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Environmental sustainability of precast and cast-in-situ concrete structures: a case-study comparison based on built supermarket facilities

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Abstract. Environmental sustainability is assuming a growing role in the strategic plans of several countries worldwide. In order to switch to more sustainable solutions in the construction field, many researchers and efforts are focusing on the material level, mainly concerning solutions aimed at partially or fully replacing the most impacting components with alternative or recycled solutions characterised by a lower carbon footprint or a higher durability, in view of a life-cycle assessment. Alongside these positive efforts, another instrument to reduce the environmental impact of construction materials, often less tackled by researchers, is reduction of material consumption by structural optimisation, often ensured by innovative technologies possibly employing high-performance materials that might even have, assuming same volume, higher impact than traditional ones. This concept is analised in the present paper by comparing the computed environmental equivalent carbon footprint of two similar single-storey supermarket facilities, designed and built in the Po valley, Northern Italy, with different technologies: precast and cast-in-situ concrete. Having at disposal the final consumptive volume of materials employed for both buildings concerning the superstructure frame without cladding, the comparison based on Global Warming Potential (GWP) certified by material producers, computed per square metre covered, allowed to evaluate the actual impact of the structure of the two solutions. Moreover, the environmental-related benefits provided by the replacement of the most impacting components (steel and cement) with alternative environmentally friendly solutions further allows to quantify and target the most effective strategies to enhance the sustainability of structural bodies.

Keywords: Environmental impact, Sustainability, Concrete structures, Precast, Cast-in-situ, Carbon footprint, Green materials.

1 Introduction

Environmental sustainability is attracting growing interest in all fields of human activities as concern towards climatic change is globally raising. The construction industry is responsible for a relevant percentage of equivalent consumption of carbon dioxide (CO_2), and hence the issue of sustainability in this field is being extensively tackled at all levels, from academic research to field applications. According to EN 15978:2001 [1], the issue of sustainable construction should be tackled from a life-cycle point of view, following the processes highlighted in Table 1 for the different life-cycle stages envisaged. As an example of these stages, a more sustainable construction could not only involve less impactive materials, but also structural or energetical solutions that may enhance its performance, for instance elongating the life of the building by selecting a more robust and durable structure or providing passive and active measures of containment/production of energy consumption.
Combined structural and energetical enhancement interventions are currently trending for the retrofit of buildings following these concepts [2].

Table 1. Life cycle stages according to EN 15978:2011.

Life Cycle Stages	Production			Construction		Use							End-Of-Life				Benefit and Loads
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Processes	Raw Material supply	Transport	Manufacturing	Transport	Construction/Installation	Use	Maintenence	Repair	Replacement	Refurbishment	Operational Energy use	Operational Water use	Deconstruction/Demolition	Transport	Waste Processing	Disposal	Reuse, Recovery and Reciclyng

Among the components that mostly affect the environmental impact of constructions, the structural bodies play a crucial role. Concerning reinforced concrete structures, the consumption of cement and the employment of steel are the main sources of carbon footprint. Research is mostly focused on finding alternative materials for these components, such as green cements based on clinkers alternative to portland, for instance based on sulfoaluminate components, or as composite mineral or plastic fibre-based material alternative to steel [3]. Binders such as fly ash, silica fume, granulated blast furnace, etc., are also being considered in partial replacement of cement to reduce the direct environmental impact of concrete and to embed in concrete polluting constituents originated from diverse industrial productions, subtracting them from waste management and disposal. This strategy, widely adopted for mix designs employed for precast concrete, may also relevantly increase the strength of concrete. Higher performance concrete, especially if combined with pre-stressing or if employed in vertical elements not affected by bending moments under gravity loads, as typically done for precast industrial structures, may increase the sustainability of concrete also from a life-cycle perspective, as schematically shown in Fig. 1.

