO_2 eq	347.77	367.11	410.51	446.59
ODP	kg CFC-11 eq	1.87E-05	1.96E-05	2.16E-05	2.30E-05
HTP-NC	CTUh	3.67E-05	4.00E-05	4.77E-05	5.18E-05
HTP-C	CTUh	5.76E-06	6.315E-06	7.63E-06	8.27E-06
PMP	kg PM2.5 eq	0.077	0.08	0.087	0.092
AP	molc H+ eq	0.96	1.02	1.155	1.25
TEP	molc N eq	2.77	2.88	3.12	3.34
LUP	kg C deficit	544.15	538.29	522.62	527.01
WRDP	m3 water eq	0.57	0.65	0.84	0.91

As can be seen in Table 4.1, in all selected impact categories; except LUP, the environmental impacts increase with the increase in the amount of RPA. For example, concrete type 3 has the highest impacts on GWP by emitting 446.59 kg CO_2 eq. This is about 28% more than the reference concrete with no RPA content, which emits 347.77 kg CO_2 eq as the mix with the lowest impact on GWP. Concrete type 2 and type 1 also emit 14% and 4.3% CO_2 eq more than reference concrete, respectively.

An important factor affecting greenhouse gas emission of concrete is cement content, which increases by the increase in cement consumption. In this study, the rise in the portion of RPA in concrete has led to increase in the cement consumption in order to compensate for the loss of compressive strength. Therefore, the amount of CO_2 eq of concrete has increased by increasing the portion of RPA (see Table 4.1). The impact categories; ODP, HTP-NC, HTP-C, PMP, AP, TEP and WRDP have also shown similar changes by increasing proportion of RPA and cement. Therefore, using RPA in concrete as fine aggregate has not shown an enhancement in these categories.

On the other hand, the LUP category in Table 4.1, has a different trend compared to the other selected impact categories. Reference concrete with no RPA content has the highest impact on LUP, concrete type 1 has the second highest impact, and concrete type 2 has the lowest impact on land use. However, in concrete type 3, the impact on LUP is slightly more than concrete type 2. As the amount of RPA increases, less natural aggregates will be consumed, which is the reason for lower impacts of concrete containing RPA compared to the reference concrete. Furthermore, the increase in cement consumption by incorporating more RPA, can also increase the impacts in LUP category. This is the main reason for slightly higher impacts (0.8% higher) of concrete type 3 compared to concrete type 2 in LUP impact category (see Appendix B). Note that the RPA content for concrete type 1, type 2 and type 3 is 14%, 47% (33% increase compared to concrete type 1) and 58% (44% increase compared to concrete type 1), respectively, however, the cement content has increased from 336 kg, to 367 kg (9.2% increase compared to concrete type 1) and 402 kg (19.6% increase compared to concrete type 1), respectively. This shows that the cement content has increased almost evenly from concrete type 1 to concrete type 2 and type 3, however, the content of RPA had a jump from concrete type 1 to concrete type 2 and considerably lower rate of increase from concrete type 2 to concrete type 3.

In order to evaluate incorporation of RPA in cement-based materials as an alternative to the other waste treatment methods, it is useful to discuss the waste management statistics in Norway to target this evaluation for further potential applications in this country.

Waste materials in Norway are treated in different ways such as sending to material recovery, biogas production, composting, filling compound and cover material, incineration, landfill or other disposal methods. The information obtained from the statistic center of Norway

(Statistisk Sentralbyrå, SSB) show that, waste plastics are mainly sent to material recovery or incineration plant (see Table 4.2).

Table 0.2. Plastic waste treatment methods in Norway in 2017 [38]

Plastic waste by treatment (1000 tons, 2017)				
Treatment, total	Sent to material recovery	Incineration	Landfill	Other disposal
222	127	84	4	6

The trend of managing waste plastics in Norway are toward avoiding landfill, and this type of material is usually sent to incineration plant if recovery option is not valid. Thermoplastics, such as PET, can normally not be re-melted (recycled) more than a limited number of times (for example 4-6 times), and incineration is the main final option in Norway for the waste plastics which cannot be recycled. Thus, using RPA in concrete can be an alternative to avoid incinerating waste plastics.

Long lifetime such as 100 years is common for cement-based materials, and there is the potential to recycle these materials after this time, without the need for re-melting RPA. The compressive strength may be affected when recycling concrete containing RPA, however, there are a wide range of non-structural applications such as separation walls, insulation boards, decorative elements, road sides, etc., that can be alternative products with minimal demand for mechanical properties. Recycling concrete containing RPA needs further experimental investigation, which is not in the scope of this study, however, the current research activities on recycling cement-based materials shows raises this potential.

Thus, to evaluate the impact of recycling waste plastics in cement-based materials, the credit obtained from recycling in concrete instead of incinerating waste PET will be considered in this section. This evaluation can give an understanding of the effect of this recycling method, and if this it is found to be a more suitable option compared to incineration, it can also be nominated as a potential treatment alternative for other types of waste plastics, such as mixed plastics, which are mainly sent to incineration plant without recycling them.

To calculate the credit for elimination of incineration, the exact amount of waste PET bottles used for the preparation of RPA for each type of concrete, is considered to be sent to the incineration site and a life cycle analysis is done by SimaPro V.8.5.2.0. The following table shows that how the incineration of such amount of waste PET contribute to environmental impacts.

Table 0.3. The environmental impacts of incineration of equivalent amount waste PET incorporated in different concrete mixes

Impact category	Unit	Concrete type 1, 60.69 kg PET	Concrete type 2, 208.13 kg PET	Concrete type 3, 252.02 kg PET
GWP	kg CO_2 eq	125.30	429.84	520.34
ODP	kg CFC-11 eq	1.52E-07	5.21E-07	6.3E-07
HTP-C	CTUh	1.6E-05	5.480E-05	6.63E-05
HTP-NC	CTUh	6.09E-07	2.09E-06	2.53E-06
PMP	kg PM2.5 eq	0.0014	0.0049	0.006
AP	molc H+ eq	0.025	0.085	0.103
TEP	molc N eq	0.127	0.436	0.527
LUP	kg C deficit	1.97	6.77	8.19
WRDP	m3 water eq	-0.0005	-0.002	-0.0023

In order to consider the credit from elimination of waste PET incineration, the kg CO_2 eq by PET incineration will be reduced from the kg CO_2 eq of producing concrete containing RPA. Fig. 4.1 shows the results for both cases of considering and not considering this credit. The GWP of concrete containing RPA are increased with increasing the amount of RPA when no credit is considered for elimination of incineration process. However, by considering the credit, the amount of CO_2 eq will be reduced considerably. While, incorporating 14% RPA reduces the amount of CO_2 eq from 367.11 kg to 241.81 kg (lower than reference concrete), increasing the RPA percentage to 47% and 58% will result in negative amounts of CO_2 eq. This shows that, increasing the amount of RPA in concrete can be beneficial for managing CO_2 eq emission by considering the credit for elimination of incineration.

