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CRITICAL ASSESSMENT OF CO_2 EMISSION OF DIFFERENT CONCRETES: FOAMED, LIGHTWEIGHT AGGREGATE, RECYCLED AND ORDINARY CONCRETE

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Abstract.

Construction materials contribute to about 75% of the CO_2 emission of all the construction processes. Concrete is one of the most widely used construction materials and is thus primarily responsible for CO_2 emission. In particular, 8 − 9% of global greenhouse gas (GHG) emission are produced by concrete. CO_2 emissions can be considerably reduced in the construction phase through a careful selection of materials with low environmental impact or through specific admixtures. In this study, different concretes are taken into consideration, including foamed concrete, lightweight aggregate concrete, recycled concrete and ordinary concrete. A series of mix designs of these four classes of concrete, characterized by a comparable mechanical strength or a comparable density, are taken from the relevant literature and compared to one another in terms of CO_2 emission. Some guidelines or possible research lines aimed at reducing CO_2 emission are finally outlined in this contribution.

Keywords: CO_2 emission, foamed concrete, lightweight concrete.

1. Introduction

In the last few decades, the attention to environmental issues is more and more increased. The European Union issued several guidelines and recommendations in order to reduce global CO_2 emissions. The objective is to achieve a 40% reduction of the 1990 CO_2 emission values by 2030 [1]. Environmental protection, saving of raw materials and effects of human activities on the climate changes are popular matters that are of interest in diverse social contexts. Consequently, the construction industry is also committed to solve these challenges, as witnessed by the large range of research topics in the relevant literature. Indeed, the building industry alone is responsible for about 40% of the total energy consumption [2]. More specifically, when coming to the concrete industry, the energy consumption is estimated to be around 3% of the total consumption value, which is associated with an overall CO_2 emission of about 8-9% of the total CO_2 emissions [3]. The environmental impact of concrete is due to the fundamental ingredient acting as binder, namely Portland cement. Indeed, the Portland clinker is obtained by cooking a mix of natural and/or artificial soils, including clay, lime, pyrite ash etc. in the blast furnace at 1400°C. During this preparation phase, the limestone included in such raw materials undergoes the calcination process with significant CO_2 emission. A twofold environmental impact can thus be recognized in this process: 1) the CO_2 emission due to the calcination process; 2) the CO_2 emission due to the energy consumption of the overall process [4]. As a result, the Portland clinker is responsible for more than 90% of the overall CO_2 emission of the concrete industry [5].

Based on the above remarks, it appears clear that the most straightforward strategy to mitigate the greenhouse gas (GHG) emission is to reduce the amount of clinker, by partly replacing it with supplementary cementitious materials, such as fly ash and ground granulated blast furnace. The latter technique allows the achievement of different objectives at a time: not only the reduction of the environmental impact in terms of GHG emission by the concrete industry, but also the re-use of by-products and recycled materials, which are converted from negative elements to a useful resource [6].

Mineral additions in parallel to clinker Portland are allowed by international standards. Indeed, in the UNI EN 197-1 five different classes of cement are reported, depending on the clinker and mineral addition contents. Evidently, cements having higher amounts of mineral additions as replacement of Portland clinker are characterized by lower CO_2 emissions. Therefore, the CO_2 emissions due to the concrete industry depend on the type of binder being adopted, which changes from country to country, as the specific culture and the available raw materials influence the preparation phases of concrete. This concept is clearly acknowledged in [7].

