Environmental LCA of innovative reuse of all End-of-life tyre components in concrete

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SUMMARY: This paper presents the environmental life-cycle assessment of concrete mixtures containing materials recycled from End-of-Life tyres, i.e. rubber particles, sorted steel wires and polymer/textile cord fibres. This life-cycle assessment is based on ILCD and the ISO standards and considers "cradle to gate", i.e. from extraction of raw materials, tyre-recycling and up to concrete production in ready mixture concrete plants. In total, 21 different concrete mixtures were analysed, including rubberised concrete and fibre reinforced concrete; mixtures with hybrid fibres were also considered (i.e. reinforced with both recycled and manufactured fibres). The results of this LCA show that, for a functional unit of 1 m^3 of concrete, cement is the main parameter contributing to the inventory of the examined concrete mixtures; this indicates the need of utilising "low energy" and low calcination cements to minimise their environmental impact. When performance-based functional units are considered in the LCA, the results highlight the importance of using these recycled materials in structural concrete applications that fully utilise the specific mechanical characteristics of each material, as demonstrated for rubberised concrete and steel fibre-reinforced concrete mixtures.

KEY WORDS: concrete, End-of-Life tyres, recycled steel fibres, recycled rubber, recycled textile fibres.

1 INTRODUCTION

An estimated one billion tyres are produced each year and a similar number reach the end of their life. In the EU alone, it is estimated that 3,400,000 tonnes of End-of-Life (EoL) tyres arise per year. Following the introduction of EU legislation on waste management, the majority of EoL tyres are either incinerated for energy recovery or mechanically treated to produce recycled rubber, steel wires and textile cord. The recycled rubber is used in a wide range of applications, while there are limited applications for the recycled steel wires and recycled textile cord [1].

To promote material recycling of EoL tyres, it is desired that innovative and high-added value applications are developed for all tyre components. This is the focus of the FP7 collaborative project "Anagennisi, which aims to innovatively reuse all tyre components in concrete construction. The recycled rubber can be used as a full/partial replacement of aggregate [2] with the aim of developing high deformability concrete. The recycled steel wires (provided they are cleaned and sorted to specific lengths [1]) can be used as fibre concrete reinforcement, to replace fully/partially manufactured steel fibres, as demonstrated by other research activities [3, 4]. The use of the recycled polymer/textile cord, recovered in the form of very fine and short fibres, has been mainly demonstrated in thermal insulation building applications, while current research activities are focused on shrinkage [5] and fire-spalling mitigation [6] of concrete elements.

To promote the reuse of all tyre components in concrete, the research activities of Anagennisis also involve environmental life cycle assessment (LCA), and this paper presents the "cradle to gate" LCA undertaken as part of the preparatory concrete mixture development of the project. In total, 21 different concrete mixtures were analysed, including rubberised concrete and fibre reinforced concrete; mixtures with hybrid fibres were also considered (i.e. reinforced with both recycled and manufactured fibres).

2 METHODOLOGY

The LCA utilised provisions of the ILCD [7] and the ISO standards [8, 9]; the software GABI-6 was used to undertake the study. The LCA system boundary considered all processes from extraction of raw materials and up to concrete production in ready mix concrete plants (Figure 1), obtaining a comprehensive energetic and environmental picture of the materials and concrete mixtures developed by the preparatory concrete mixture study.

