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Case study

The carbon footprint of normal and high-strength concrete used in low-rise and high-rise buildings

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ABSTRACT

To reduce the mass of CO_2 released into atmosphere by the construction industry, the performance strategy can be adopted. It is based on the use of High-Strength Concrete (HSC) in alternative to Normal-Strength Concrete (NSC). Such concretes are herein considered to design the reinforced concrete structures of three buildings, having 14, 30 and 60 floors, respectively. For each building, the structural analyses, carried out for four classes of concrete (i.e., C25, C40, C60 and C80) in accordance with Eurocode 2, provides different dimensions of the structural elements. In other words, the amount of CO_2, released in the atmosphere due to the production of the structural materials, is a function of both concrete strength and height of the building. As a result, the minimum impact of low-rise buildings occurs when the structural elements are made with NSC. Conversely, only when HSC is used to cast the structural elements of tall buildings, can the carbon footprint be effectively reduced.

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1. Introduction

1.1. State of the art

Nowadays, the greenhouse gases reduction is one of the biggest challenges for mankind. To face this problem, all the industrial sectors, responsible for the 25% of the global CO_2, must be involved. This is particularly true for the cement industry, which produces about 7% of the carbon dioxide released in the atmosphere [1,2]. To be more precise, 95% of this CO_2 is due to the production process, whereas the remaining 5% is related to the transportation of raw materials and cement-based composites [3].

It is also interesting to note the proportions of CO_2 emitted for the production of clinker. Indeed, the calcination of limestone produce 74% of carbon dioxide, and only 26% is caused by the burning of fossil-based fuel used to cook the raw materials [4,5]. As a consequence, in addition to the strategies that substitute the traditional fuels with alternative energy sources, other strategies are needed to effectively reduce the environmental impact. New solutions should reduce both the environmental impact per unit volume of the cement-based composites, such as concrete and mortar, and the total amount of these products used to build the typical structures and infrastructures [6].

A lower environmental impact, with respect to the volume of cement, can be achieved by substituting part of the clinker with supplementary cementitious materials (SCMs) [7,8]. In some researches, the environmental impact of SCMs has been evaluated by taking into account not only the greenhouse gas emission but also the energy required during concrete

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production [9]. On the other hand, by using concrete systems with high mechanical performances, the volume of concrete structures can be drastically reduced as well. This “performance strategy”, which consists of the use of high-performance concrete, leads to the reduction of carbon dioxide emissions because less material is necessary for the same structural performances. However, higher concrete strength provides a larger carbon footprint, especially in the production stage [6], because larger amounts of binder (and sometimes fibers) are needed. Therefore, the material reduction could not be always enough to compensate the increase of CO_2 emissions caused by high concrete classes. Accordingly, in this paper an extensive analysis will be carried out to discern whether the use of High-Strength Concrete (HSC) is effective or not, both in low rise and high-rise buildings.

1.2. Research significance

In the last years, several strategies have been applied to reduce the carbon dioxide emissions of reinforced concrete (RC) structures. Many of these studies aimed only to measure the environmental properties of concrete materials and to tailor more eco-friendly cement-based composites. However, only few studies were devoted to compare both the structural and the environmental performances with respect to the height of the building. For these reasons, this study is aimed at answering to following questions:

- Does the reinforced concrete structure of high-rise building show a lower carbon footprint with respect to that of low -rise construction?
- In both high-rise and low-rise RC structures, does the use of HSC lead to a lower carbon footprint compared to that of Normal-Strength Concrete (NSC)?

2. Materials and methods

The analyses carried out herein regard three existing RC building of 14, 30 and 60 floors, whose structures are designed through a finite element software, in the case of 4 different concrete classes. In this way the total amount of concrete and reinforcement necessary to satisfy static and dynamic requirements was calculated. If such quantities are multiplied by the unitary carbon dioxide emissions of the materials, the global impact of the construction is evaluated.

2.1. Concrete and reinforcing steel

The construction industry produces several types of concrete, which are classified according to their compressive strength. In this study, four concrete classes, namely C25, C40, C60, and C80 (each number corresponds to the characteristic value of the cylindrical compressive strength), are taken into account. It must be noted that C25 is the most used concrete class in Europe, whereas C80 represents the highest strength of concrete currently available which is listed by the European concrete producers. The other classes of NSC (i.e. C40) and HSC (i.e. C60) were chosen in between C25 and C80 in order to define a representative relationship between compressive strength and CO_2 emissions. Their mechanical proprieties, defined by the “parabola-rectangle” stress-strain relationships, σ-ε, are illustrated in Fig. 1.a. whereas Fig. 1.b shows the tri-linear constitutive relationship of the steel rebars, as defined by Eurocode 2 [10].