Besides the introduction of mineral components as partial replacement of the Portland cement, which is the conventional strategy adopted in the range of ordinary density concretes, the CO_2 consumption can be well reduced for special concretes, including foamed concretes (FCs) and aerated autoclaved concretes (AACs). These special concretes are more convenient for the preparation of low-to-medium density concrete mixes. Considering the low density, these special mixes are also featured by good thermal insulation properties [8], which is associated with lower energy demands for heating and cooling processes, thus contributing to a lesser amount of CO_2 emissions not only in the preparation stage, but during the whole service life of the structure [2]. This is particularly convenient in hot climates during the summer season in terms of thermal inertia, when compared to classical insulation panels currently available in the market. Recent research on foamed concrete has focused on the determination of the mechanical strength [9] and thermal properties [10], the impact of different ingredients such as foaming agent [11], [12], cement type and presence of superplasticizers [13], the influence of the curing conditions [13], the influence of the presence of by-products and slags, such as fly ash [14] and biochar [15], the influence of mixing intensity [16], the possibility of improving the mechanical characteristics via short fibers [17, 18], or bi-directional grid reinforcement [19, 20] and the fracture behaviour [21–23]. However, to the authors best knowledge, there is no extensive study in the literature concerning the CO_2 emissions of foamed concrete mixes compared to alternative concrete mixes such as ordinary concretes (OCs), lightweight aggregate concretes (LACs) and recycled concretes (RCs) either by recycled aggregates or by replacing part of the clinker with recycled components. To fill this gap, the present work aims to present a comparative study focused on the CO_2 emission of such different cementitious pastes. The comparison is made assuming mixes with similar values of mechanical strength or similar values of density. In this way, the evaluation of the CO_2 emission is made assuming homogeneous conditions among four classes of concrete (OCs, LACs, FCs, RACs). A critical discussion is finally made regarding the possibility of adopting alternative concrete mixes (as substitute of ordinary concretes) characterized by lower CO_2 emissions.

2. Materials and mix design

In this Section, a series of mix designs of different experimental campaigns taken from the relevant literature are presented. These mix designs concern several concrete mixes selected to assess the CO_2 emissions taking into account different parameters such as density, compressive strength, composition of the mix and main ingredients, presence of mineral additions or recycled elements. Through this comparative study, it is possible to shed light on key aspects primarily responsible for the GHG emissions, so as to plan future experimental campaigns on special concretes wherein the reduction of the CO_2 emission is the main objective. Moreover, the sources of the CO_2 emissions that are inherent in the conventional preparation processes of ordinary and special concretes will be discussed. In particular, the study comprises four different types of concretes, namely FCs, LACs, RCs, and OCs. A preliminary selection process is made in order to identify certain common properties of the different mix designs related to the different types of concrete. As an example, the CO_2 emission will be comparatively analysed for mix designs characterised by the same compressive strength (but different densities), or alternatively by the same density (but different compressive strengths). The motivation for including these different types of concrete is due to the significantly different compositions in terms of mix design. For instance, in FCs a part of volume is occupied by air voids generated by the presence of a preformed foam, or introduced in the matrix through proper chemical reactions during the initial phases of the preparation. Besides these FC specimens, another widely used class of lightweight concretes is represented by LACs. In this case, the cementitious matrix is the same as in ordinary concretes, but the self-weight reduction is achieved by the partial replacement of normal aggregates with lightweight aggregates. In the cases discussed in this paper, expanded clay was used in the specimen preparation. Finally, another interesting class of concretes is represented by RCs in which part of the aggregate is replaced by recycled materials. In this specific case, the recycled components are represented by lightweight recycled aggregates as partial replacement of normal aggregates. In this way, lightweight characteristics are achieved also in this class.

With regard to FC, three reference studies are included. More specifically, the mix designs presented by some of the authors in [13] and labelled as #1, #2.1 and #4.1 in the referenced paper [13] are included, which are characterized by the presence of cement, water and preformed foam resulting in different densities spanning from about 400 kg/m^3 to 800 kg/m^3. Moreover, another paper presenting mix designs of FCs addressed in this study is [24], where, unlike the previous experimental campaign, the specimens contained also fly ash. Also in the latter study the densities span a wide range, from 750 kg/m^3 to 1250 kg/m^3, so as to supplement the previous experimental campaign [13] with higher-density specimens. Finally, the third study is [25], where ultra-lightweight foamed concrete specimens (density ranging from 100 to 250 kg/m^3) with the use of fly ash were documented. In this way, a very broad range of densities of FCs are included in this examination.