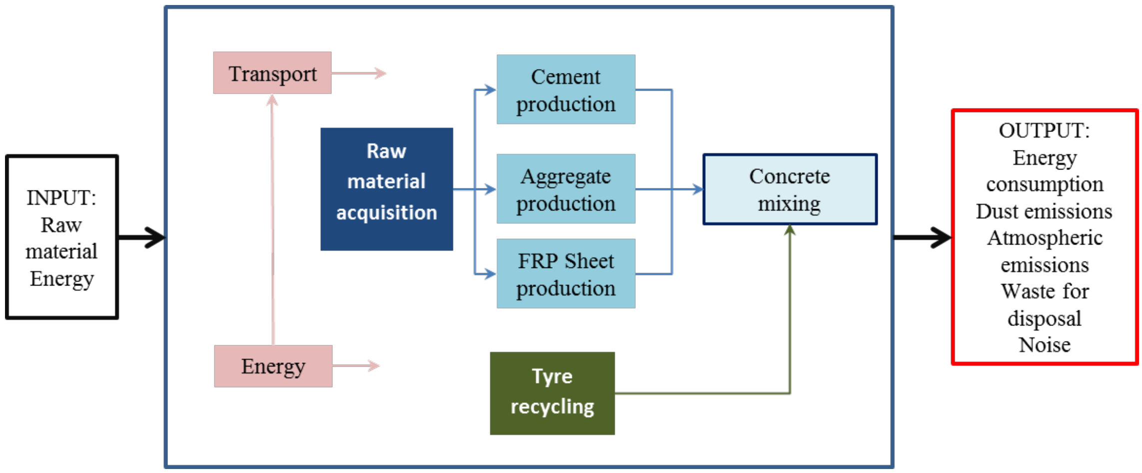

Figure 1: System boundary for the analysis

The LCA was implemented into four phases: goal definition, scope definition, inventory analysis and impact assessment. The intended goal of the LCA study was to evaluate and interpret the environmental impact of the following:

- recycled materials derived from EoL tyre recycling (rubber, steel wires and polymer/textile fibres),
- rubberised concrete mixtures (obtained by replacing a partial volume of coarse and fine aggregate with recycled tyre rubber in the modified concrete mixtures),
- fibre reinforced concrete mixtures (obtained by using tyre-recycled steel wires – RTSF - and polymer/textile fibres – RTPF - in concrete mixtures).

The LCA examined 21 concrete mixtures that were considered suitable for a range of applications, including precast elements, pavements and reinforced concrete building frames. The main functional unit was the production of 1 m^3 of concrete containing recycled materials from EoL tyres and, thus, three reference flows were considered: 1 m^3 of plain concrete mixture, 1 m^3 of fibre reinforced concrete, 1 m^3 of rubberised concrete. To account for the specific performance characteristics of concrete containing tyre-recycled materials, additional performance-based functional units were also considered for the rubberised concrete and steel fibre-reinforced concrete mixtures.

3 INVENTORY ANALYSIS

The Life Cycle Inventory analysis was based on "Situation A: Micro-level support", i.e. attributional. In this case, the input and output processes of the system (Figure 1) were modelled as they occurred. Furthermore, the ILCD provision for subdivision and virtual subdivision for black box unit processed was followed. "Open loop - different primary route" and "Allocation with determining Physical Causality" were considered to solve the multi-functionality of tyre recycling. In addition, a Euro 4 diesel truck with 5t payload capacity was considered for material transportation. It is noted that the feedstock energy of the recycled materials was not accounted in the analysis.

3.1 Concrete mixtures

Table 1 outlines the materials used in the concrete mixtures examined by the LCA study. The concrete mixtures included 3 plain concrete mixtures (used as the basis for comparison), 2 rubberised concrete mixtures, 10 steel fibre-reinforced concrete mixtures and 6 polymer/textile reinforced concrete mixtures.

Table 1: Material details and proportions of concrete mixtures

Constituent materials	Rubberised concrete	Steel fibre reinforced concrete	Polymer fibre reinforced concrete
Fine Aggregate (kg/m^3)	Natural sand (820)	Natural sand (804)	Crushed limestone (219)
Coarse Aggregate (kg/m^3)	Round gravel (1001)	Round gravel (1097)	Crushed limestone (1417)
Water (l/m^3)	Potable (150)	Potable (150)	Potable (215)
Cement (kg/m^3)	CEM II / A-LL 52.5N (42)	CEM I 52.N (150)	CEM II/BM SV 42.5 N (470)
Cement replacement (kg/m^3)	PFA (42.5)	GGBS (150)	-
Chemical additive (l/m^3)	Superplasticizer (5.1)	Superplasticizer (2.3)	Superplasticizer (3.1)
EoL Tyre secondary goods (kg/m^3)	Rubber (volume replacement: 10% = 24.75 & 40% = 99)	Sorted steel wires (30)	Polymer/textile fibres (1, 2, 3, 15, 30)