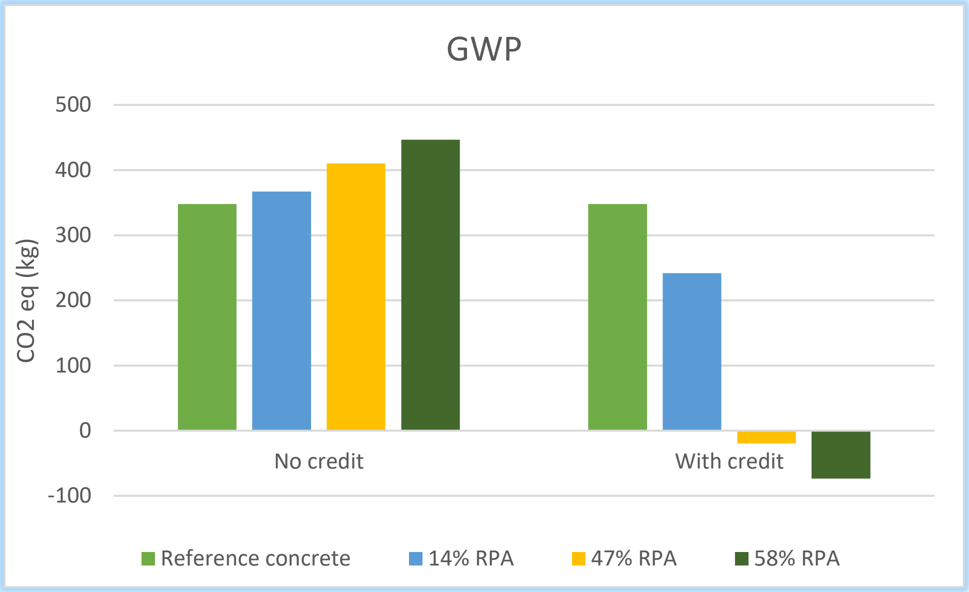

Fig. 4.1. Impacts on GWP with and without considering credit on incineration

The same comparison is also made for the other impact categories and the results are presented in Figs. 4.2-4.9. Different trends are observed for different impact categories. The amount of CFC-11 eq increases with increase in the amount of RPA for both cases (see Fig. 4.2), however, by considering the credit, the CFC-11 eq emissions have slightly reduced for the same type of concrete.

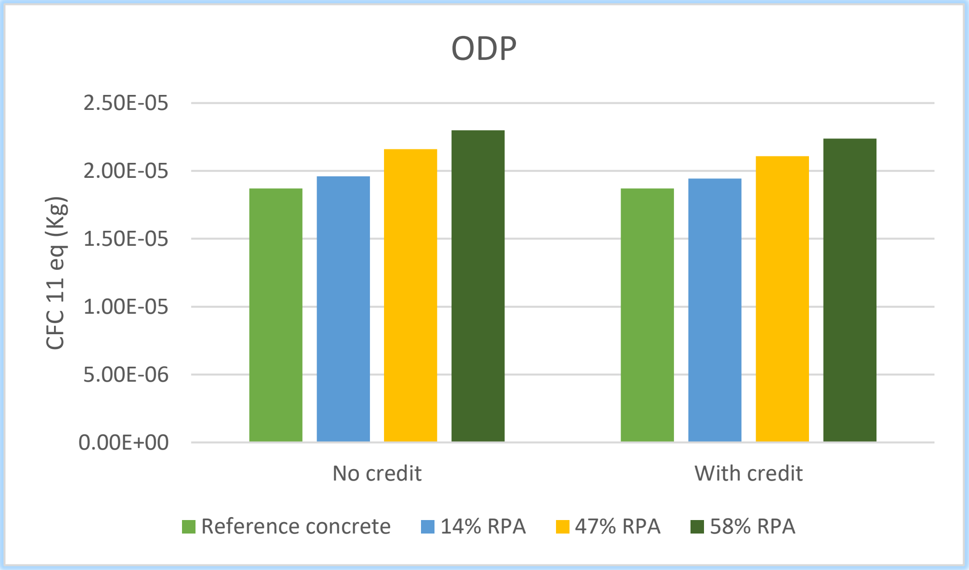

Fig. 4.2. Impacts on ODP with and without considering credit on incineration

On the other hand, the impacts of HTP-C and HTP-NC show descending trends when considering the credit from elimination of incineration process (see Figs. 4.3& 4.4). The results for comparative toxicity units for human (CTUh) with cancer effects decreases by increasing the portion of RPA when considering the credit leading to lower impact compared to reference concrete even for the case of using 14% RPA. The slight jump for 58% RPA compared to 47% RPA is due to the increase in cement content while the RPA content is not increased considerably when compared to the difference between concrete type 1 and type 2 (see Appendix B). On the other hand, the results for non-cancer effects when considering the credit of elimination of incineration process, show a significant reduction in CTUh by increasing the amount of RPA in concrete.