With regard to LACs, only one benchmark study is considered [26], in particular the specimens labelled

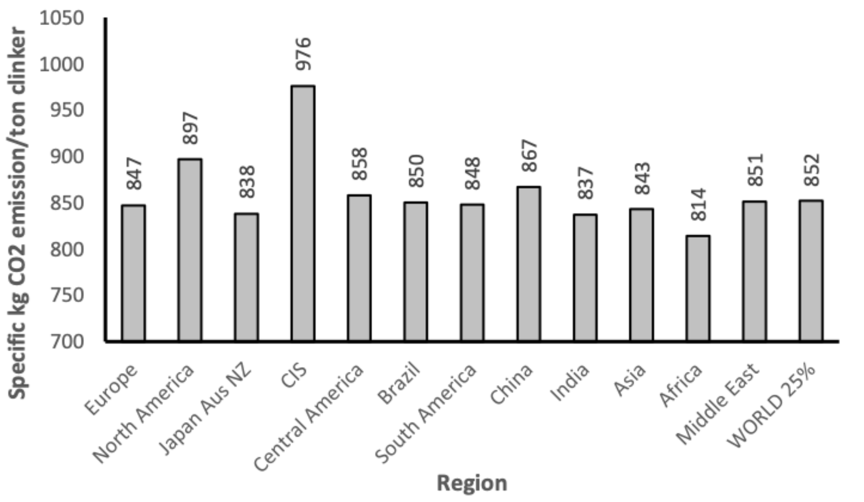

Figure 1. Distribution of CO_2 emissions related to 25% of world cement production (data from [7]).

LT30, LT40 are included. In this case, the lightweight properties of the specimens were achieved by the addition of expanded clay. In particular, keeping a constant amount of 500 kg/m^3 of cement, the authors investigated the effect of different contents of expanded clay ranging from about 200 to 330 kg/m^3, obtaining densities from 1280 to 1600 kg/m^3 approximately.

With regard to RCs, only two specimens were taken from the extensity study in [27], labelled CM20RM and CHD50RM. Besides the classical aggregates and Portland cement, these specimens contained lightweight recycled aggregates and expanded clay.

Finally, in order to compare the results pertinent to the above-described mixes with traditional concretes having densities of about 2400 kg/m^3, two classical mix designs were also included in the study, which are characterized by compressive strengths of around 25 and 30 MPa (comparable to some of the aforementioned special concretes). These specimens have an aggregate-to-cement ratio in the range from 2.7 to 4.78, and a water-to-cement ratio of around 0.5. Extensive details of the mix designs of all the considered concretes can be found in the quoted experimental studies, to which the Reader is referred to.

3. CO_2 evaluation

A basic procedure for the computation of the CO_2 is adopted in this study. Based on the mix design proportions and the amount of the single components, an estimate of the contribution of each component to the overall CO_2 emission is performed through assumptions from the literature. In particular, the present study is limited to the assessment of the CO_2 emission related to the production phase. In other words, this evaluation does not include the emissions related to the transportation from the manufacturing place to the concrete plant, nor the emissions related to the casting in the construction site, nor the lifecycle data (e.g. recovering part of CO_2 emissions through carbonation of concrete [28]).

As a first remark, it is worth noting that the main source of CO_2 emission in the mix design is represented by the cement. However, slightly different values of the kg CO_2 emissions per ton of clinker are reported in the literature from country to country [7], as illustrated in Figure 1. The differences are due to the different technologies adopted in the various countries in the concrete industry, and due to the different fuels employed.