Regarding the environmental performances of concrete structures, the use of SCMs leads to a reduction of the carbon footprint [11,12], as they include more eco-friendly binder than Ordinary Portland Cement (OPC) [13]. However, the substitution ratio of the SCMs has to be carefully designed to achieve the desired mechanical properties of concrete [14], especially in high-rise building where high-strength is usually required [15,16]. To evaluate the sustainability of a building, Life Cycle Assessment (LCA) needs to be to carry out in accordance with the methodology indicated by the standards, both on building components and materials [17], and on the whole construction [18]. Nevertheless, assuming that only the class of concrete and the size of the buildings can vary, whereas boundary conditions are the same for all the buildings (i.e., the location, distance between the construction site and producers, etc.), only the CO_2 released during the production of materials is considered herein.

As the following analyses are only related to the concrete and steel performances, the components of the four concretes are not specified. In other words, the whole Life Cycle Assessment (LCA) is not computed, and the environmental data, extrapolated by the Purnell’s analyses [7], are used (see Table 1).

In literature there are indicators that relate the carbon footprint of concrete to both the unit volume of cement and the compressive strength (see, for instance, Damineli et al. [2]). Nevertheless, Habert and Roussel [6] introduced the following empirical relationship that allows to estimate the unit CO_2 emissions as a function of cylindrical compressive strength:

$$kg\ of\ CO_2 per\ cubic\ meter\ of\ concrete = \delta\sqrt{Class\ of\ concrete} \tag{1}$$

where δ is a constant equal to 46.5 $kg_{CO_2}/\sqrt{MPa}$. Compared to the quantities of CO_2 produced by a unit volume of concrete, and reported in Table 1, Eq. (1) seems to be very effective. The comparison is illustrated in Fig. 2, where the values of carbon dioxide given by Purnell [7] and those computed with Eq.(1) are both reported as a function of concrete class. Fig. 2 shows

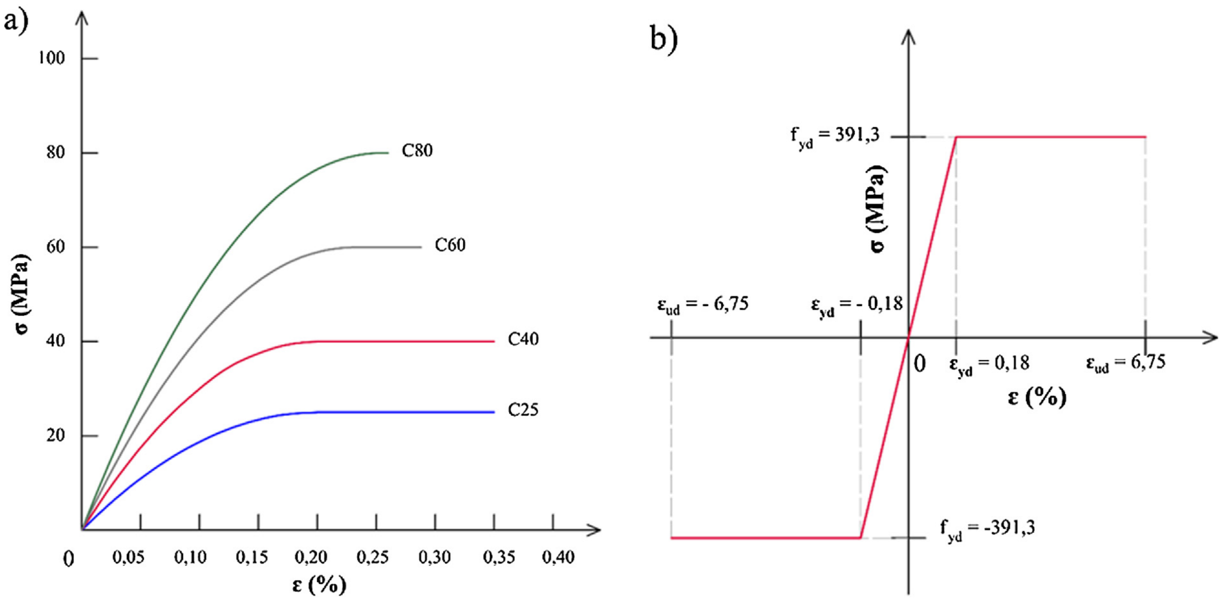

Fig. 1. The stress-strain relationships of concrete in compression (a) and of steel rebar (b), as defined by Eurocode 2 [10].

that only when a reduction of the volume of concrete and rebar is possible, the increment of CO_2 of the high-strength concrete can be compensated.