The two rubberised concrete mixtures contained recycled rubber particles (sieve sizes: 0-4 mm, 4-10 mm and 10-20 mm) which were used as partial aggregate replacement (at 10% and 40% volume replacement). The steel fibre-reinforced concrete mixtures contained sorted recycled and manufactured fibres at different contents. One mixture contained only sorted recycled steel wires (at 30 kg/m^3), three mixtures were reinforced only with manufactured steel fibres (at 30, 35 & 45 kg/m^3), while six mixtures contained both sorted recycled steel wires (R) and manufactured (M) steel fibres, since the effectiveness of hybrid steel fibres has already been demonstrated, e.g. [4]. The hybrid fibre contents were 20M10R,15M15R, 10M20R, 35M10R, 22.5M22.5R and 10M35R. The diameter of the sorted recycled steel wires was less than 0.3 mm while their length ranged between 15 to 25 mm; two types of manufactured steel fibres were used: their diameter/length was 08/55 & 1/60. Three of the polymer reinforced concrete mixtures contained only manufactured polymer fibres (at 1, 2, 3 kg/m^3), while the remaining three mixtures contained recycled polymer/textile fibres (at 1, 15 and 30 kg/m^3).

3.2 Tyre Recycling Data

A data survey was undertaken amongst the tyre recyclers participating in Anagennisi in order to gather data on the energy consumption of the ambient-temperature mechanical-treatment of EoL tyres. The collected data was analysed and the multi-functionality of EoL tyre recycling was solved according to the ILCD recommendations where the inventory of the recycling process was shared between the two co-functions of the tyres (as per §14.1 of the ILCD handbook). It is noted that a gate fee is normally paid to the recycling plant in order to accept the EoL tyres for recycling and, hence, the EoL tyres were assumed to have a negative value up to the gate of the recycling plant. For this reason, the inventory of the waste management processes up to the gate of the recycling plant (i.e. collection and transportation of the tyres) was fully allocated to the first co-function of the tyre.

Based on the collected data, a typical recycling plant (which uses ambient-temperature mechanical-treatment technology) consumes on average 430 kWh to treat one tonne of EoL tyres. On the absence of detailed data on the processes and equipment used to treat the EoL tyres, it was decided to provisionally share 50% of this energy consumption (215kWh) to the first co-function and the other 50% (215kWh) to the second co-function of the tyres (i.e. provide secondary goods for use in other systems). The 215 kWh per tonne was allocated by mass to each secondary good produced by the mechanical treatment of EoL tyres (Table 1).

Table 1: Allocation of energy consumed during the ELT recycling process

EoL Tyre secondary goods	Mass per tonne of EoL Tyres (kg)	Allocated energy consumption (kWh/ kg)	Total allocated energy consumption (KWh)
Steel wires	150	0.215	32.25
Polymer (textile) fibres	50	0.215	10.75
Rubber	800	0.215	172
Total	1000	-	215

4 IMPACT ASSESSMENT & INTERPRETATION

Figure 2 outlines the results for the ILCD impact category “Climate change midpoint” obtained for the two rubberised concrete mixtures as well as for the plain concrete mixture, used as a basis of comparison. It is clear that, for the specific functional unit of 1 m^3 concrete, there is only a marginal increase on the amount of CO2-Equiv. as a result of the partial replacement of natural aggregate with recycled rubber particles. In this case, cement is the main factor contributing to the LCA inventory of these mixtures, since the mechanical behaviour of the mixes is not accounted in the analysis. However, a different outcome is obtained by changing the functional unit of these concrete mixes, e.g. to provide a 100 kN axial load capacity for a concrete column. As shown in Figure 3, the partial replacement of aggregate with rubber leads to an increase to the expected amount of CO2-Equiv, since the compressive strength of concrete decreases due to replacement of aggregate with recycled rubber particles. Hence, a bigger cross-section is required to provide the 100kN axial load capacity. To arrive at environmentally friendly applications for rubberised concrete, it is important that this material is used in structural applications that fully utilise the mechanical characteristics of the material. One possibility, it is to use rubberised concrete in structural applications which require high-deformability; and this is one of the main applications currently being developed for rubberised concrete by the Anagennisis project [2].