Nevertheless, also different life-cycle oriented strategies aimed at enhancing the durability and the resilience of structural bodies are being tackled. An emblematic solution aimed at mitigating the life-cycle environmental impact of concrete consists in adding healing admixtures in the mix design providing concrete with the new capacity to self-repair the cracks [4-7], which directly affects the durability of cast-in-situ concrete structures, typically cracked under service load. Despite an initial higher cost of the concrete mix, such a solution may allow the original structural performance to regain its initial level without direct and indirect repair costs, respecting the planned life cycle or increasing it (Fig. 2).

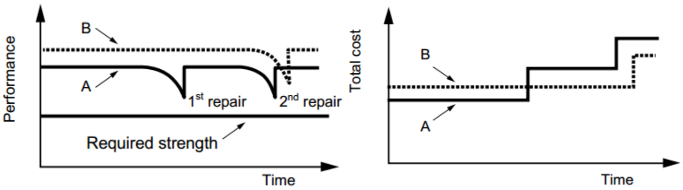


Fig. 1. Performance (on the left) and cost (on the right) as function of time for normal (A) and high quality (B) structures (adapted from [4]).

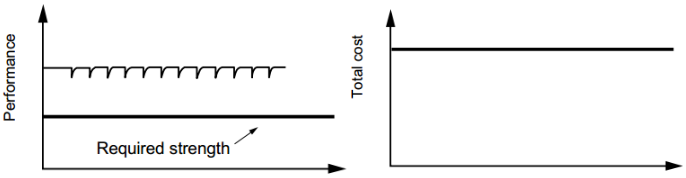


Fig. 2. Performance (on the left) and cost (on the right) with elapse of time for a structure made of self-healing concrete (adapted from [4]).

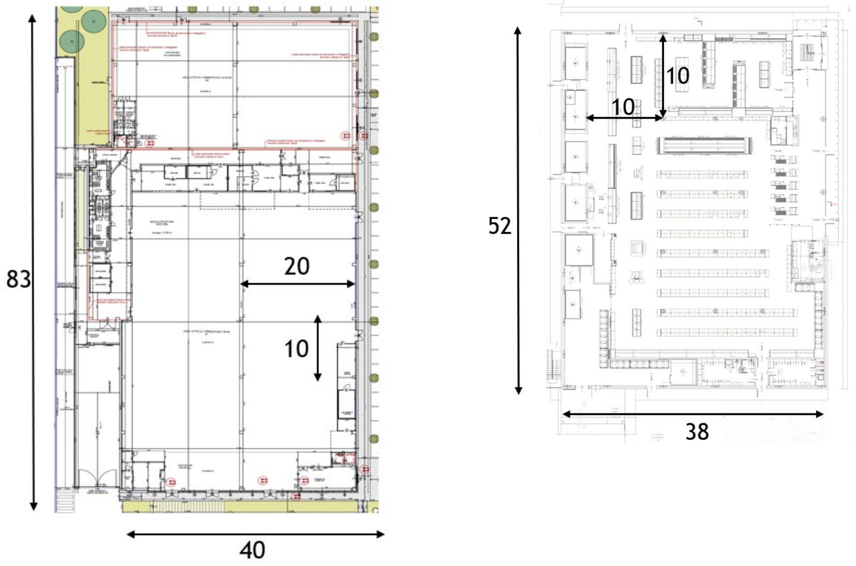
Alongside these positive efforts, another crucial source of reduction of environmental impact for constructions relies on the mere limitation in the consumption of material, which may be provided more at structural design level, rather than material, by employing optimised highly engineered structures. To be noted that this approach to sustainability only indirectly enters into the classification of the actions listed in Table 1.

Precast concrete structures are naturally prone to attain such objective, since complex cross-sections and large spans can be achieved by the combined use of highly technological metallic moulds and by the employment of the prestressing pre-tensioning technique [8,9], making its use indeed technologically much different with respect to cast-in-situ structural bodies. As a counterbalance, precast elements usually can attain the structural optimisation by employing high-performance materials having larger environmental impact than those employed in cast-in-situ constructions, such as high-strength cement and prestressing steel.

