Environmental and Economic Analysis of Using Recycled Concrete Aggregates in Composite Steel-Concrete Slabs

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Abstract. The needs to reduce the environmental impact of concrete buildings is gaining more importance. In particular the consumption of natural aggregates requires the opening of new quarries and represent an environmental problem. A good solution for the latter is the use of concrete recycled aggregates obtained from construction and demolition waste. Composite slabs offer many advantages over traditional reinforced concrete slabs, including increased strength and stiffness, improved fire resistance, faster and easier installation, and greater environmental friendliness. Thus, the use of composite slabs with concrete recycled aggregates represents a promising strategy to reduce the constructions environmental impact. The aim of this paper is to analyze the environmental impact and the economic aspects of the use of concrete with recycled aggregates for composite steel-concrete slabs with variable spans from 2.5 m up to 8 m and different service loads. In particular, the amount of carbon dioxide saved by replacing natural aggregates with recycled ones has been evaluated considering 30%, 50%, up to the total of 100% replacement percentages. In addition, the construction costs have been estimated, always comparing the use of ordinary concrete with natural aggregates and the use of recycled ones. Results show that using recycled aggregates reduces the environmental impact of composite slabs with a very little economic cost reduction.

Keywords: Composite slab, Concrete, Recycled Aggregate, Sustainable design.

1 Introduction

The concrete industry has a significant environmental impact in terms of energy consumption, CO_2 emissions, and land use. In fact, it is responsible for approximately 5% of global carbon dioxide emissions [1]. According to the European Commission, the construction sector alone accounts for 40% of the primary energy demand in the EU and 36% of greenhouse gas emissions. In Italy, the entire building sector requires up to 27.9% of the energy demand and emits up to 24.2% of climate-changing emissions.

Regarding the impact on the environment due to the demand for building materials, there are over 4,000 authorized quarries and more than 14,000 disused ones in Italy.

Every year, over 29 million cubic meters of sand and gravel are extracted, along with more than 26 million cubic meters of limestone required for cement production [2].

In concrete constructions, 90% of the energy required for their construction is consumed during the production phase of raw materials, particularly clinker, while only the remaining 10% is related to concrete packaging, transport, and on-site use [3].

Literature review [4-11] shows that concretes made with recycled aggregates are suitable for structural use even for high percentages of replacement of natural aggregates with recycled ones. Indeed, the reduction of mechanical performance at material scale is compensated by the structural behavior at structural scale.

Thus, the use of recycled aggregates allows reducing carbon dioxide emissions into the atmosphere without increasing construction costs for construction companies, provided that there is a network of facilities for the treatment and recycling of construction and demolition waste appropriately spread throughout the territory.

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Figure 1- Composite slabs before (left) and after concrete casting (right).

Composite slabs [12], see Figure 1 are a combination of steel and concrete and have become increasingly popular for use in building constructions in recent years. This is because they offer many benefits over traditional reinforced concrete slabs. One of the primary advantages of composite slabs is their increased strength and stiffness. By combining the tensile strength of steel with the compressive strength of concrete, the resulting composite slab is much stronger than either material used alone. This means that it can support heavier loads without experiencing excessive deflection, making it ideal for use in structures with high service loads. Composite slabs are also faster and easier to install than traditional reinforced concrete slabs. This is because they are typically prefabricated off-site and then transported to the construction site for installation. This reduces the amount of time required for on-site construction, making the construction process more efficient and cost-effective. Last and not least, composite slabs are also more environmentally friendly than traditional reinforced concrete slabs. This is because they require less concrete, which is a significant source of carbon dioxide emissions. In addition, composite slab can be re-used in different constructions [13] and the components of the slab (both steel and concrete [14]) are often made from recycled materials, further reducing its environmental impact.

This paper will analyze the environmental impact and the economic aspects of the use of concrete with recycled aggregates for composite steel-concrete slabs. After this introduction Section 2 will present the adopted models while the results are shown in Section 3. Finally, some conclusive remarks are drawn in Section 4.