2.2. The RC structures

To analyze realistic RC structures, three different existing buildings of 14, 30 and 60 floors were selected. As buildings with the same area of the floors, but different heights, do not exist, we considered those reported in Fig. 3 (having a floor area of 800 m^2 ± 200 m^2). Specifically, Fig. 3 shows the FEM meshes of the following RC buildings:

Structure #1: The Roy and Diana Vagelos Education Center (New York, USA) [19], 14-story university building with a total living surface S = 8250 m^2

Structure #2: The Boston Bank Headquarters (Sao Paulo, Brazil) [20], a 30-story office building with a total living surface S = 24,420 m^2

Structure #3: The Elysian Hotel and Private Residences (Chicago, USA) [21], a 60-story building with a total living surface S = 56,320 m^2

2.3. Structural analyses

The structural analyses of the three buildings were carried out by a finite element modeling (FEM) approach included in the "CDM Dolmen" software [22]. Structural elements, such as columns, beams and shear walls, were designed in accordance with the Eurocode 2 requirements [10].

To define the loads acting on the buildings at Ultimate Limit States (ULS) and Serviceability Limit States (SLS), the RC structures depicted in Fig. 3 are supposed to be built in Turin (Italy), a city located in the low-seismicity area of central Europe. To assess the effects produced by the four classes of concrete considered herein (see Fig. 1a and Table 1), the design procedure was repeated four times for all the three structures. Fig. 4 shows, as an example, a continuous RC beam of the Structure #1 and the corresponding longitudinal reinforcement computed for each concrete class. Moving from concrete C25 (Fig. 4a) to C80 (Fig. 4d), both the area of beam cross-section, and the volume of concrete, decrease. Also the lower amount of steel reinforcement is evident for higher concrete classes. Table 2 shows the total amount of steel and concrete necessary for

Table 1
Environmental proprieties of different concretes and steel rebar [7].

Material	Concrete				Steel
	C25	C40	C60	C80	
CO_2 Parametric Amount	[kg/m^3] 215	[kg/m^3] 272	[kg/m^3] 350	[kg/m^3] 394	[kg/kg] 1.38

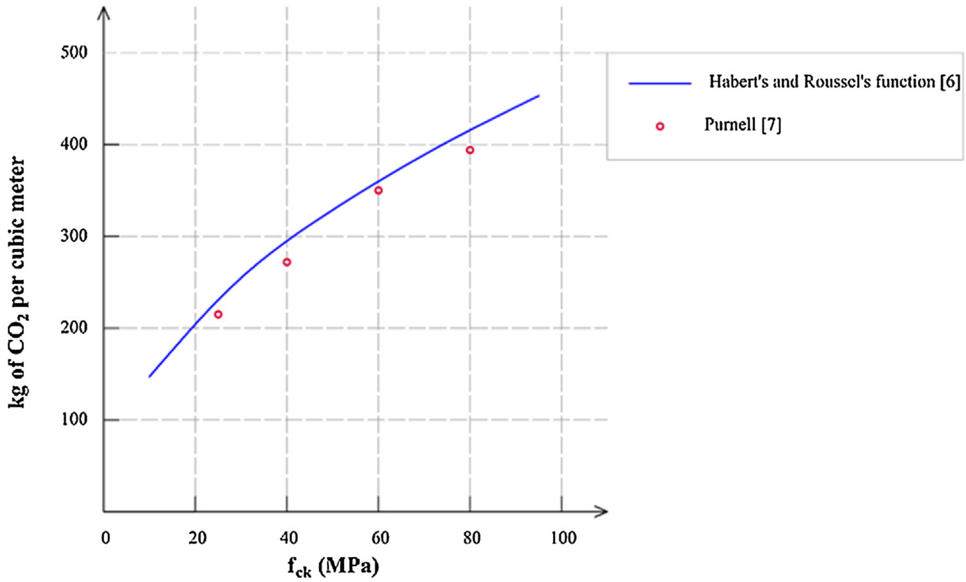

Fig. 2. Comparison between the Habert and Roussel's relationship [6] and the experimental data measured by Purnell [7].