Moreover, besides cement, the other predominant ingredients being present in the mix designs analysed in this study are: i) sand; ii) expanded clay; iii) fly ash; iv) water; v) recycled aggregate; vi) foam. These secondary ingredients contribute to the overall CO_2 emission to a far less extent in comparison with cement. However, they are included for completeness. In particular, the specific CO_2 emissions of ash and cement are calculated according to the guidelines provided in [29]. Whereas the specific CO_2 emissions of sand, recycled aggregates, water and components of foam are computed according to the instructions provided by the KEITI (Korea Environmental Industry & Technology Institute), Environmental Declaration Office, available at website epd.or.kr/eng/lci/lciCO$_2$00.do. Finally, the specific CO_2 emissions of the expanded clay are evaluated according to the Environmental Product Declaration provided by the Italian Company Laterlite S.p.A. The calculation of the CO_2 emissions due to the foam in FCs is made taking into account the different concentration of the foaming agent and the actual density of the foams used in the mix designs documented in the referenced papers.

Based on the assumptions described above, Figure 2 illustrates the CO_2 emission (expressed in kg of CO_2 per m3 of concrete) for FCs, LACs and OCs at a comparable compressive strength of 25 MPa and 30 MPa,

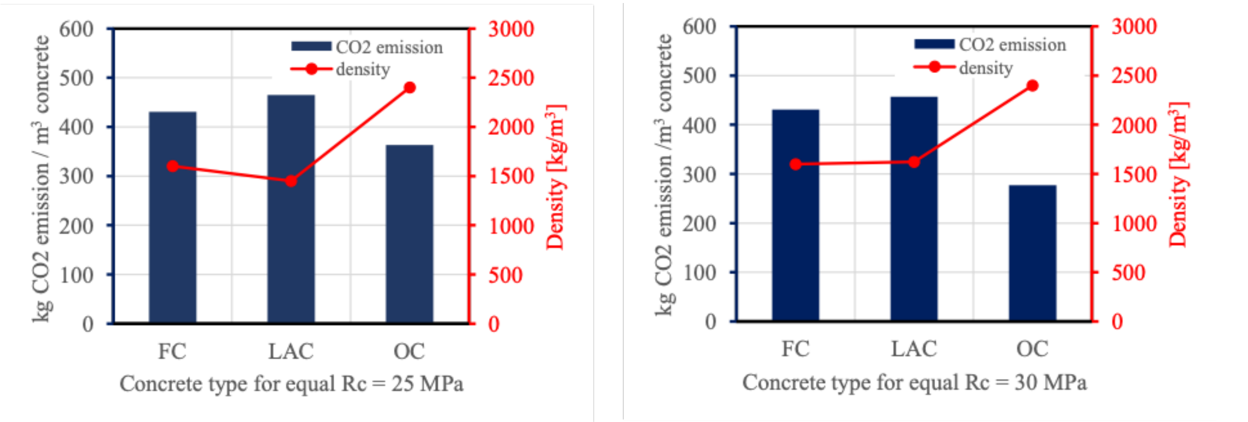

Figure 2. CO_2 emission comparison alongside related density values among three classes of concrete for equal compressive strength of 25 MPa (left) and 30 MPa (right).