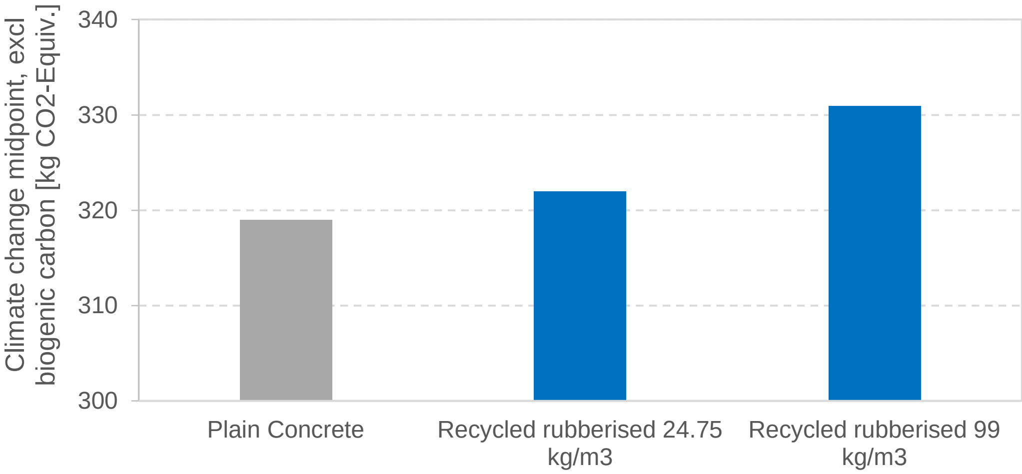

Figure 2: Rubberised concrete mixtures – Climate change midpoint, excl. biogenic carbon

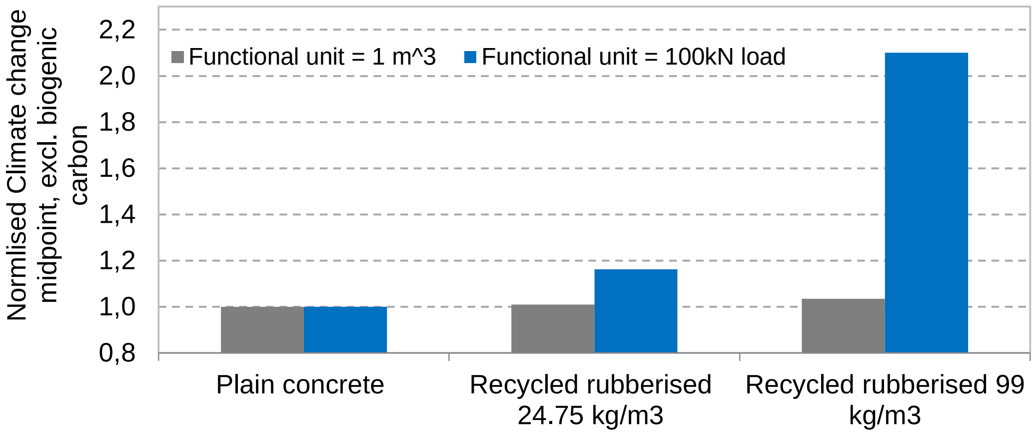

Figure 3: Rubberised concrete mixtures – Functional unit comparison

Figure 4 shows the results for the ILCD impact category “Climate change midpoint” obtained for the steel fibre-reinforced concrete mixtures. As expected for a functional unit of 1 m^3 of concrete, the amount of CO2-Equiv increases with the fibre content. By comparing mixtures with similar fibre contents (e.g. 30 kg / m^3), it is clear that the inventory of mixtures with manufactured fibres is much higher than that for mixtures with hybrid or recycled steel wires. When the content of manufactured fibres equals to 45 kg / m^3, the amount of CO2-

Equiv associated with fibre addition is almost the same as the amount attributed to the cement and GGBS (i.e. 99 kg CO2-Equiv). By considering a performance-based functional unit (e.g. design criteria for industrial ground floors [10]), the LCA results for "Climate change midpoint" indicate that the use of recycled steel wires or hybrid fibres (with at least an equal amount of recycled fibres, e.g. mixtures C and I) can provide an environmentally friendlier solution than plain concrete or a mixture containing only manufactured steel fibres (Figure 5). This demonstrates the high-performance obtained by the synergy of recycled wires and manufactured fibres [4].

