The contribution of tire recycled materials in the circular economy of cement-based composites

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Abstract. Materials coming from end-of-life tires (so-called Tire Recycled Materials - TRM) can provide a valuable contribution to enhance the circularity of mortars and concretes. Within a cementitious mixture, secondary rubber from end-of-life tires can partially substitute stone aggregates, which is scarce in some areas of the Earth. However, this substitution is not always effective. As the content of rubber increases, both the reduction of strength and the increment of the potential impact on climate change can be observed in cement-based composites. Accordingly, a new assessment procedure, based on the eco-mechanical analysis, is herein proposed for mortars containing TRM. The aim is to increase mechanical performance and the use of secondary materials, as well as to reduce the environmental impacts. As a result, through a suitable combination of both rubber and steel fibers from end-of-life tires, new mortars showing better structural and environmental performances can be introduced.

Keywords: rubber, steel fibers, mortars, three-point bending test, LCA.

1 Introduction

Materials from end-of-life tires can be used in the construction industry because they effectively substitute some of the concrete components. Accordingly, several studies in technical literature focus on the substitution of stone aggregate with rubber (see, for a review, Azunna et al. [1]). The so-called rubber concrete can behave better than traditional concrete, showing lower density and a greater resistance to high strain-rate loads.

By shredding old tires, steel fibers can also be obtained and used in place of manufactured fibers, which often reinforce concrete mixtures. Indeed, fiber-reinforced concrete exhibits greater fracture toughness than plain concrete [2]. Moreover, the addition of recycled steel fibers from end-of-life tires can increase (of more than 50%) the flexural strength of unreinforced concrete [3].

By means of these tire recycled materials (TRM), the application of the European green public procurement (GPP) is possible, and “greener” structures and infrastructures are likely to be built. According to the Italian GPP, it is mandatory the use of cement-based composites containing at least 5% of recycled materials in public constructions [4]. However, this prescriptive approach to sustainability does not include the quantitative evaluation of potential environmental impacts of the overall structure made with cementitious materials. As many different variables can influence the environmental performance of building components, also the use of high contents of recycled material does not always guarantee sustainable solutions. For example, the recycled content could influence the mechanical properties of the component, the service life of structures, the recyclability at the end-of-life, etc. To fairly measure and compare the environmental impact of alternative components/materials, it is necessary to evaluate the different options in a more comprehensive way, through a life cycle perspective. The Life Cycle Assessment (LCA) is a standardized and internationally recognized methodology to perform these analyses considering different environmental indicators. Among the indicators that can be included in an LCA study, the calculation of carbon footprint (also called climate change indicator and measured in kg $CO_{2\ eq}$) of products is the most used.

The limitations of the GPP prescriptions become evident when stone aggregates are substituted by rubber granulates. Indeed, rubber concrete shows a decrement of compressive strength [5], which can be re-established by increasing the content of cement [6]. In most of the cases, the increment of $CO_{2\ eq}$ with the content of cement is higher than the reduction of the environmental impact produced by the replacement of stone aggregate with rubber. Thus, despite the application of GPP (or the presence of more than 5% of recycled materials), the environmental impact of rubber concrete can be higher than that of traditional concrete.

Although several environmentally friendly cement-based materials are tailored in accordance with the prescription of GGP, studies in which the prescription of the minimum content of TRM is combined with an analytical evaluation of LCA are very scarce in the technical literatures. The authors believe that the results of the experimental and theoretical analyses presented herein, concerning the mechanical and ecological performances of three different cementitious mortars, will be particularly useful to promote the use of tire recycled materials in the circular economy of construction industry.

2 Items of investigation

Mortars mixtures with TRM, either used to replace natural components (i.e., the substitution of sand with rubber), or added to the current cement-based mixtures (i.e., steel fibers as a reinforcement), are herein investigated. The aim is to measure the effects produced on the mechanical and environmental performances by the presence of these unconventional materials.

2.1 Materials, specimens, and mechanical tests

Three cement-based mortars are taken into consideration:

- M#1 is the UNI 196-1 [7] standard mortar, composed of 450 g/liter of cement (CEM II A-LL 42.5 R), by 225 g/liter of tap water, and by 1350 g/liter of sand (CEN Silica Sand). The granulometric fractions of the CEN Silica Sand are reported in Table 1.

Table 1. The granulometric fractions of the CEN Silica Sand [7] .