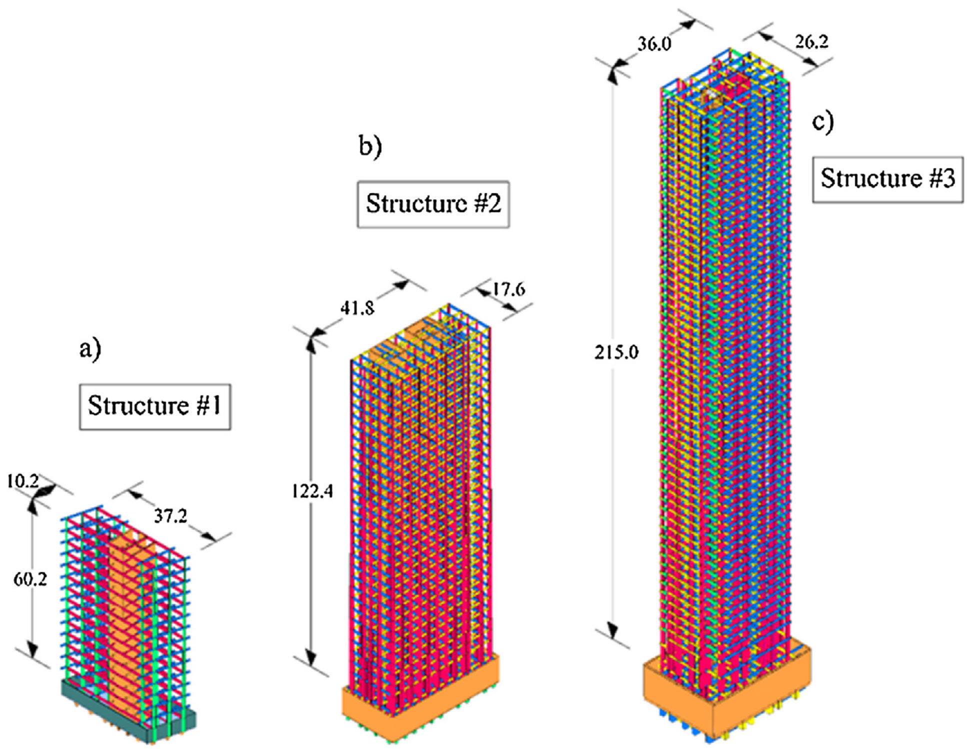

Fig. 3. The RC structures of the existing building meshed with CDM Dolmen [13]: a) The Roy e Diana Vagelos Education Center [19]; b) The Boston Bank Headquarters [20]; and c) The Elysian Hotel and Private Residences (Chicago, USA) [21].