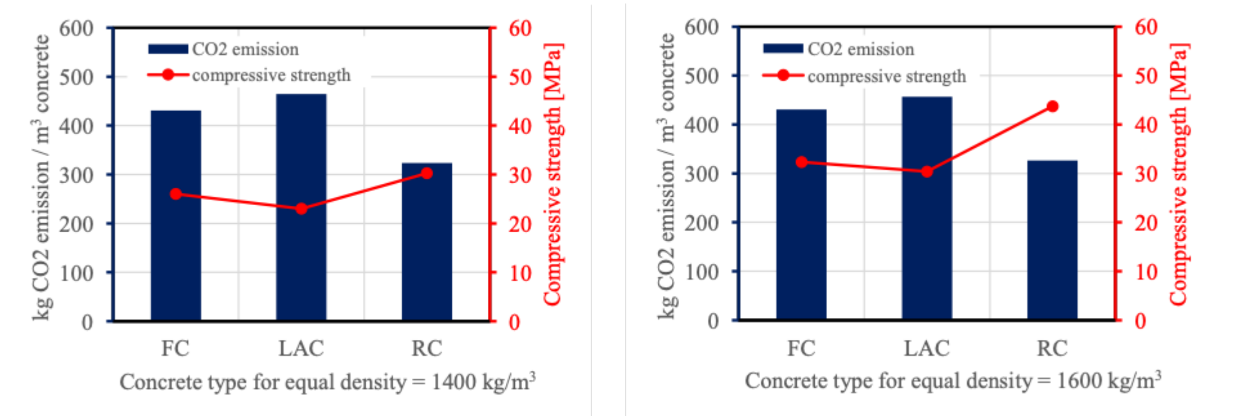

Figure 3. CO_2 emission comparison alongside related compressive strength values among three classes of concrete for equal density of 1400 kg/m^3 (left) and 1600 kg/m^3 (right).

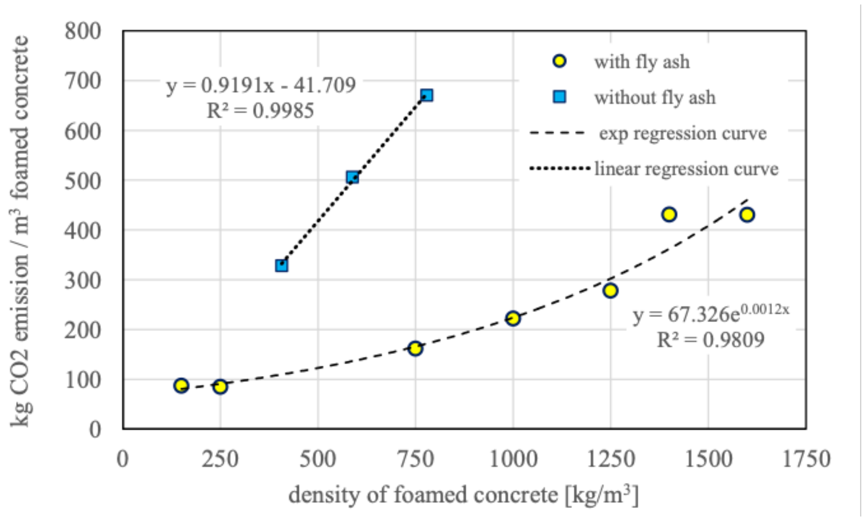

Figure 4. Increase of CO_2 emission for foamed concrete with and without fly ash in the mix design as a function of the density.

respectively. In the figure, the density of the various classes of concrete is also reported along a secondary vertical axis for completeness, wherein it is easily seen that OC is characterized by a much higher density than both FC and LAC. By inspection of the plot, it is seen that for both compressive strength classes (i.e. 25 and 30 MPa), OCs are characterized by a lower quantity of CO_2 emission in comparison to FCs and LACs. This is justified by the fact that in the mix design of OCs a lower amount of cement is used. Indeed, in FCs and in LACs the amount of cement is around 500 kg/m^3 in order to attain reasonably good mechanical strengths with lower densities, whereas in the traditional concretes (OCs) typically this quantity does not exceed 350 kg/m^3. Moreover, LACs are characterized by a slightly higher CO_2 emission compared to FCs (for equal amount of cement) because the CO_2 emissions underlying the production process to realize the expanded clay are surely higher than the CO_2 emissions related to the production of the foam (one order of magnitude higher approximately, based on the previous guidelines adopted for the calculation).