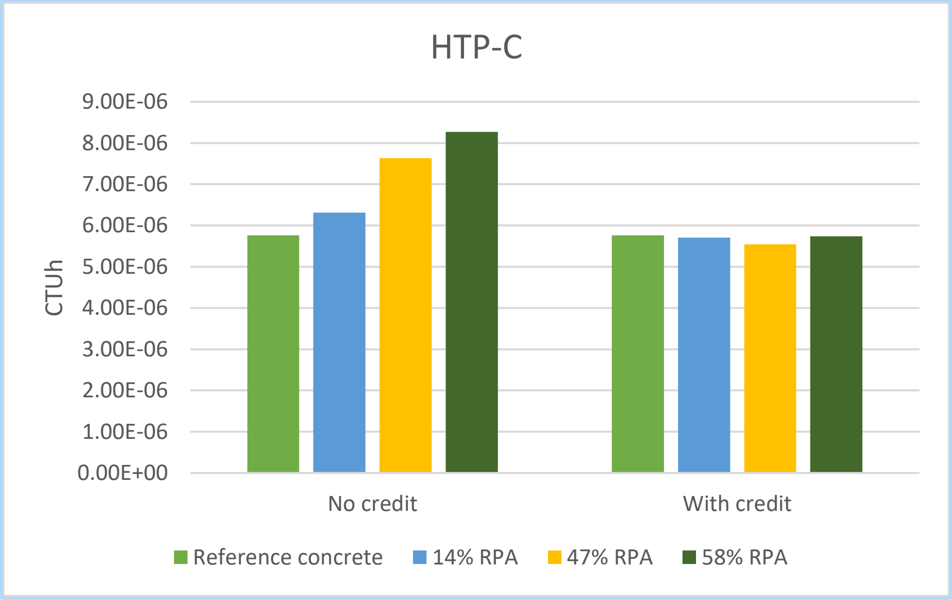

Fig. 4.3. Impacts on HTP-C with and without considering credit on incineration

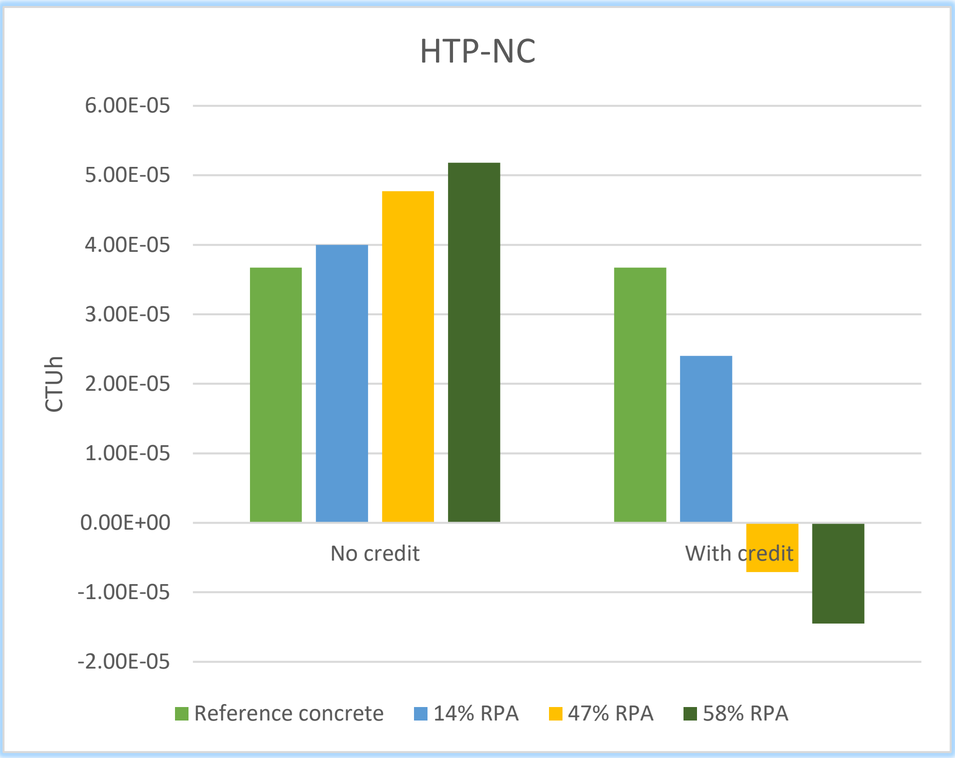

Fig. 4.4. Impacts on HTP-NC with and without considering credit on incineration

Impact categories such as PMP and AP have approximately similar changes in results when considering the credit for elimination of incineration process. The amount of PM 2.5 eq and H+ eq are increased by increasing the portion of RPA for both of the cases of considering and not considering the credit. However, by considering the credit for elimination of incineration the impacts are lower compared to the case of no credit consideration.

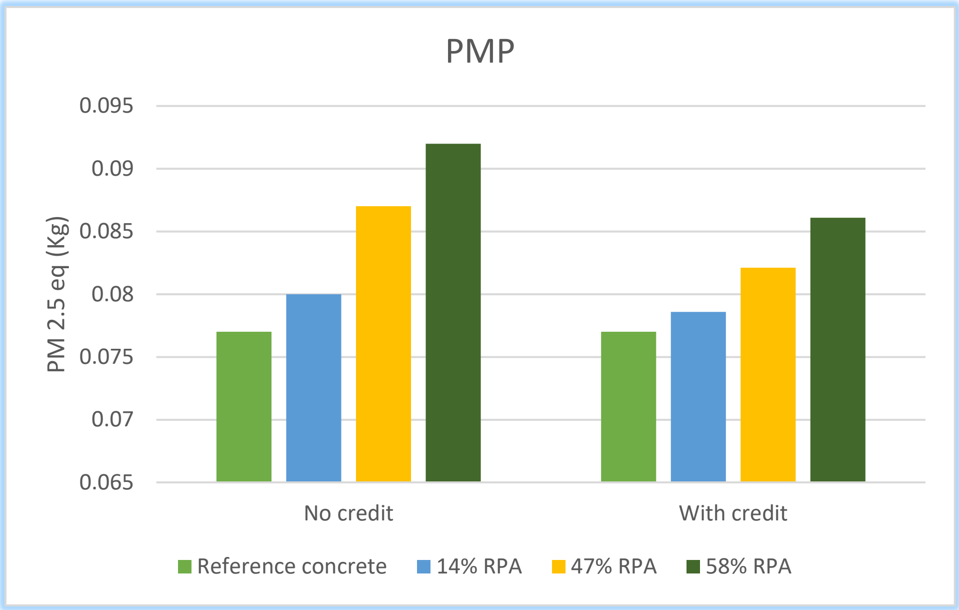

Fig. 4.5. Impacts on PMP with and without considering credit on incineration

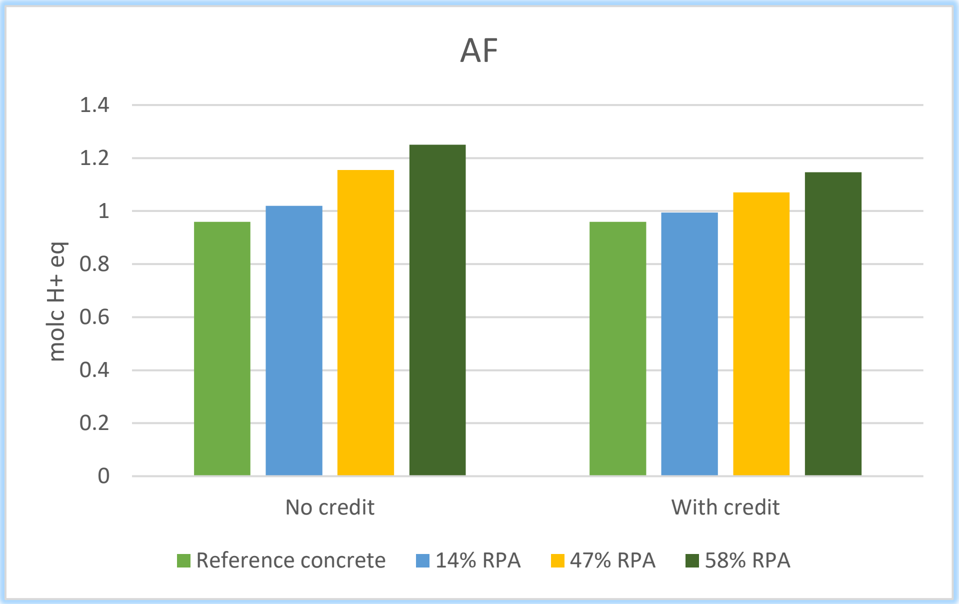

Fig. 4.6. Impacts on AP with and without considering credit on incineration

Fig. 4.7 presents the results of TEP category, where increasing in the portion of RPA has resulted in producing more amount of N eq when the credit is not considered. Considering the credit has however, given lower impacts for concrete mixes containing 14%, 47% RPA, compared to the reference concrete. For the case of 58% RPA, the results are slightly higher than the reference concrete, which is due to the same reason discussed for the cases of HTP-C. i.e. considerable increase in the cement content compared to the increase in RPA content.