Sieve residue (g)					
2.00 mm	1.60mm	1.00 mm	0.50 mm	0.16 mm	0.08 mm
0	95	378	431	270	176

- M#2 is a modified mortar, composed by 450 g/liter of cement (CEM II A-LL 42.5 R), by 225 g/liter of tap water, by 980 g/liter of CEN Silica Sand, and by 93 g/liter of rubber granulates from end-of-life tires (sieve residue at a 0.5 mm, as illustrated in Fig.1a). With respect to M#1, 6% by mass of natural materials have been substituted by recycled rubber.
- M#3 is another modified mortar, composed by 450 g/liter of cement (CEM II A-LL 42.5 R), by 225 g/liter of tap water, by 980 g/liter of CEN Silica Sand, by 93 g/liter of rubber granulates (sieve residue at a 0.5 mm), and by 95 g/liter of recycled steel fibers from end-of-life tires (average length = 34 mm, as shown in Fig.1b).

A single prism (H= 40 mm, B= 40 mm, and L= 160 mm) was cast with each mortar and, after 28 days, it was tested in three-point bending, as suggested by UNI 196-1 [7] (see Fig.2).

(a) (b)

Fig. 1. Tire recycled materials used in the cement-based mortars: (a) rubber granulates (sieve residue at a 0.5 mm); (b) recycled steel fibers (average length 34 mm).

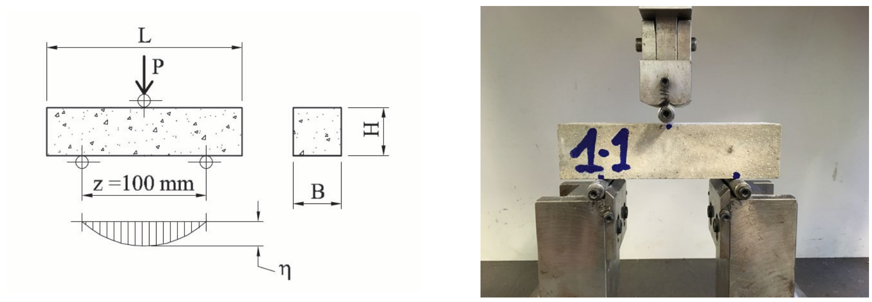


Fig. 2. The three-point bending tests of cement-based prisms (UNI 196-1 [7]).

The external load P was applied through a loading machine (with a maximum loading capacity of 50 kN) by driving the displacement of the loading cell, whose stroke moved at a velocity of 0.5 mm per minute. Both the applied load P and the midspan deflection η of the beam were recorded during the tests, till the complete failure of the specimen.

2.2 Calculation of the Material Circularity Indicator (MCI)

Since one of the aims of this study is to enhance the circularity of the mortar production, an indicator to measure this aspect has been considered. It is the Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation and Granta Design (https://www.ellenmacarthurfoundation.org/material-circularity-indicator).

The MCI assesses a product circularity by evaluating both the origins of the components of the product and the product's end of life, as listed in Table 2. The variables included in the calculation are in line with the Ellen MacArthur Foundation. The result of the MCI can range from 0 (fully linear process) to 1 (fully circular process), meaning that the higher the score the higher the circularity of the product under investigation.

In the case of the three mortars, composed by cement and sand (M#1), rubber granulates from end-of-life tires (for M#2 and M#3), and the steel fibers from end-of-life tires (only for M#3), Table 2 summarizes the values used for calculating MCI, starting from the mass of materials included in each cementitious mixture.

2.3 The Carbon footprint of the mortars

A complementary environmental analysis has been developed to estimate the carbon footprint of 1 liter of the three mortars, by means of the LCA methodology.

In this project, the LCA model has been realized with the support of the software Simapro 9.6 and the database Ecoinvent 3.10 (allocation, cut-off), whereas impacts have been calculated with the method EF3.1. The selected datasets for the cement and sand are respectively "Cement, CEM II/A {Europe without Switzerland}| market for cement, CEM II/A | Cut-off, S" and "Silica sand {GLO}| market for silica sand | Cut-off, S". The rubber granulates and the steel fibers have been modeled according to the data introduced in previous studies [8], which consider the entire production, from the collection of end-of-life tires to the production of both the recycled materials.

Initially, the functional unit of this LCA is 1 liter of mortar, but in the next sections, beams having the same bearing capacity of 20 kN are also analyzed.