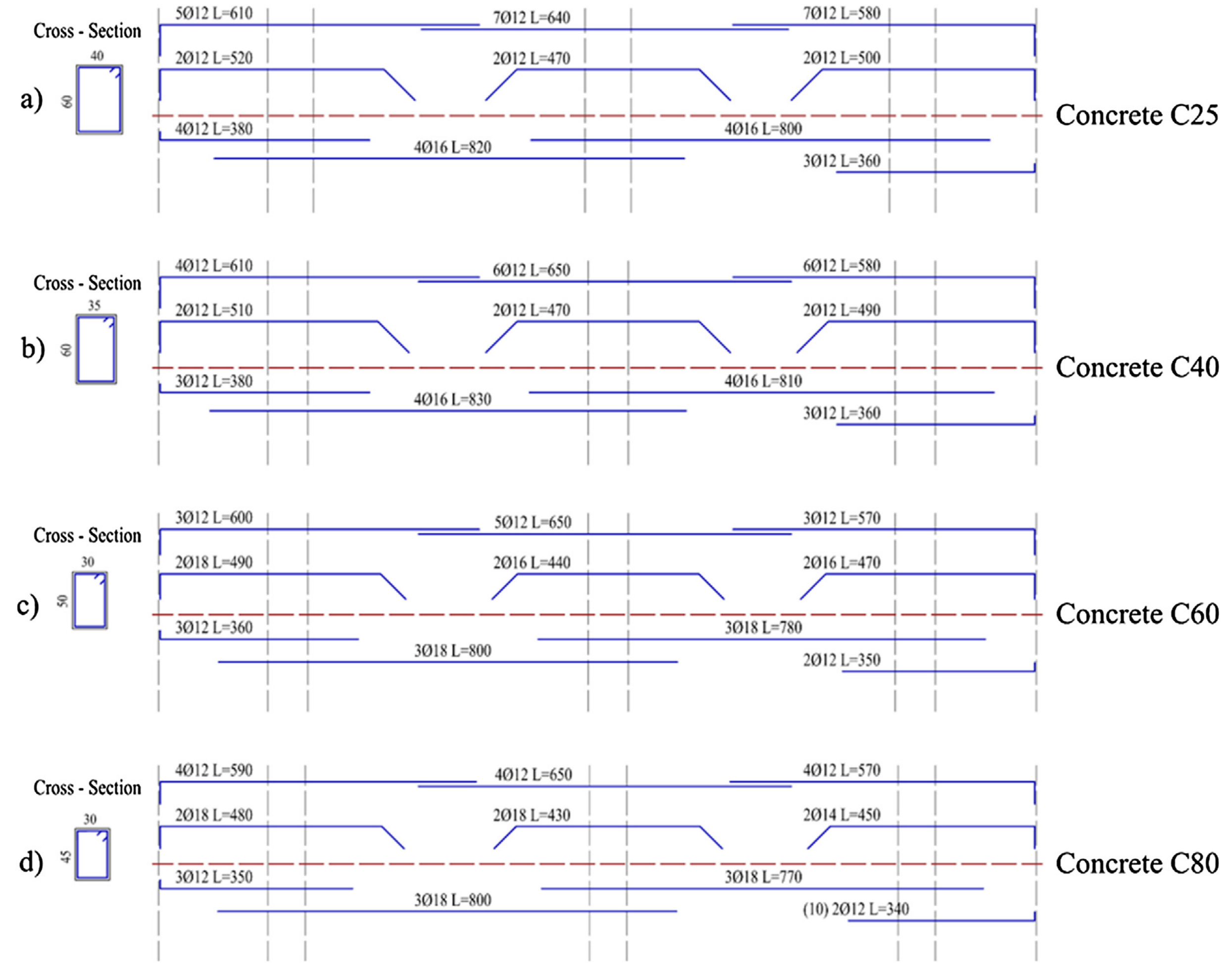

Fig. 4. The geometrical properties of a continuous RC beam of the Structure #1 in the case of: a) concrete class C25; b) concrete class C40; c) concrete class C60 and d) concrete class C80.

Table 2
The total amount of CO_2 emitted (concrete + steel) for each structure at different concrete class.

		Concrete class							
		C25		C40		C60		C80	
Structure	Total living area [m^2]	Concrete [m^3·10^3]	Steel [kg·10^3]	Concrete [m^3·10^3]	Steel [kg·10^3]	Concrete [m^3·10^3]	Steel [kg·10^3]	Concrete [m^3·10^3]	Steel [kg·10^3]
#1	8250	4.70	443.46	4.41	428	3.96	391.12	3.67	349.06
#2	24,420	18.80	2419.03	16.73	2135	14.18	1717.89	11.79	1428.31
#3	56,320	30.42	7211.14	24.30	4721.30	19.00	3746.38	15.98	3424.34

the three buildings and for the four concrete classes investigated herein. As expected, in each structure the amount of the structural materials reduces when concrete strength increases.

3. Results and discussions

To obtain the mass of carbon dioxide released in the atmosphere due to material production, the unit values of carbon footprint (see Table 1) are multiplied by the quantities of concrete and steel computed by the structural analyses (and reported in Table 2). The results are shown in Fig. 5, where the CO_2 emitted by Structure #1 (Fig. 5a), Structure #2 (Fig. 5b) and Structure #3 (Fig. 5c), is shown to be function of concrete class.

It is worth noting that in the Structure #1, with the lowest number of stories, there is a progressive increase of CO_2 with concrete class (Fig. 5a). Vice versa, in the 60-storey building (i.e., Structure #3 – Fig. 5c), the carbon footprint decreases if the