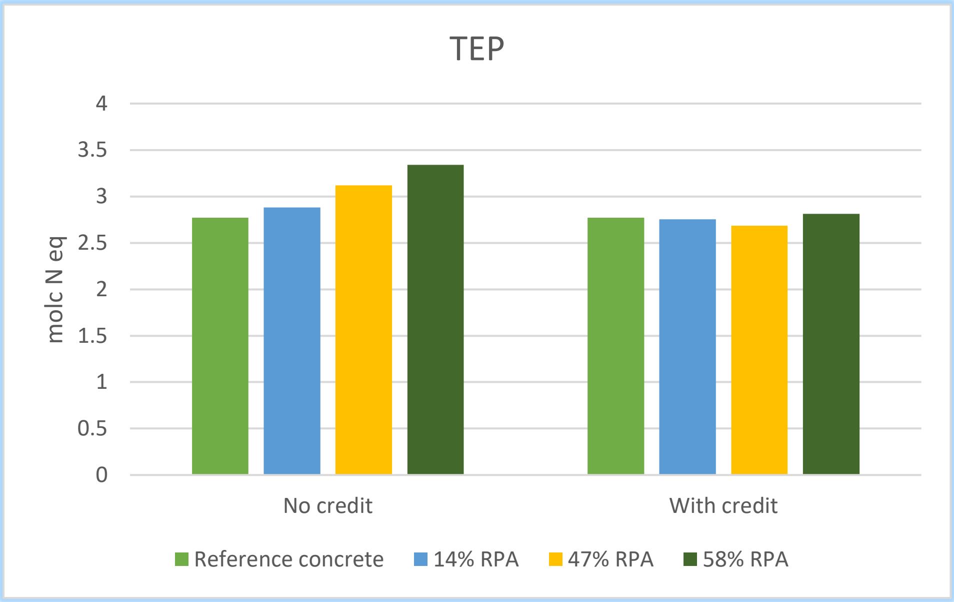

Fig. 4.7. Impacts on TEP with and without considering credit on incineration

Fig. 4.8 present the results of LUP with and without credit on elimination of incineration process. Cement and natural aggregates are main factors affecting LUP. By increasing the portion of RPA, the amount of used natural aggregates is decreased while the amount of cement usage is increased. This is the only category where the impact using RPA is lower than the impact of reference concrete without considering the credit for elimination of incineration process. The results from considering the credit show similar trend compared to the no credit situation, but with even lower impact for the same concrete type. Similar to HTP-C and TEP, concrete containing 58% RPA had higher impact compared to the concrete containing 47% RPA, which shows that there is an optimal point to achieve minimum impact for these categories balancing the effect of RPA content and cement content.

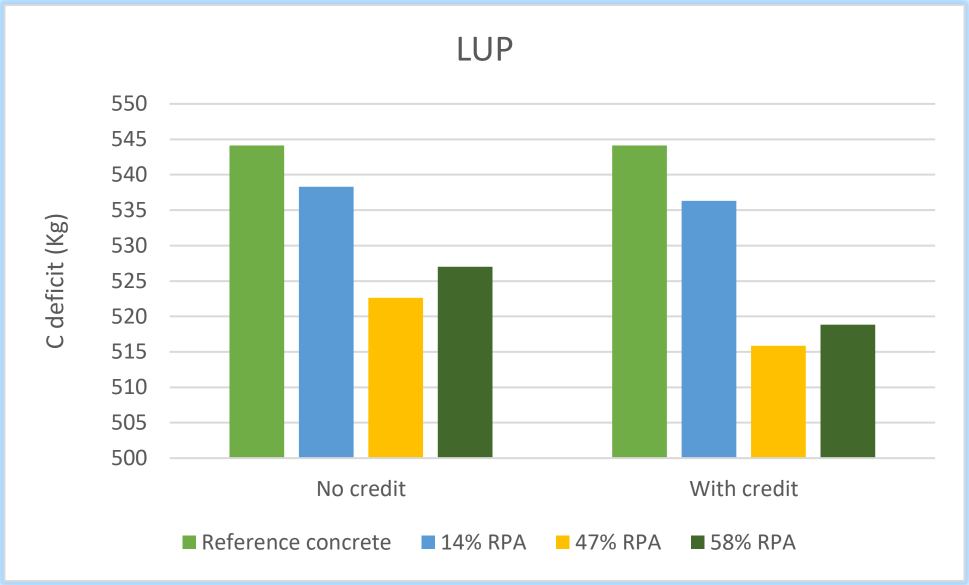

Fig. 4.8. Impacts on LUP with and without considering credit on incineration

The last category considered in this study is WRDP, and the results are shown in Fig. 4.9. As can be seen from the figure, the amount of water eq with credit consideration is slightly higher than not considering the credit. This is due to the negative impact of incineration process on WRDP, which is presented in Table 4.3.