The present paper aims at exploring how the structural optimisation and subsequent low volume of materials employed in precast structures can balance the higher environmental impact of the materials themselves. This is carried out through a a-posteriori comparison on two similar supermarket buildings designed and actually constructed in near areas of the Po valley under practically identical boundary conditions (similar layouts, similar ground properties, identical load requirements). The analysis is carried out firstly by analysing the consumptive material bills of the two structures, then weighing them through the pertinent Global Warming Potential (GWP) indexes of the different components of the structural materials employed. Finally, the potential reduction of impact provided by the use of alternative materials is also evaluated.

2 Case study buildings

The two case study supermarket buildings have layout shown in Fig. 3, where the precast (Fig. 3a) and the cast-in-situ (Fig. 3b) buildings have similar width of about 40 m, while the former is 83 m long, more than the latter, which measures 52 m.



(a) (b)

Fig. 3. Layouts of the case study buildings: (a) precast; (b) cast-in-situ.

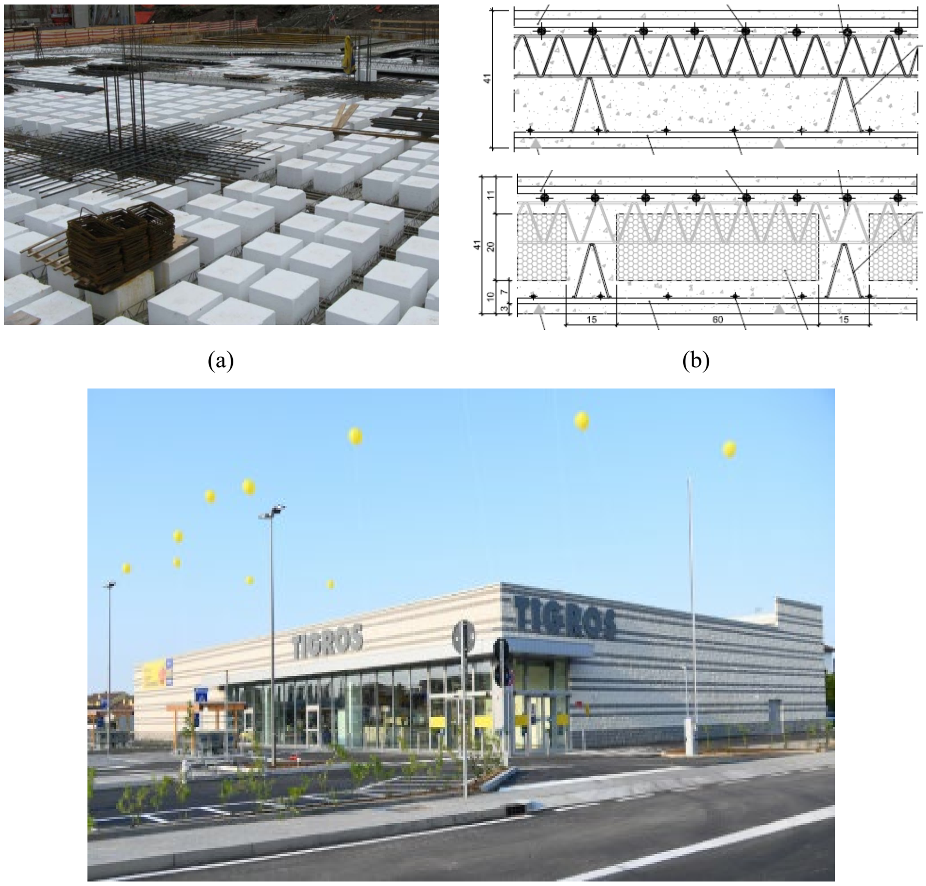
The precast building is characterised by a regular structural grid of 10 m by 20 m (Fig. 3a), with compact-shape 0,6~0,8 cm deep prestressed beams resting on square columns running along the short side, and 0,85 m deep and 2,5 m wide prestressed wing-shaped roof elements running along the longer side. In between the roof wing-shaped elements, spaced at an interaxis of 6 m, flat 3-ribbed concrete plates are installed. Fig. 4a shows an internal view of a building employing the same technology, while the roof cover system is sketched in cross-section and viewed from the top in Fig. 4b. This roof system provides a lightweight solution: given the wing-shaped element average vertical-equivalent thickness of 12,8 cm and the 3-ribbed concrete plate average thickness of 5,5 cm, the total average vertical-equivalent roof thickness becomes equal to only 8,5 cm. A picture of the building under construction extracted from a drone footage is shown in Fig. 4c. To be noted that the two additional columns visible on the shorter side edges of the building are installed for support of peripheral horizontal cladding panels only. The materials employed are concrete C45/55, reinforcing mild steel B450C, and prestressing steel grade 1860.