3 Test results

3.1 Mechanical properties

The results of the three-point bending test are reported in Fig. 3. More precisely, the load deflection diagrams of all the specimens are shown in Fig.3a, whereas the histogram of Fig.3b illustrates the values of the maximum load P_{max}, and of flexural strength f_{ctf}, measured during the tests.

Table 2. Parameters and values used for the calculation of the MCI.

		M#3			
		M#2			
		M#1			
Symbol	**Definition**	**Cement**	**Sand**	**Rubber granulates**	**Steel fibers**
FR	Fraction of the product's raw material mass derived from recycled sources	0.0326	0	1	1
FU	Fraction of the product's raw material mass sourced from reused sources	0	0	0	0
FS	Fraction of the mass of biological materials	0	0	0	0
CC	Fraction of the product's mass intended for composting	0	0	0	0
CE	Fraction of the product's mass intended for energy recovery	0	0	0	0
CR	Fraction of the product's mass collected for recycling	1	1	1	1
CU	Fraction of the product's mass intended for component reuse	0	0	0	0
EC	Efficiency of the recycling process used for the portion of the product destined for recycling (post-consumer)	0.75	0.75	0.75	0.83
EF	Efficiency of the recycling process used to produce recycled raw material with which the product was made (pre-consumer)	0.8	1	0.8	0.83
L	Average actual lifespan of a product in years	50	50	50	50
Lav	Average lifespan in years of a typical product in the same sector	50	50	50	50
U	Number of functional units reached during the product's use phase	1	1	1	1
Uav	Number of functional units reached during the use of a typical product in the same sector	1	1	1	1

The latter is computed in the linear elastic regime with the following formula:

$$f_{ctf} = \frac{3}{2}\frac{P_{max}\,z}{B\,H^2} \tag{1}$$

where B = H = 40 mm, and z = 100 mm.

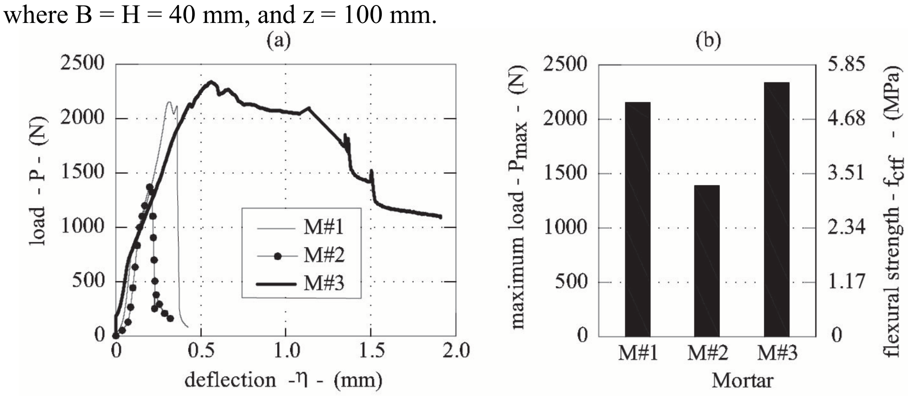


Fig. 3. Three-point bending tests on the beams investigated in this project: (a) load-deflection (P-η) diagrams; (b) the maximum load P_{max} (and flexural strength f_{ctf}) measured during the tests.

It comes as no surprise that the reduction of strength in the mortar containing rubber in place of the stone sand. More precisely, the flexural strength of mortar M#2 is 35% lower than that measured in mortar M#1. This result agrees with the analyses carried out by Gregori et al. [5], in which the compressive strength of rubber concrete reduces by more than 30%, when the substitution rate of stone aggregate with rubber is about 5%.

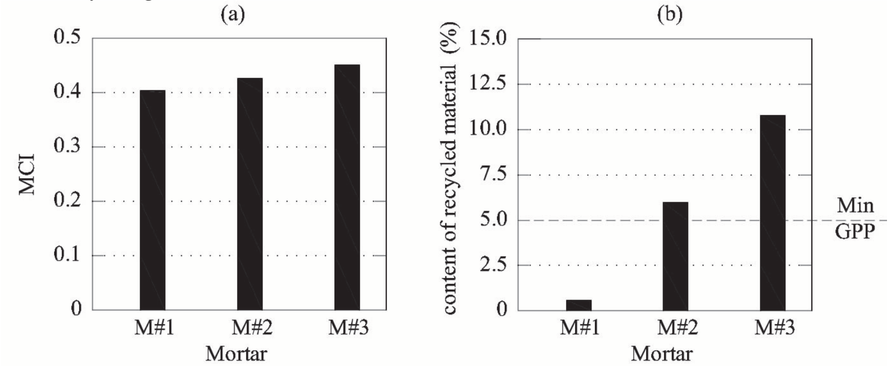
However, recycled steel fibers, similarly to the those industrially manufactured, can generate a deflection hardening behavior in fiber-reinforced concrete [9]. Consequently, an increment of flexural strength is observed in mortar M#3, in which f_{ctf} is 68% higher than in M#2, and 9% higher than in M#1. Therefore, a suitable combination of different TRM (as in mortar M#3) can even increase the mechanical performance of the cement-based composites made with only virgin materials (like mortar M#1).