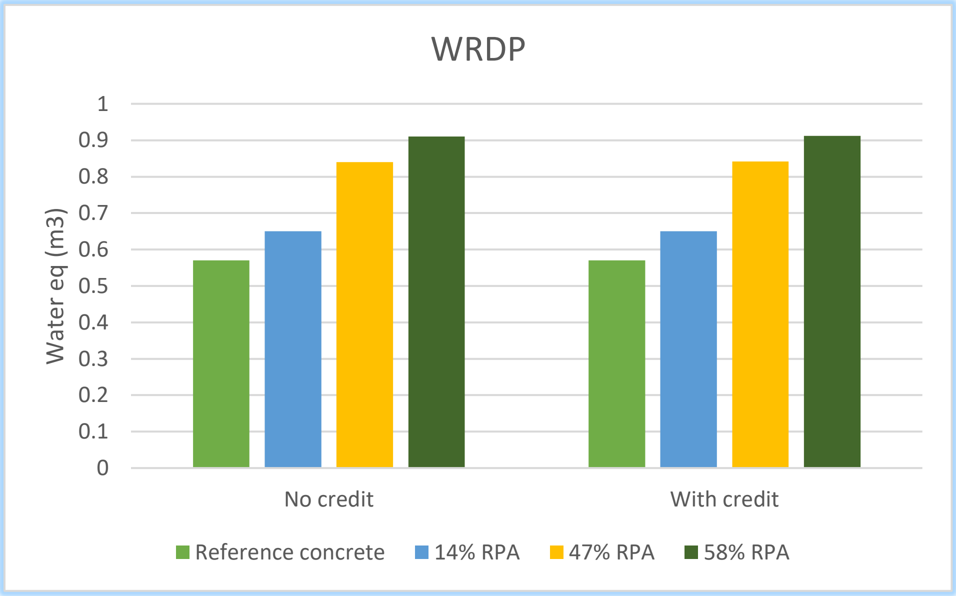

Fig. 4-9. Impacts on WRDP with and without considering credit on incineration

Producing concrete containing RPA instead of incinerating the waste PET has revealed considerable advantages for different impact categories. GWP and HTP-NC benefit from increasing the amount of RPA in concrete resulting in negative impacts in higher portion of RPA. In case of HTP-C, TEP and LUP the impacts can also be lower than the reference concrete when the credit is considered. However, increasing the RPA does not always result in the lowest impact for these categories and the mix design of the concrete need to be optimized to avoid increase in the impacts due to other factors such as increase in the cement content.

Moreover, concrete containing RPA had still higher impacts compared to reference concrete for impact categories such as ODP, PMP and AF. However, the impacts were reduces compared to the case of not considering the credit. WRDP is the only impact category that had slightly higher impact for all the RPA mixes when considering the credit from incineration. This marginal increase is due to the negative impact of the incineration process and is negligible when compared to the impacts when the credit is not considered. Optimizing the washing process of the waste PET bottles and the aggregates can reduce the impacts in this category.

It is noteworthy that there are different potential methods that can be used in order reduce the environmental impacts of this product. For example, improvements in the recycling techniques of waste plastics to produce RPA with higher compatibility and strength (such as gamma radiation method [39]) can lead to lower demand for cement consumption. Furthermore, using supplementary cementitious materials such as fly ash and silica fume and slag can introduce binders with lower emission. On the other hand, the focus of this study was on producing concrete containing RPA with a 30MPa compressive strength, which is in the range of structural concrete. However, there are some cementitious products such as separation walls, insulation boards or decorative elements, that do not demand such a high compressive strength and 3MPa or even lower strength (self-standing element) would be acceptable for the product. For such products, the current strength of RPA can be higher than the strength required for the binder. Thus, the strength of binder will be controlling the compressive strength of the element leading to minimal or no need to increase the cement content to compensate for using RPA.

The results can be a motivation for producing cement-based composites containing recycled plastic aggregates sourced from other types of waste plastics such as mixed plastics, which are mainly incinerated in different countries including Norway. Achieving this goal requires extensive experimental investigation considering different factors affecting environmental impacts of the cementitious composites such as mechanical properties of recycled plastic aggregates, properties of the interface between cement and the aggregates as well as composition of the cementitious binder. Furthermore, it is noteworthy that recycling concrete containing waste plastics into new cement-based products without re-melting the plastics would also be beneficial for the environment, and concrete industry have the potential to move toward this direction.

5. Conclusion

This master thesis presented an LCA study on incorporation of waste PET bottles as RPA in concrete production. While waste plastics are one of the main global challenges, concrete industry is also suffering from high amount of greenhouse gas emissions as well as increasing use of natural resources. Thus, this study evaluated a solution that can address the challenges in both concrete- and plastic industry.

This study revealed that the main advantage of this method of using RPA in concrete when no credit from elimination of incineration process is considered was reducing environmental impacts on LUP category and the other selected categories had higher impacts compared to reference concrete. On the other hand, considering the credit by using RPA in concrete resulted in considerable advantages in different impact categories. Increasing the amount of RPA in concrete led to negative impacts on GWP and HTP-NC by considering this credit. The impacts for LUP, HTP-C and TEP showed also reduction compared to the reference concrete. However, concerning these categories, the mix design of the concrete need to be optimized to avoid increase in the impacts due to other factors such as increase in the cement content. Applying the credit reduced the environmental impacts for ODP, PMP and AF categories compared to the no credit case but introducing RPA had still higher impacts than the reference concrete. WRDP was the only impact category that had slightly higher impacts for all the RPA mixes when considering the credit from incineration. Optimizing the washing process of waste PET bottles and the aggregates can reduce the impacts in this category.

The results can be a motivation producing cement-based composites containing recycled plastic aggregates sourced from other types of waste plastics such as mixed plastics, which are mainly incinerated in different countries including Norway. Achieving this goal requires extensive experimental investigation by considering different factors affecting environmental impacts of cementitious composites such as mechanical properties of recycled plastic aggregates, properties of the interface between cement and the aggregates as well as composition of the cementitious binder. Furthermore, targeting the cement-based composites that do not demand high compressive strength such as separation walls, insulation boards or decorative elements can be the other approach for avoiding the demand for high cement content in cementitious composites containing recycled plastic aggregates and thus, avoiding the increase in environmental impacts. It is also noteworthy that recycling concrete containing waste plastics into new cement-based products without re-melting the plastics would also be beneficial for the environment, and concrete industry have the potential to move toward this direction.

6. Further research

- Cradle to grave LCA study on using RPA in concrete, which considers different impact categories, waste treatment options, other methods of recycling plastic wastes as well as recycling of concrete containing RPA into new products. This needs extensive experimental investigation.
- Optimizing the recycling process by using methods such as enhancing mechanical properties of recycled plastic aggregates, improving properties of the interface between cement and the aggregates, modification of composition of the cementitious binder as well as improving the washing process of waste PET bottles and natural aggregates.
- Evaluating cement-based composites containing recycled plastic aggregates from other types of waste plastics such as mixed plastics, which are mainly incinerated in different countries including Norway.
- Using recycled waste plastics in concrete in different forms such as fiber, filler, rebar, aggregate as well as combination of them.
- Using waste plastics in cement-based composites that do not demand high compressive strength such as separation walls, insulation boards or decorative elements.