(b)

(a) (c)

Fig. 4. Precast building: (a) internal view of a building employing the same precast system considered for the case study (courtesy of Stai Prefabbricati); (b) 3D render view of the roof system employing wing-shaped prestressed elements and completing 3-ribbed plates (courtesy of Stai Prefabbricati); (c) picture extracted from a drone footage of the case study supermarket building under construction.

The cast-in-situ building is characterised by an irregular grid whose maximum dimensions become around 10 m by 10 m (Fig. 3b), although one side reduces down to about 6 m in several locations. The structural solution adopted for the roof system is that of a flat slab resting on either square or rectangular elongated columns. In order to sustain the stress originated in the larger grid area, while finding a balance with the structural weight of the slab, the central portions of the slab grids subjected to less shear and punching stresses were internally enlightened by the use of polystyrene panels embedded into the concrete cast as shown in Fig. 5a referring to a similar building than that of the case study. The 41 cm deep slab cross-sections employed in the case study building are shown in Fig. 5b. Solid concrete slab was cast in proximity of the columns and along the peripheral equivalent beams of each grid, as shown in Fig. 5a. A picture of the completed building is shown in Fig. 5c. The materials employed are concrete C28/35, and reinforcing mild steel B450C.



(a)

(b)

(c)

Fig. 5. Cast-in-situ building: (a) view of a slab under construction employing a technique similar to that of the case-study building; (b) solid and polystyrene-lightened cross-sections of the structural slab; (c) picture of the case study supermarket building after construction.

3 Consumption of material

The consumptive bill of material employed for the construction of the building was made available by the construction company which carried out and supervised the erection of both buildings. In order to derive a meaningful comparison, the structural load-bearing elements making part of the superstructure only were considered, which includes columns, beams, and slabs. Foundations and reinforced concrete employed for the façade system, rather complex and mixed with other materials for the supermarket buildings, are not part of the following calculations.

The absolute and specific (per covered surface) material quantities employed for the two buildings are listed in Table 2. The bill of materials was delivered with more specific items for the precast building. For a meaningful comparison, specific values should be considered.

Differences of about 4 times exhibit between the two technologies: the average concrete thickness per covered surface rises from 11 cm in the precast system to 45 cm in the cast-in-situ system; steel consumption rises from 17 kg/m^2 to 79 kg/m^2.

Table 2. Material consumption for the two buildings.

	UNIT	TOTAL	PER COVERED SURFACE (/m^2)
PRECAST			
TOTAL CONCRETE C45/55	mc	456	**0,11**
MILD STEEL CAGES (columns+beams)	kg	18.601	4,33
MILD STEEL CAGE (roof+plates)	kg	11.356	2,64
MESHES	kg	5.246	1,22
BENT MESHES	kg	11.315	2,63
TRUSSES (plates)	kg	5.073	1,18
STRANDS (including scrap)	kg	19.919	4,63
GRAND TOTAL STEEL	kg	71.966	**16,73**
CAST-IN-SITU			
TOTAL CONCRETE C28/35	mc	873	**0,45**
TOTAL MILD STEEL	kg	153.000	**78,87**

As previously mentioned, this considerable reduction of the use of material comes with the high engineering of all elements, obtained by employing more performant concrete classes and steel grades, which comes at a cost from the environmental point of view which may partially balance the global reduction of material consumption.