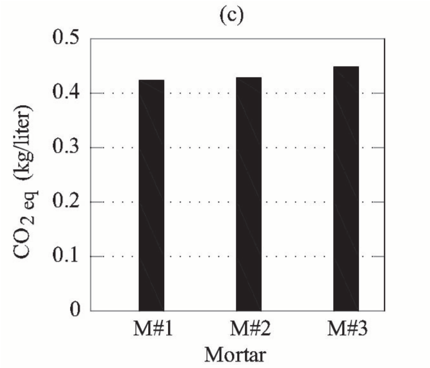
3.2 The environmental impact

Obviously, in mortar M#3 the best use of recycled materials is achieved. because the content of TRM (Fig.4b) is the highest. Therefore, also the MCI shows the highest value (Fig. 4a). As it can be noticed, the scores obtained by the three mortars are more or less the same, ranging from 0.40 (for M#1) to 0.45 (for M#3). This is because the majority of the mortars are composed of silica sand and cement, which are primarily derived from virgin materials. It must be remarked that the content of recycled material in mortar M#2 (6%) and in mortar M#3 (11%) is higher than the minimum imposed by the Italian GPP (see Fig.4b).

However, the results of LCA reveal an opposite trend, as illustrated in the histogram in Fig. 4c. When considering 1 liter of product, the carbon footprint of the three mortars increases with the content of recycled materials. This is due to a combination of factors.

Firstly, the primary contributor to the total impact (accounting for more than 80% across all three mortars) is cement, whose quantity remains unchanged in all the mortar mixtures. Secondly, the partial replacement of sand (which has a low carbon footprint) with recycled rubber and steel adds additional impacts, due to the processes involved in tire recycling.





	Mortar		
	M#1	M#2	M#3
MCI	0.40	0.43	0.45
Recycled materials	0.58%	5.96%	10.8%
Carbon footprint (kg $CO_{2\,eq}$ /liter)	0.42	0.43	0.45
P_{max} (N)	2150	1390	2340
f_{ctf} (MPa)	5.01	3.26	5.48

Fig. 4. Environmental performances of the mortars investigated herein: (a) the coefficient MCI; (b) the mass of recycled materials with respect to the minimum content prescribed by GPP (i.e., 5%); (c) The carbon footprint estimated through LCA, and measured in kg $CO_{2\,eq}$.

Finally, it has to be observed that M#3 shows the highest flexural strength, which can lead to a lower environmental impact, if the bearing capacity of the beam is assumed to be the functional unit of LCA (see section 4.1).

4 Discussion

The ecological and mechanical analyses previously described can be combined within the non-dimensional diagram shown in Fig.5 [10]. On the abscissa of this diagram, the mechanical ratio (i.e., the ratio between the mechanical performance MI and its lower bound value MI_{inf}) is reported, whereas the ecological ratio is on the vertical axis. The latter can be obtained in two different ways: if the ecological index EI is something that has to be minimized (such as $CO_{2\,eq}$), then the ecological ratio is equal to upper bound value of ecological impact EI_{sup} divided by EI. Whereas, if the ecological index EI is something that have to be maximized (e.g., the content of recycled material), then EI must be divided by the lower bound value of the ecological impact EI_{inf} . All the bounds can be either prescribed by code rules (like GPP) or imposed by tender requirements.