2 Methods

The composite slabs were designed in accordance with Eurocode 4 [15], considering three types of service loads (2, 4, 6 kN/m) and varying span lengths between 2.5 m and 8 m. The chosen width of the composite slab is 15 meters. For ultimate limit states (Flexural strength, Shear resistance, Bonding resistance), and service limit states (Deformability) assessments, simply supported beam scheme have been considered under a uniformly distributed load.

Concrete with strength class C30/37 was utilized, and three different mix designs were taken into account, featuring replacement percentages of recycled aggregates at 30%, 50%, and 100%. The mixture that does not contain any recycled aggregates, referred to as ordinary concrete with aggregates derived solely from natural sources, is utilized as a benchmark for the final values of CO_2 emissions and cost.

Two different profiles of corrugated sheet were considered: SG 55/600-750 and SG 110, see [16] and Figure 2. The thickness of the sheet metal used varies from 0.8 mm up to 2.75 mm. The concrete slab has been reinforced with a B450C steel [17] electro-welded mesh 150x150 mm with 6 mm diameter.

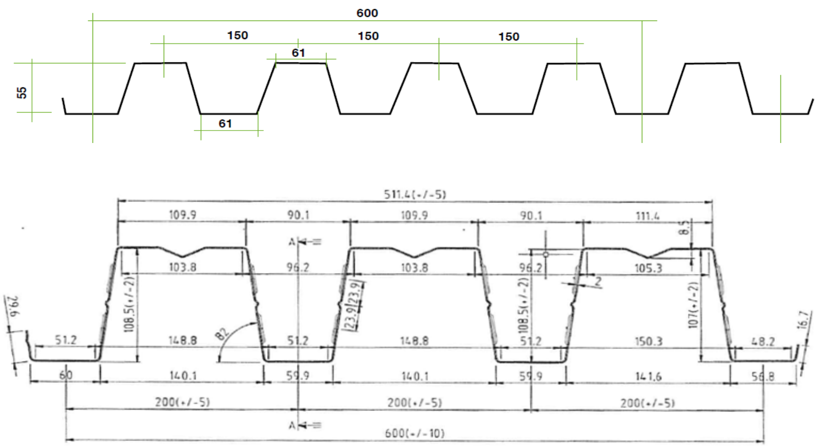

Figure 2- SG 55/600-750 (bottom) and SG 110 (top) corrugated sheets. Measures are in mm.

In order to simplify the problem, given that the critical limit state is the bonding resistance and the influence of the mechanical properties of concrete for this resistance is negligible, for this reason the mechanical performance of concrete mixtures containing variable recycled aggregate replacement rates (30%, 50% and 100%) has been considered equal to the one of ordinary concrete class C30/37. For technological reasons, the total thickness of the composite slab cross section must not exceed 355 mm.

To determine the quantities of carbon dioxide released into the atmosphere in the construction of these slabs, the following unit values reported in the following Table 1 have been considered:

Material	Equivalent CO_2 produced (kg/tonn)
Cement	693
Natural Coarse Aggregates	33
Natural Fine Aggregates	33
Recycled Coarse Aggregates	12
Recycled Fine Aggregates	12
Steel for corrugated sheets	2320
Steel for rebars	1380

Table 1: carbon dioxide emitted by the materials constituting the composite slabs.

The CO_2 emission values related to the production of concrete were taken from [8], [18], [19].

To calculate the total carbon dioxide emissions released, the values were multiplied by the total amount of steel mass and concrete volume obtained from the design of the composite slabs considering different span length and service loads. These calculations were used to obtain the total emissions of carbon dioxide released into the atmosphere.

To determine the CO_2 emissions per unit of built area, the total emissions were divided by the respective composite slab area.

The economic costs of materials necessary for the composite slabs were taken from the price list of the Sardinia Region [20] assuming that the composite slabs will be built in Sardinia (Italy), see Table 2. Furthermore, the cost of recycled aggregates, corrugated sheet and electro-welded mesh were evaluated considering the average prices offered by different stakeholders. In order to simplify the problem difference in materials cost of transportation and labor cost are not considered. These costs are kept constant for both recycled and natural aggregates.