7. References

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Appendix A: Technical details of the machinery considered in this study

BOGDA
MACHINERY 博格达
Plastic Extrusion & Recycling
ROOM-1505

Production Model:

BG-1000kg/h waste plastic recycling machine

Technical Details

Application:	Waste PET bottle recycling machine
Automatic Grade:	Automatic
Production Capacity:	1000KG/H
Place of Origin:	Jiangsu, China (Mainland)
Brand Name:	BOGDA
Voltage:	220V,380V,440V
Power(W):	200KW
Dimension(L*W*H):	L55m x W6m x H5m (optional)
Weight:	12--20T
material:	3mm 304 stainless steel
motor:	About 300kw
Water consumption:	5-6 tons/h
labor:	6-8 people
sieve diameter:	17mm
Moisture:	Less than2%
Plastic Type:	PET bottles

Product Description

Production process of 1000kg per hour capacity PET bottle recycling washing machine line:

1. Belt conveyor: put the waste PET bottles on the running belt to feed them into label scraping machine. (workers)
2. Label scraping machine: can remove 85-95% of the labels on the surface of bottles, rest sticky labels will be removed by later label separator.
3. Manual separating table: pick up the no-needed bottles, stones or some labels etc. (workers)
4. Metal detector: will detect the metals and stop the belt.
5. Belt conveyor: to feed the bottles into crusher.
6. Crusher with water: crush the bottles into small pieces
7. Screw conveyor: to feed the flakes into next step.
8. Floating washer: bottle flakes, caps and dirt will be separated. Screw conveyor at bottom will push flakes forward, caps will float and be collected at end.
9. Screw conveyor: to feed the flakes into next step and rub the material.
10. Steam washer: hot water to wash the stirred material, can add soap to wash the bottle flakes cleaner.
11. Screw conveyor: to feed the material into next step and rub the material.
12. High speed friction washer: high speed rotary and friction create centrifugal force to smash and remove the dirt again.
13. Screw conveyor: to feed the material into next step and rub the material.
14. Floating washer: cola water will wash the material again to remove soap. Then material here will be clean.
15. Screw conveyor: to feed the material into next step and rub it.
16. Dewatering machine: high speed rotary will remove the water, the brush outside of mesh will clean the mesh to improve efficiency of drying.
17. Drying machine: Blow the dry material into next step, the hot air from the heater will dry the material in the pipes.
18. Label separator by air: After hot air, rest adhesive labels will be separated from flakes, the blower will suck the light labels and blow them out, last flakes will drop with no labels to the silo.
19. Storage hopper: collect the final clean PET bottle flakes in the storage hopper after label separator by air.
20. Electric elements: control the whole washing recycling line

belt conveyor

label scraping machine

manual separating table

the discharging mouth of label scraping machine

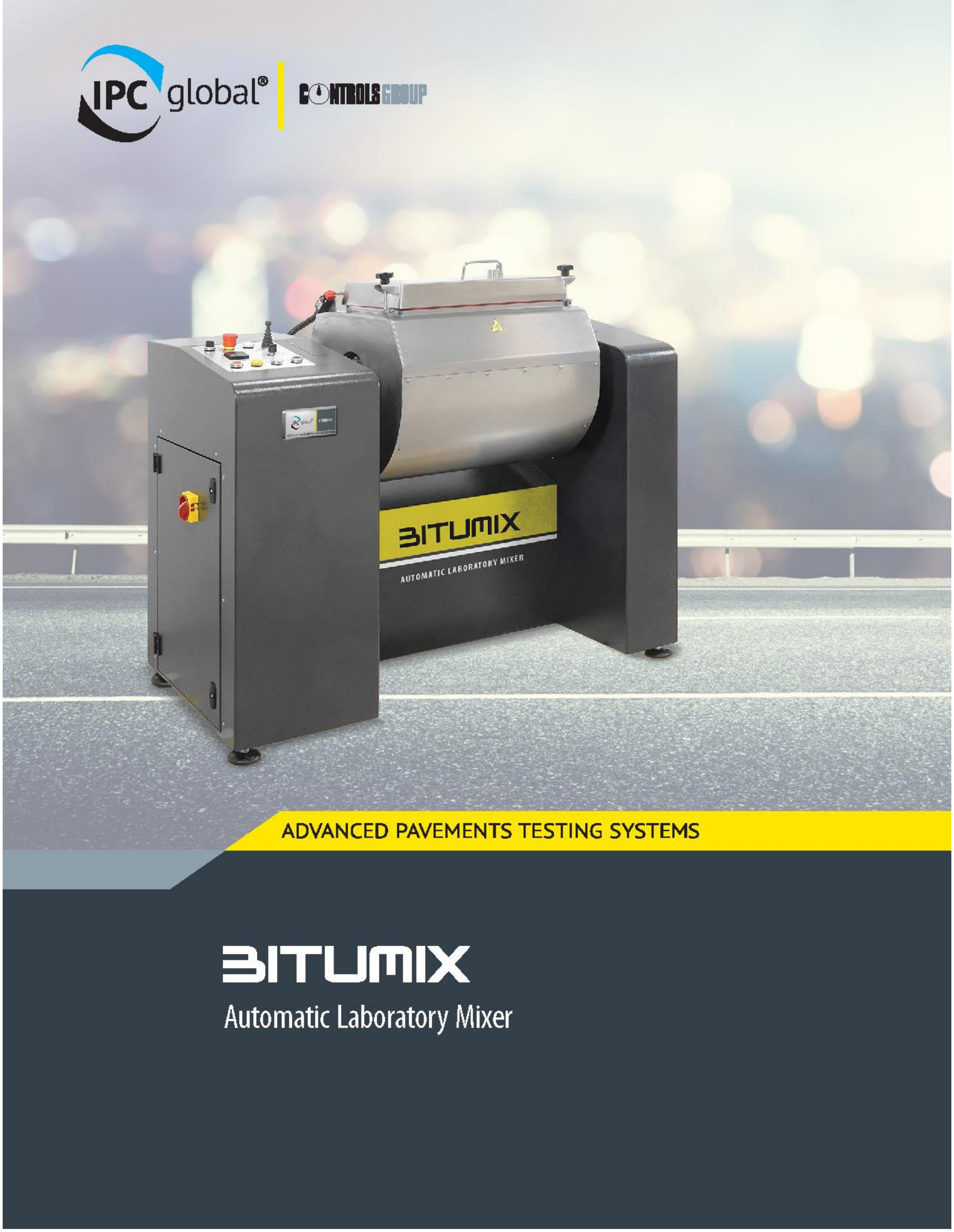
metal detector

belt conveyor and crusher


screw conveyor from crusher to floating washer
floating washer
two screw conveyors and steam washer
high speed friction washer


floating washer ---screw conveyor ---dewatering machine
dewatering machine
drying system
storage hopper
label separator by air

control cabinet for automatic plastic washing recycling line



ADVANCED PAVEMENTS TESTING SYSTEMS

BITUMIX

Automatic Laboratory Mixer

BITUMIX AUTOMATIC LABORATORY MIXER

main features

- Conforms to EN 12697-35
- Ideal for preparing laboratory samples for mix design
- New improved mixing drum and heating system quickly adjustable up to 250°C
- Mixing capacity up to 30 liters
- Mixing speed adjustable from 5 to 35 rpm
- Mixing temperature adjustable up to 250° C
- Stainless steel (AISI 304) mixing container
- Temperature control with PT 100 probe
- Digital temperature display
- Easy unloading by motorized tilting system, total rotation up to 130°