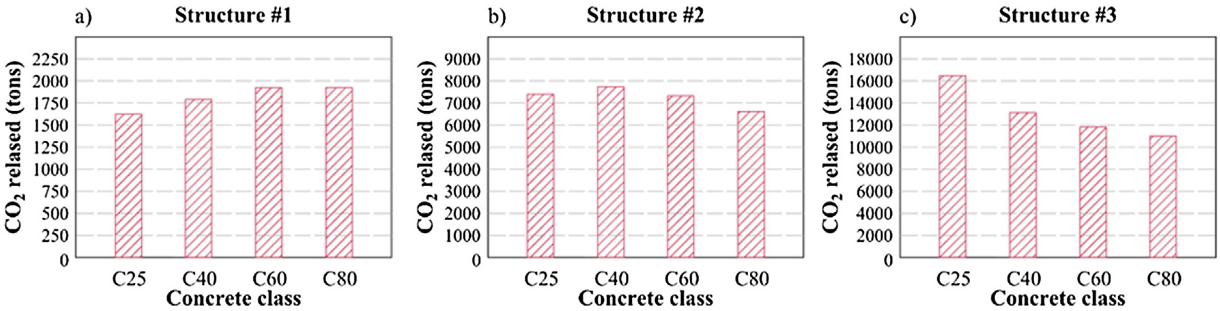

Fig. 5. Carbon footprint of steel and concrete versus concrete strength in the case of: a) structure #1; b) structure #2 and c) structure #3.

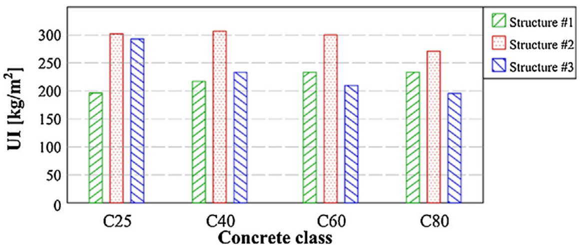

Fig. 6. The unitary impact of the three structures as a function of the concrete class.

strength of concrete increases. In the Structure #2, having 30 stories (see Fig. 5b), the emitted CO_2 increases moving from C25 to C40, whereas the emissions reduce for higher classes (especially from C60 to C80).

The differences observed moving from low-rise to high-rise buildings are mainly due to the different ratio between the necessary amounts of materials and the minimum dimensions of the structural elements, as required by the Eurocode 2 [10]. Specifically, in Structure #1 (14-storey building), most of the elements possess a size equal to the minimum, even in the case of NSC. For these RC elements, the use of higher concrete class is not convenient, because the volume of steel and concrete cannot be furtherly reduced. In other words, the greater carbon footprint of HSC cannot be compensated by the volume decrement of the materials (see Figs. 2 and 5a). On the contrary, in the 60-story building (Structure #3), the geometrical properties of structural elements are generally larger than the minimum sizes suggested by Eurocode 2 [10], especially in the case of NSC. Thus, in this case, the use of HSC is much more effective and leads to a considerable reduction of concrete mass, and of CO_2 emissions as well (Fig. 5c).

Finally, in the 30-story building (Structure #2), the size of several structural elements is larger than the minimum, but the number of those that require the minimum dimensions is higher compared to Structure #3. Therefore, with the progressive increase of concrete strength, the carbon dioxide emission first increases, then decreases (Fig. 5b).

To compare the quantities of CO_2 previously computed for the three buildings, the living surface is herein considered as the functional unit. More precisely, it is possible to compare the performances of the three structures by calculating their unitary impact (UI), which is the quantity of CO_2 emitted by the unit value of living surface:

$$UI = \frac{CO_{2,\ emitted}}{living\ \ surface} \tag{2}$$

where the values of CO_2 emitted by each building and the corresponding living area are in Fig. 5 and Table 2, respectively. As illustrated in Fig. 6, where the values of UI related to the three structures and to the four concrete classes are reported, the smallest UI occurs in low-rise buildings (14 floors) when NSC (i.e., C25) is used, as well as in high-rise buildings (60 floors) in presence of HSC (C80). Conversely, the 30-storey building shows the greatest UI regardless of the concrete class.

4. Conclusions

The results of the structural analyses performed in this paper provide the answers to the initial questions, regarding the use of high-rise building and/or high-strength concrete. Accordingly, the following conclusions can be drawn:

- For low-rise buildings (14 floors), the lowest impact can be assured by using normal strength concrete (e.g., C25). Indeed, regardless of the effects of actions, code rules impose minimum dimensions to the structural elements and a minimum amount of reinforcement. The aim is to avoid buckling and excessive deformability of slender elements, and to provide sufficient ductility as well. In some cases, also in presence of low strength concrete, the theoretical area of cross-section can be lower than the minimum. Consequently, the use of HSC in these elements does not imply that lower amounts of concrete and steel rebar are possible. Conversely, it leads to an increase of CO_2 emissions with respect to NSC, especially in low-rise buildings.

- On the contrary, the use of high-strength concrete leads to the lowest impact of high-rise buildings (60 floors). Thus, the application of the performance strategy [6] to reduce the environmental impact of concrete structures becomes very effective in tall buildings, because the volume of the structural elements can be remarkably reduced.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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