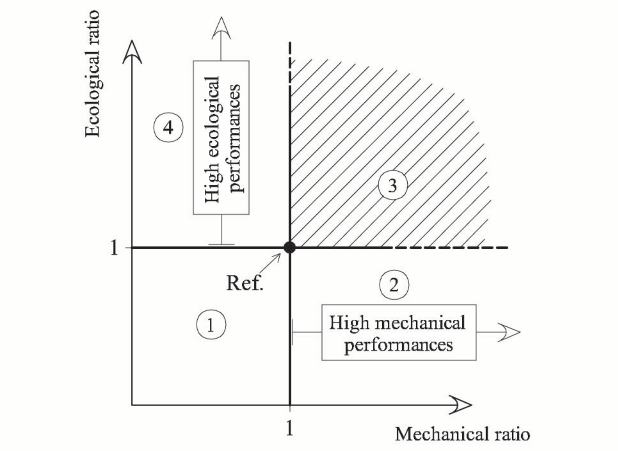


Fig. 5. The non-dimensional eco-mechanical chart for the comparative analyses of cement-based composites.

Accordingly, four different zones can be defined within the non-dimensional diagram of Fig.5:

- Zone 1: Low mechanical performances– Low ecological performances.
- Zone 2: High mechanical performances– Low ecological performances.
- Zone 3: High mechanical performances– High ecological performances.
- Zone 4: Low mechanical performances– High ecological performances.

In the mortars investigated herein, only flexural strength was considered. Thus, P_{max} of mortar M#1 (= 2150 N) is assumed to be the lower bound value of the mechanical index (i.e., MI_{inf}). If the ecological index is based on the content of recycled materials, either EI_{inf} = 0.4 (the value of MCI in mortar M#1) or EI_{inf} = 5% (the minimum content of recycled materials imposed by the Italian GPP) can be taken into consideration. In both these cases, the non-dimensional diagrams illustrated in Fig.6a and Fig.6b, respectively, show the same result.

In mortar M#2, where rubber granulates partially replaced natural sand, the environmental performances improved with respect to mortar M#1. Due to the presence of recycled materials, M#2 is in the fourth sector of the diagrams depicted in Fig.6a and Fig.6b. However, in this sector the mechanical performance is lower than that of the reference mortar M#1, because the flexural strength of M#2 is remarkably lower than that of M#1. The addition of recycled steel fibers (in mortar M#3) produces an increment of the mechanical performance (which is higher than that of M#1) and a more environmentally friendly mortar. As the fibers increased the mass of recycled materials, mortar M#3 falls within the third sector of the non-dimensional charts depicted in Fig.6, with the highest mechanical and ecological performances.

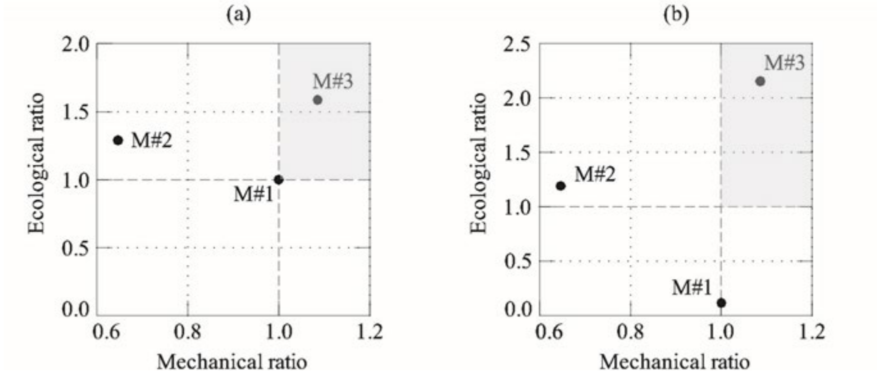


Fig. 6. Eco-mechanical analyses of the mortars when MI_{inf} = 2150 N (flexural strength of Mortar #1): (a) EI_{inf} = 0.4 = value of MCI of the mortar M#1; and (b) EI_{inf} = 5% = minimum content of recycled materials imposed by GPP.

If the ecological performances are based on GWP through the evaluation of the $CO_{2\ eq}$, it is possible to consider EI_{sup} = 0.42 kg CO_2/m^3 (i.e., the carbon footprint of mortar M#1). In this way, the corresponding non-dimensional eco-mechanical chart depicted in Fig.7a shows the three mortars close to the line $EI_{sup}/EI = 1$. In fact, there is not a great variation of the $CO_{2\ eq}$, because the greatest contribution to carbon footprint is given by the content of cement, which is always the same. However, mortars M#2 and M#3 are in two different sectors, as the flexural strengths are respectively lower and higher than that of M#1.