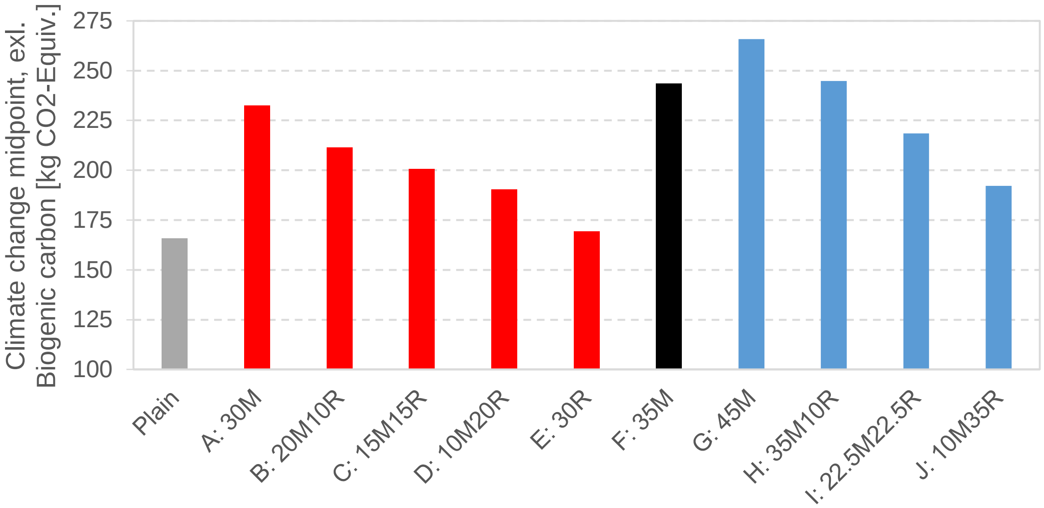

Figure 4: Steel fibre-reinforced concrete mixtures – Climate change midpoint, excl. biogenic carbon

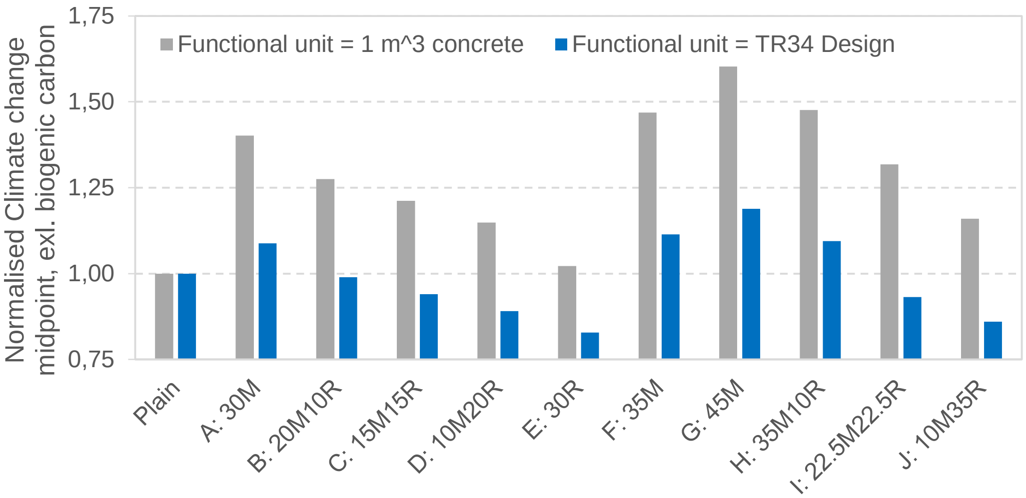

Figure 5: Steel fibre-reinforced concrete mixtures – Functional unit comparison

Figure 6 shows the LCA results for the ILCD impact category "Climate change midpoint" obtained for the polymer reinforced concrete mixes. Similarly, to steel fibre reinforced concrete mixes, the amount of CO2-Equiv increases with the amount of polymer/textiles fibres added to the concrete mixture. However, the results indicate that the use of recycled polymer/textile fibres leads to marginal increase of the amount of CO2-Equiv;

thus, demonstrating the environmental benefits of using recycled materials. However, this claim should be further elaborated with performance-based functional units, which are currently under development by the Anagennisis project.