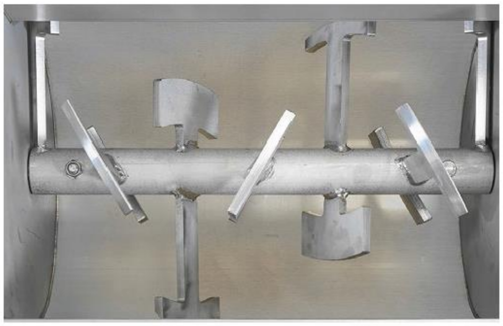
Standards EN 12697-35

The design and testing of bituminous mixtures includes various laboratory tests such as Marshall stability (EN 12697-34), Gyratory compaction (EN 12697-31), Slabs laboratory compaction (EN 12697-33) to prepare specimens for Wheel tracking (EN 12697-22) and Determination of stiffness including Beam fatigue testing (EN 12697-26, EN 13108).

To produce samples for performing the above tests, it is essential that the preparation of a bituminous mixture is carried out at a reference temperature and within a limited time period in order to reduce mechanical degradation of the aggregates. The mixer should also be capable of entirely coating all mineral substances in not more than 5 minutes as stated by EN 12697-35.

The mixer consists essentially of a horizontal stainless steel mixing container with a helical mixing shaft. The container is thermally insulated and comes complete with a heating element and probe sensor which provide uniform temperature control. The container can be easily tilted by the electric motor for the unloading operation.

The control panel includes: a digital display to monitor mixing temperature, a digital thermo-regulator, a mixing speed controller and various commands.



77-PV0077/C Detail of drum with helical mixing shaft

Ordering information

77-PV0077/C
BITUMIX automatic laboratory mixer,
30 liters capacity.
380–400 V, 50 Hz, 3 ph.

77-PV0077/CZ
As above but 220 V, 60 Hz, 3 ph.

77-PV0077/C Detail of aggregate loading

Technical specifications

- Mixer capacity: 30 liters
- Mixing speed: adjustable from 5 to 35 rpm
- Mixing temperature: adjustable from ambient to 250°C
- Heater: 4500 W
- Temperature control: PT 100 sensor
- Tilting angle up to 130°
- Power: 7,000 W (total)
- Voltage: 380–400 V, 50 Hz, 3 ph or 220 V, 60 Hz, 3 ph
- Overall dimensions: 1,350 x 650 x 1,205mm (W x D x H)
- Weight: approx. 320kg

77-PV0077/C Detail of unloading. The mixing cylinder is rotated by a motorized tilting system for easy unloading. The tilting angle is adjustable to 130° to speed up the unloading operation.

77-PV0077/C

ZK 500 HE

Technical details

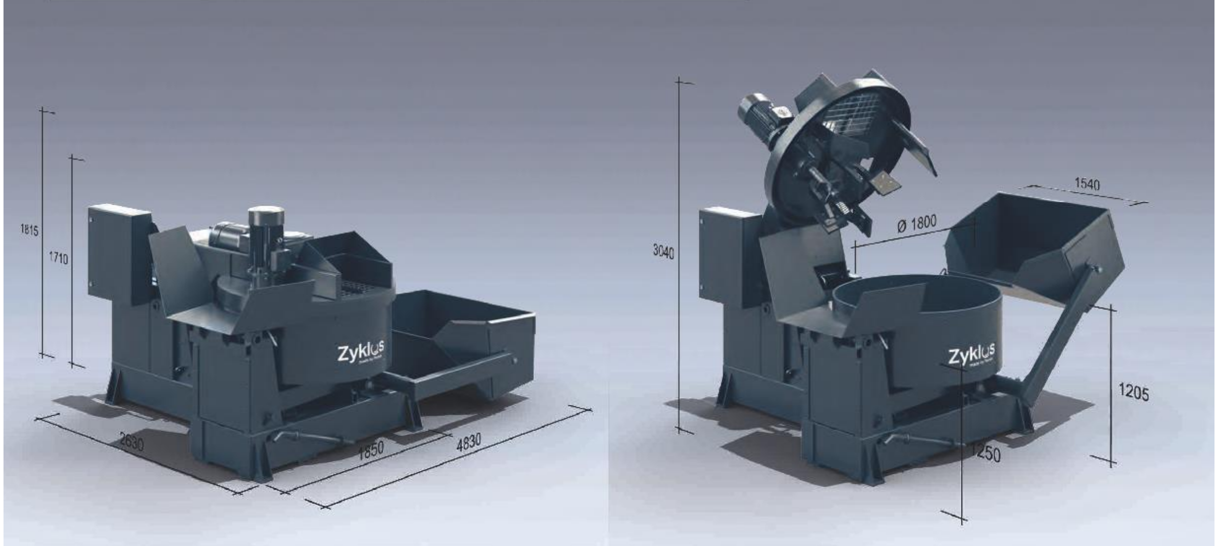
Zyklos
made by Pemat

Zyklos Rotating Pan Mixer from Pemat

ZK 500 HE

Zyklos Rotating Pan Mixer

Zyklos
made by Pemat



ZK 500 HE

Zyklos Rotating Pan Mixer from Pemat

Technical details	
Batch capacity (standard concrete) ready-mix approx. l	500
Dry Filling (max.) approx. l / kg	865 / 800
Mixing pan diameter mm	1.704
Mixing pan design	hydraulically tiltable
Tilting arm design	hydraulically
Skip design	hydraulically
Power mixing star kW	15
Power hydraulic kW	7,5
Power mixing pan kW	5,5
Power tiltable mixing pan kW	–
Pneumatic	–
Voltage V	400
Frequency Hz	50
Weight approx. kg	4.250