Considering that the OCs produce lower amount of CO_2 emissions than lightweight concretes, attention is then paid to the comparison among three classes of lightweight concretes, namely FCs, LACs as well as RCs. Figure 3 depicts the comparison of CO_2 emissions of the three lightweight concretes at equal density of 1400 kg/m^3 and 1600 kg/m^3, respectively. Also in this case a secondary vertical axis is added on the right-hand side of each plot, showing the values of the compressive strengths. Based on this comparison, it emerges that RCs are the most favourable ones in terms of both highest compressive strengths and lowest CO_2 emissions. Varying the density, it is confirmed that LACs are characterized by the poorest performance, from both environmental and mechanical perspectives. Comparing the two plots on the left and on the right, it is also noticed that the CO_2 emissions do not vary significantly in relationship to the two analysed values of density. In the case of LACs and RCs, this is due to the fact that the increase of density was obtained by reducing the lightweight aggregates while keeping the cement amount quite constant. Analogously, in FCs the increase of density was achieved through a lower amount of foam while keeping the cement amount quite constant.

The above statements concerning FCs are valid for medium-to-high densities. Nevertheless, by significantly widening the range of the examined densities for FCs it is noted that the density plays a key role in the overall CO_2 emissions. This is shown in Figure 4, which reports the CO_2 emissions for a range of densities from 150 (ultra-lightweight foamed concretes) up to 1600 kg/m^3. In the low-density range, the amount of cement drastically decreases, while the quantity of the foam is simultaneously increased, thus generating a significant reduction of the resulting CO_2 emissions. Values of CO_2 emissions even five times lower for ultra-lightweight foamed concretes compared to medium-density foamed concretes are indeed observed. However, for lower densities the compressive strength values decrease accordingly, thus making them unable to cope with structural applications [13, 25]. Indeed, such ultra-lightweight elements are mostly used in non-structural applications for thermal insulation and acoustic absorption purposes. In Figure 4 two sets of data are reported, including mix designs of FCs with and without fly ash. Obviously, the fly ash has a considerable effect on the CO_2 emissions because it is used as partial replacement of the cement in the mix design, thus significantly reducing the CO_2 emission. As an example, for FCs having density of 750 kg/m^3 the addition of fly ash allows the reduction of the CO_2 emissions of more than 300%. In Figure 4 two regression curves for FCs with and without fly ash, respectively, are superimposed. These curves, whose parameters are determined through least-square regression, well agree with the reported or computed values of CO_2 emission, as confirmed by the high value of the coefficient of determination R2 being higher than 0.98. These curves can be used within the range examined in this paper to predict the CO_2 emission produced by FCs depending on whether fly ash is incorporated or not in the mix design.

4. Discussion and conclusions

This study has presented a numerical investigation on the CO_2 emission produced by four classes of concretes with different mix designs but comparable properties in terms of mechanical strength or density. Since the main cause of CO_2 emission is due to the amount of Portland cement, in order to keep the CO_2 emission to within an acceptably low level, the optimization of the mix design of special concretes plays a key role. In foamed concretes it is well known that abundant use of Portland cement is made to obtain good mechanical strengths. Therefore, the elaboration of novel mix designs wherein the clinker is replaced by alternative elements, such as fly ash and silica fume, is very useful. However, such replacement is rather limited in practice, because the quantity of cement (despite the introduction of fly ash or silica fume) remains still too high ($\geq$ 500 kg/m^3) in most of the studies from the literature. Subsequent studies on foamed concretes should be directed toward a compromise between a further reduction of Portland cement (e.g. $\leq$ 400 kg/m^3) and good mechanical strengths that can be acceptable for structural purposes (e.g. Rck $\geq$ 20 MPa). An attractive alternative solution is represented by geo-polymer foamed concretes, but relevant literature in this regard is rather scarce. Instead, the CO_2 emissions are notably reduced for ultra-lightweight foamed concretes, in which part of the cement is replaced by fly ash or other mineral additions. Similar remarks can be made with regard to lightweight aggregate concretes realized with expanded clay, since also in this case the quantity of Portland clinker remains relatively high. In contrast, recycled concretes represent an optimal balance between mechanical strength and CO_2 emission. Evidently, in the latter case the primary aspect to investigate regards the durability of this special kind of concretes.

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