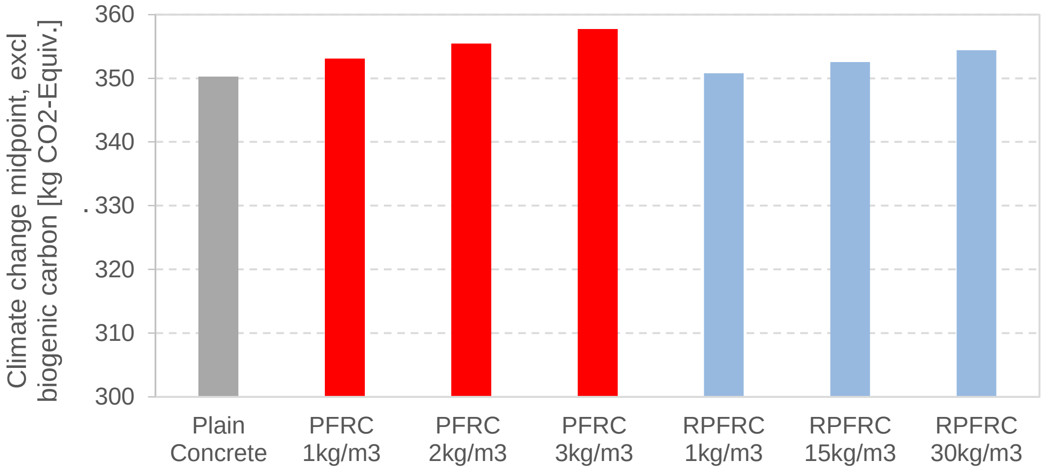

Figure 6: Polymer fibre-reinforced concrete mixes – Climate change midpoint, excl. biogenic carbon

5 CONCLUSIONS

This paper presented a "cradle to gate" environmental life-cycle assessment undertaken for concrete mixtures containing materials recycled from End-of-Life tyres, such as rubber particles, sorted steel wires and polymer/textile fibres.

Results of the ILCD impact category "Climate change midpoint" indicate that, for a functional unit of 1 m^3 of concrete, cement is the main factor contributing to the amount of CO2-Equiv; and this highlights the importance of using less-polluting cements, such as "low energy" and low calcination cements. Furthermore, for this functional unit, the results showed that the amount of CO2-Equiv increases marginally by the addition of tyre-recycled materials.

When performance-based functional units are considered in the LCA, the results highlight the importance of using these recycled materials in structural concrete applications that fully utilise the specific mechanical characteristics of each material.

ACKNOWLEDGMENTS

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REFERENCES

[1] Pilakoutas K, Neocleous K, Tlemat H. Reuse of Tyre Steel Fibres as Concrete Reinforcement. Proceedings of the Institution of Civil Engineers, Engineering Sustainability 157. 2004;ES3:131 - 8.
[2] Raffoul S, Garcia R, Pilakoutas K, Guadagnini M, Medina NF. Optimisation of rubberised concrete with high rubber content: An experimental investigation. Constr Build Mater. 2016;124:391-404.
[3] Neocleous K, Angelakopoulos H, Pilakoutas K, Guadagnini M. Fibre-reinforced roller-compacted concrete transport pavements. PROCEEDINGS OF THE INSTITUTION OF CIVIL ENGINEERS-TRANSPORT. 2011;164:97-109.
[4] Bjegovic D, Baricevic A, Lakusic S, Damjanovic D, Duvnjak I. Positive interaction of industrial and recycled steel fibres in fibre reinforced concrete. Journal of Civil Engineering and Management. 2013;19:S50-S60.
[5] Serdar M, Baricevic A, Jelcic Rukaniva M, Pezer M, Bjegovic D, Stirmer N. Shrinkage Behaviour of Fibre Reinforced Concrete with Recycled Tyre Polymer Fibres. International Journal of Polymer Science. 2015;2015:9.
[6] Huang S, Angelakopoulos H, Pilakoutas K, Burgess I. Reused tyre polymer fibre for fire-spalling mitigation. 4th International conference on Applications of Structural Fire Engineering ASFE'1. Dubrovnik Croatia2015. p. 6.
[7] European Commission - Joint Research Centre - Instistute for Environment and Sustainability. International Reference Life Cycle Data System (ILCD) Handbook - General Guide for Life Cycle Assessment - Detailed guidance. Ispra, Italy: European Union; 2010. p. 394.
[8] European Committe for Standardization. EN ISO 14044 Environmental management - Life cycle assessment - Requirements and guidelines. Brussels: CEN; 2006. p. 58.
[9] European Committe for Standardization. EN ISO 14040 Environmental management - Life cycle assessment - Principles and framework. Brussels: CEN; 2006. p. 32.
[10] Concrete Society. Technical Report 34 Concrete industrial ground floors, a guide to design and construction. Oxford UK: Concrete Society; 2013. p. 87.