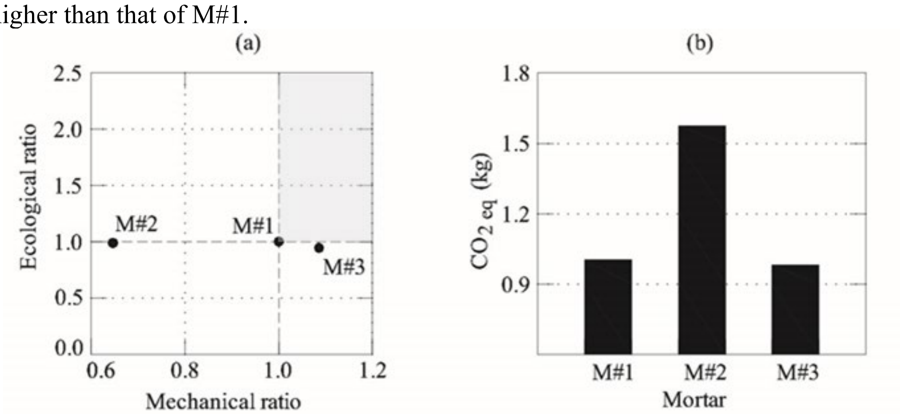


Fig. 7. Eco-mechanical analysis of the mortars performed (a) at material level, considering MI_{inf} = 2150 N (flexural strength of mortar M#1) and EI_{sup} = 0.42 kg CO_2/m^3 (carbon footprint of mortar M#1), and (b) at structural level, when the maximum load capacity of the three beams is constant (P_{max} = 20 kN).

As none of the mortars fall in sector 3, it is possible to conclude that the use of TRM does not reduce the environmental impact of reference mortar M#1. In other words, the prescription of more than 5% of recycled materials, as suggested by the GPP, does not always reduce the GWP, especially when the eco-mechanical analysis is performed at material level.

4.1 Eco-mechanical analyses at structural level

As in mortar M#3 the flexural strength is higher than that observed in the reference mortar M#1, the eco-mechanical analysis at structural level provides different conclusion. Indeed, when the performance strategy is applied to reduce the environmental impact [11], high performance cement-based materials show higher carbon footprint as observed before. Nevertheless, if performance increases, the global volume of the structure tends to decrease, and the corresponding $CO_{2\ eq}$ reduces as well [12].

As an example, in the beam illustrated in Fig.2, the depth H is fixed (and equal to 40 mm) whereas the width B changes in order to have the same strength P_{max} = 20kN in the three mortar beams (see Fig.3b). The values of B, as reported Table 3, can be obtained from Eq.(1):

$$B = \frac{3}{2}\frac{P_{max}\, z}{f_{ctf}\, H^2} \tag{2}$$

where P_{max} = 20 kN and z = 100 mm.

Table 3. Eco-mechanical analyses performed in beams having P_{max} = 20 kN.

Mortar	H (mm)	L	f_{ctf} (MPa)	At material $CO_{2\ eq}$ (kg/liter)	B (mm)	Volume = B×H×L (liter)	In beams GWP (kg $CO_{2\ eq}$)
M#1	40	160	5.05	0.42	371	2.38	1.01
M#2	40	160	3.26	0.43	575	3.68	1.57
M#3	40	160	5.48	0.45	342	2.19	0.98

The comparison of the impact on climate change of each beam, calculated as the product of the volume (B × H × L) times the carbon footprint at material level (in kg $CO_{2\ eq}$/liter), is reported in the last column of Table 3 and in the histogram of Fig.6. It is possible to state that the lowest environmental impact is obtained in the beam made with the mortar M#3, although the strength of all the beams is the same (P_{max} = 20 kN).

5 Conclusions

According to the experimental findings and to the computational analyses illustrated in the previous sections, the following conclusions can be drawn:

- In cement-based mortars, the prescription of the Italian Green Public Procurement can be easily reached by substituting natural sand with rubber.

- As the substitution of sand with rubber tends to reduce the flexural strength, recycled steel fibers can also be added to maintain (or increase) this strength.
- At the material level, $CO_{2\,eq}$, evaluated with a LCA analysis, slightly increases when sand is substituted by rubber and recycled steel fibers are used to reinforce cement-based mortars.
- However, the addition of fibers produces an increment of flexural strength, which in turn determines a reduction of the final volume of beams in bending. Consequently, the GWP of structural elements can reduce when TRMs are properly used.

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