Table 3. Concrete mix design for the two buildings (values in kg/m^3).

	PRECAST (C45/55)	CAST-IN-SITU (C28/35)
CEM I 52,5 R	420	-
CEM IV 32,5 N	-	350
SAND + GRAVEL	1820	1870
SUPERPLASTICISER	7	-
WATER	132	190
TOTAL	**2378**	**2400**
W/C RATIO (-)	0,31	0,54

Table 3 contains the specifications of two mix designs associated to the concrete classes employed in the two case study buildings. It can be noted that in the precast mix design not only higher-class cement is used, but also in higher quantity relative to a cubic metre. Moreover, the strong reduction in water consumption in the precast mix is compensated by the use of a superplasticizer admixture, a chemical product which also comes with a certain environmental impact.

4 Evaluation of environmental impact

The evaluation of the environmental impact comes through the definition of the GWP indexes, as previously introduced, in order to derive the quantity of equivalent carbon dioxide associated to each component of the structural bodies. The list of Table 4 is derived on the basis of voluntary Environmental Product Declaration (EPD) documents emitted by certified material producers located in Italy. To be noted that, besides an almost negligible GWP associated to water and aggregates (sand and gravel), relatively high GWPs are found for cement, steel, and superplasticizer admixture. In particular, it is noted that the GWP associated to the high-performance cement class I 52,5 R is 35% higher than that associated to the lower-class cement employed in the cast-in-situ mix design. Moreover, the GWP of prestressing steel is considerably (2,74 times) higher than that of mild steel.

The GWPs for alternative materials are listed at the bottom of Table 4. Sulfoaluminate cement allows for a reduction of GWP of 19% with respect to more traditional high-performance Portland cement; composite Glass Fibre Reinforced Polymer (GFRP) bars, apparently characterised by a higher impact due to the higher GWP, need to be evaluated by equal weight employed, and thus need to be mediated by the much lower density with respect to steel, attaining a reduction of about 40% of equivalent mass of carbon dioxide. To be noted that GFRP or BFRP (basalt-based) bars can directly replace mild steel (at a higher cost) due to similar design strength properties, but about a double volume should be employed to replace prestressing strands due to their higher strength, although technological and rheological issues still need to be completely solved before a large-scale application could be done [3].

Weighing the GWP by the quantities of material components employed for the case-study buildings, the absolute and specific environmental impacts of the two case-study buildings are listed in Table 5. Again considering for a more meaningful comparison the specific values, it can be concluded that the GWP associated to the precast and cast-in-situ technologies are equal to 68 and 186 kg of equivalent carbon dioxide per square metre of covered surface, respectively. The difference, although slightly lower with respect to the global consumption of material due to the higher impact of more performant materials, is again hugely pending in favour of the precast construction technology, associated to a reduction of 62% in the emission of equivalent carbon dioxide with respect to the cast-in-situ technology.

Analysing the relative weight of each component, it can be noticed that more than half of the total impact is associated with cement (59% and 51%); the other important component is given by steel (33% and 40%); the contribution of the superplasticizer admixture, used in the low quantity of 7 kg/m^3 of concrete, provides a practically negligible contribution despite its high potential GWP.

A resuming picture including the scenarios employing alternative materials is shown in Table 6. It can be observed that the replacement of mild steel with GFRP bars, despite the higher cost, could ensure a GWP reduction of 15% of the cast-in-situ construction. For this technology, the use of sulfoaluminate cement is not analysed since it is hardly suitable for cast-in-situ applications due to its rapid hardening. A similar reduction of 15% with GFRP bars is found for the precast technology, which becomes 26% if adding the contribution of sulfoaluminate cement replacing portland.