Material	Economic Costs	Units
Cement	0.29	€/kg
Natural Coarse Aggregates	25	€/m^3
Natural Fine Aggregates	28	€/m^3
Recycled Coarse Aggregates	18	€/m^3
Recycled Fine Aggregates	18	€/m^3
Corrugated sheets	75	€/m^2
Steel for rebars	0.48	€/kg

Table 2: economic costs of the materials constituting the composite slabs.

Also in this case, to calculate the total cost of the composite slabs, the values were multiplied by the total amount of steel mass and concrete volume necessary for the designed composite slabs considering different span length and service loads. In any case the pursuit of the minimum amount of materials have been developed, thus a general optimization of economic costs of composite slabs cross sections have been obtained.

3 Results and discussion

3.1 Environmental costs

Figure 3 reports the environmental impact in terms of $\frac{kg\,CO_2}{m^2}$ of composite slabs for a service load $Q_{k1} = 2\frac{kN}{m^2}$ considering different span lengths. It is interesting to highlight that the trend is not monotonically increasing, but a clear oscillation is present between the span length of 5.5 m and 6.5 m. The latter oscillation is caused by the bonding resistance limit state, which cannot be achieved with the SG 55/600-750 sheet that with a span length of 6 meters. Therefore, it is necessary to use the SG 110 sheet, which has better mechanical performances. Furthermore this sheet requires less concrete to satisfy ultimate and serviceability limit states, resulting in reduced carbon dioxide emissions due to the smaller amount of material needed. Furthermore, it can be observed that the CO_2 emissions of the 2.5 m and 3 m span length slabs are identical. This is because the design requirements mandate a concrete slab with a minimum thickness of 50 mm, which is necessary in both cases resulting in the same cross section.

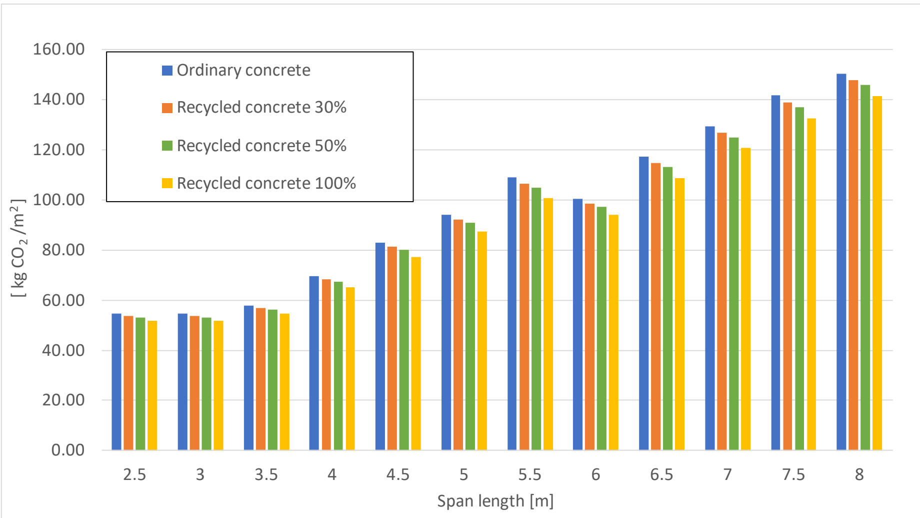

Figure 3 CO_2 emissions of residential slabs as a function of span length, service load Qk1=2 kN/m^2

Figure 4 shows that the amount of carbon dioxide saved depends on the replacement percentages of recycled aggregates. For instance, compared to normal concrete composite slabs, the savings range from 0.85 kg/m² for a 2.5 m slab that uses 30% recycled aggregates, to a maximum of 9.07 kg/m² for an 8 m span length slab that completely replaces natural aggregates with recycled materials (100%).