Appendix B: The details of LCA results for different concrete mixes

The details of LCA results for concrete containing 0% RPA

Impact category	Unit	Total	Tap water	Portland cement	Gravel	Sand	Transportation of cement	Transportation of gravel	Transportation of sand	Electricity
GWP	kg CO2 eq	347.7730834	0.067606677	291.3205305	10.82063343	10.59909944	5.26092665	14.72928593	14.51498824	0.460012581
ODP	kg CFC-11 eq	1.87369E-05	6.58953E-09	9.25308E-06	1.55081E-06	1.53114E-06	9.68111E-07	2.71047E-06	2.67103E-06	4.56592E-08
HTP-NC	CTUh	3.67036E-05	3.88421E-08	2.3047E-05	2.85553E-06	2.80556E-06	1.19593E-06	3.34831E-06	3.29959E-06	1.12828E-07
HTP-C	CTUh	5.75935E-06	2.87364E-08	3.33944E-06	6.69745E-07	6.57491E-07	1.5777E-07	4.41716E-07	4.3529E-07	2.9162E-08
PMP	kg PM2.5 eq	0.076670868	4.20047E-05	0.041846556	0.009343323	0.009130915	0.002460971	0.006890108	0.006789863	0.000167127
AP	molc H+ eq	0.96445514	0.000400187	0.683993729	0.087534284	0.085825104	0.015885	0.044474049	0.043826992	0.002515797
TEP	molc N eq	2.772994246	0.000625712	2.030102297	0.267668057	0.263196105	0.031742507	0.088871123	0.087578129	0.003210317
LUP	kg C deficit	544.1541983	0.095269612	150.3666891	132.5295214	130.5687703	19.85763151	55.59642851	54.78755111	0.352336799
WRDP	m3 water eq	0.574259265	0.028959056	0.156398184	0.196630838	0.188373336	0.00015487	0.000433598	0.00042729	0.002882091

The details of LCA results for concrete containing 14% RPA

Impact category	Unit	Total	Tap water	Portland cement	Gravel	Sand	RPA 1	Transportation of cement	Transportation of gravel	Transportation of sand	Transportation of RPA 1	Electricity
GWP	kg CO2 eq	367.1106	0.068027	304.3647	10.88688	8.908502	8.844922	1.061753	14.81946	5.49649	12.19979	0.460013
ODP	kg CFC-11 eq	1.96E-05	6.63E-09	9.67E-06	1.56E-06	1.29E-06	8.73E-07	1.95E-07	2.73E-06	1.01E-06	2.24E-06	4.57E-08
HTP-NC	CTUh	4E-05	3.91E-08	2.41E-05	2.87E-06	2.36E-06	2.91E-06	2.41E-07	3.37E-06	1.25E-06	2.77E-06	1.13E-07
HTP-C	CTUh	6.32E-06	2.89E-08	3.49E-06	6.74E-07	5.53E-07	5.35E-07	3.18E-08	4.44E-07	1.65E-07	3.66E-07	2.92E-08
PMP	kg PM2.5 eq	0.0799	4.23E-05	0.04372	0.009401	0.007674	0.003188	0.000497	0.006932	0.002571	0.005707	0.000167
AP	molc H+ eq	1.022393	0.000403	0.71462	0.08807	0.072136	0.043264	0.003206	0.044746	0.016596	0.036836	0.002516
TEP	molc N eq	2.880367	0.00063	2.121002	0.269307	0.221215	0.062408	0.006406	0.089415	0.033164	0.073609	0.00321
LUP	kg C deficit	538.2879	0.095862	157.0995	133.3409	109.7425	10.91684	4.007639	55.9368	20.74678	46.04872	0.352337
WRDP	m3 water eq	0.65259	0.029139	0.163401	0.197835	0.158327	0.100017	3.13E-05	0.000436	0.000162	0.000359	0.002882

The details of LCA results for concrete containing 47% RPA

Impact category	Unit	Total	Tap water	Portland cement	Gravel	Sand	RPA 2	Transportation of cement	Transportation of gravel	Transportation of sand	Transportation of RPA 2	Electricity
GWP	kg CO2 eq	410.512	0.068791	332.446	10.27311	5.610057	30.34136	3.642325	7.68272	6.003607	13.98399	0.460013
ODP	kg CFC-11 eq	2.17E-05	6.71E-09	1.06E-05	1.47E-06	8.1E-07	3E-06	6.7E-07	1.41E-06	1.1E-06	2.57E-06	4.57E-08
HTP-NC	CTUh	4.77E-05	3.95E-08	2.63E-05	2.71E-06	1.48E-06	9.97E-06	8.28E-07	1.75E-06	1.36E-06	3.18E-06	1.13E-07
HTP-C	CTUh	7.63E-06	2.92E-08	3.81E-06	6.36E-07	3.48E-07	1.84E-06	1.09E-07	2.3E-07	1.8E-07	4.19E-07	2.92E-08
PMP	kg PM2.5 eq	0.087251	4.27E-05	0.047754	0.008871	0.004833	0.010936	0.001704	0.003594	0.002808	0.006541	0.000167
AP	molc H+ eq	1.154965	0.000407	0.780553	0.083105	0.045427	0.148411	0.010998	0.023197	0.018127	0.042224	0.002516
TEP	molc N eq	3.116982	0.000637	2.31669	0.254124	0.139309	0.214083	0.021976	0.046355	0.036224	0.084374	0.00321
LUP	kg C deficit	522.6162	0.096939	171.5938	125.8236	69.10948	37.44895	13.74814	28.99881	22.66092	52.78326	0.352337
WRDP	m3 water eq	0.84123	0.029467	0.178477	0.186681	0.099705	0.343096	0.000107	0.000226	0.000177	0.000412	0.002882

The details of LCA results for concrete containing 58% RPA

Impact category	Unit	Total	Tap water	Portland cement	Gravel	Sand	RPA 3	Transportation of cement	Transportation of gravel	Transportation of sand	Transportation of RPA 3	Electricity
GWP	kg CO2 eq	446.5887	0.069174	364.1507	10.09173	4.363668	36.75255	4.411833	5.975847	6.576158	13.73709	0.460013
ODP	kg CFC-11 eq	2.3E-05	6.74E-09	1.16E-05	1.45E-06	6.3E-07	3.63E-06	8.12E-07	1.1E-06	1.21E-06	2.53E-06	4.57E-08
HTP-NC	CTUh	5.18E-05	3.97E-08	2.88E-05	2.66E-06	1.16E-06	1.21E-05	1E-06	1.36E-06	1.49E-06	3.12E-06	1.13E-07
HTP-C	CTUh	8.27E-06	2.94E-08	4.17E-06	6.25E-07	2.71E-07	2.22E-06	1.32E-07	1.79E-07	1.97E-07	4.12E-07	2.92E-08
PMP	kg PM2.5 eq	0.092599	4.3E-05	0.052308	0.008714	0.003759	0.013246	0.002064	0.002795	0.003076	0.006426	0.000167
AP	molc H+ eq	1.247359	0.000409	0.854992	0.081638	0.035334	0.17977	0.013321	0.018044	0.019856	0.041478	0.002516
TEP	molc N eq	3.344031	0.00064	2.537628	0.249637	0.108358	0.259319	0.026619	0.036056	0.039678	0.082885	0.00321
LUP	kg C deficit	527.0096	0.097478	187.9584	123.602	53.7554	45.36182	16.65269	22.55613	24.82204	51.85133	0.352337
WRDP	m3 water eq	0.905446	0.02963	0.195498	0.183385	0.077554	0.415594	0.00013	0.000176	0.000194	0.000404	0.002882

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