Table 4. GWP indexes employed.

MATERIAL	**DENSITY (ton/m^3)**	**GWP (kg Co_2 eq/ ton)**	**GWP (kg Co_2 eq/ m^3)**
CEMENT I 52,5 R	3,15	**910**	2866,5
CEMENT IV 32,5 N	3,15	**588**	1852,2
MILD STEEL	7,85	**924**	7253,4
STRAND	7,85	**2530**	19860,5
SAND + GRAVEL	1,5	20,7	31,1
SUPERPLASTICISER	1,1	**1888**	2076,8
WATER	1	-	-
SULFOALUMINATE CEMENT	3,15	740 (-19%)	2331
GFRP BARS	1,9	2303 (-40%)	4375,7

Table 5. Environmental impact of the structure of the two buildings.

PRECAST	**tonCO_2 eq**	**kgCO_2eq/ m^2**	**% of CO_2 emission**
CEMENT I 52,5 R	174,28	40,04	58,6
MILD STEEL	48,09	11,18	16,2
PRESTRESSING STEEL	50,39	11,64	17,1
SUPERPLASTICISER	6,02	1,43	2,1
SAND + GRAVEL	17,18	4,00	5,8
TOTAL	**295,97**	**68,29**	**100**
CAST-IN-SITU			
CEMENT IV 32,5 N	179,66	94,1	50,5
MILD STEEL	141,37	73,9	39,6
SAND + GRAVEL	35,62	18,1	9,9
TOTAL	**356,65**	**186,1**	**100**

Table 6. Specific environmental impact of the structure of the two buildings including alternative material use (values in $kgCO_2eq/m^2$).

	PRECAST				CAST-IN-SITU	
MATERIALS	ORD	GFRP + SULF	GFRP	SULF	ORD	GFRP
CEM I 52,5R	40,04	-	40,04	-	-	-
CEM IV 32,5N	-	-	-	-	94,1	94,1
SULF CEM	-	32,56	-	32,56	-	-
GFRP BARS	-	7,00 + 5,3(*)	7,00 + 5,3(*)	-	-	46,06
MILD STEEL	11,18	-	-	11,18	73,9	-
PREST STEEL	11,64	-	-	11,64	-	-
SAND+GRAVEL	4,00	4,00	4,00	4,00	18,4	18,4
SUPERPLAST	1,43	1,43	1,43	1,43	-	-
TOTAL	**68,3**	**50,3 (-26%)**	**57,8 (-15%)**	**60,8 (-11%)**	**186,1**	**158,3 (-15%)**
TOTAL/MAX	**38%**	**28%**	**32%**	**34%**	**100%**	**85%**

(*): the second term concerns replacement of prestressing steel, which is assumed with double volume of GFRP bars
ORD: ordinary (portland cement, mild steel, prestressing steel);
GFRP: reinforcement replaced by glass-fibre-reinforced-polymer bars;
SULF: portland cement replaced by sulfoaluminate cement

5 Conclusion

Precast reinforced concrete employ materials having higher impact per concrete volume with respect to cast-in-situ techniques. However, the high engineering and structural optimisation of the structural elements brings to relevant reductions of consumption of material. In the supermarket buildings analysed, the precast technology allows for a reduction of 3/4 of the consumption of concrete and steel with respect to the cast-in-situ technology employed. The global reduction of material consumption highly predominates over the higher environmental impact of the material employed, ensuring a global reduction of 62% of emission of equivalent carbon dioxide per covered surface. This huge margin may even be increased if, at a higher cost, alternative green materials such as sulfoaluminate cement and/or composite bars are employed, ensuring a reduction of 11%~26% with respect to the nominal impact. It is however noted how this reduction is much less effective with respect to the switch from a traditional cast-in-situ technology to a more engineered one envisaging prefabrication. This trend is confirmed also for other building typologies [10], despite generally for multi-storey buildings the environmental impact reduction becomes shallower due to the need to employ elements having flat surfaces.

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