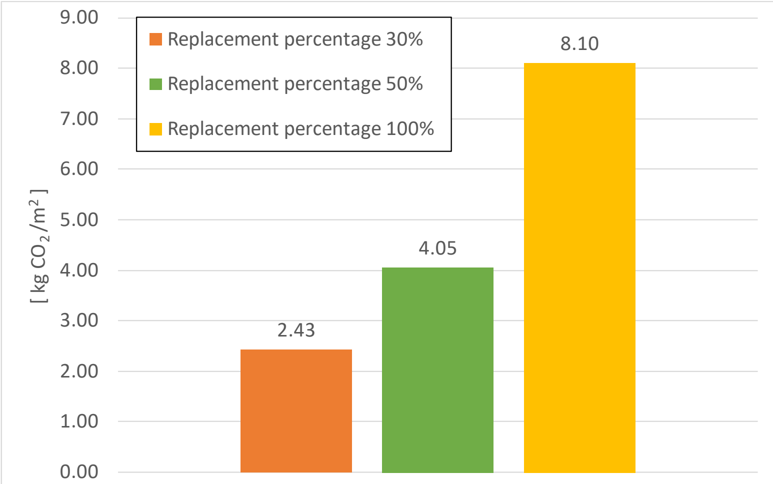

Figure 4 CO_2 savings for composite slabs with span length equal to 5.5m realized with recycled aggregates in comparison with normal concrete composite slabs.

Furthermore, considering the case of a composite slabs with span length equal to 5.5 m (generally the most used size), there is a saving of CO_2 respectively of 2.43 kg/m^2 in the case of 30% replacement percentage, 4.05 kg/m^2 for 50% and 8.10 kg/m^2 for 100%.

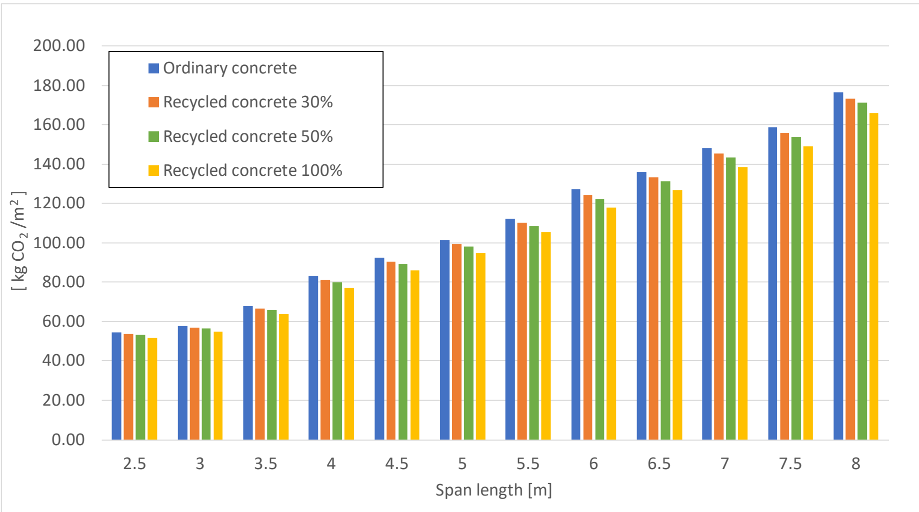

Figure 5: CO_2 emissions of composite slabs as a function of span length for service load Qk1=4 kN/m^2

Figure 5 depicts a nearly linear relationship between CO_2 emissions and span length for the case of service load equal to 4 kN/m2. When compared to an ordinary concrete composite slabs, the amount of CO_2 saved varies from 0.85 kg/m2 to 10.34 kg/m2. Always considering the case of a composite slab with span length of 5.5 m, there is a saving of CO_2 respectively of 2.05 kg/m2 in the case 30% recycled aggregate replacement, of 3.41 kg / m 2 for 50% and 6.82 kg / m 2 in the case of total replacement.

Figure 6 presents the relationship between CO_2 emissions and span length for the case of service load equal to 6 kN/m^2. Compared to the composite slab made with ordinary concrete, the amount of carbon dioxide saved varies from a minimum of 0.85 kg/m^2 for a 2.5 m slab with a replacement rate of recycled aggregates of 30%, up to a maximum of 10.33 kg/m^2, in the case of 8 m span and with the complete replacement of aggregates (100%). Considering the case of a composite slab with a length of 5.5 m, there is a saving of CO_2 respectively of 2.83 kg/m^2 in the case of concretes with replacement of recycled aggregates of 30%, of 4.72 kg/m^2 for 50% and 9.44 kg/m^2 replacements in the case of 100 % replacement percentage.

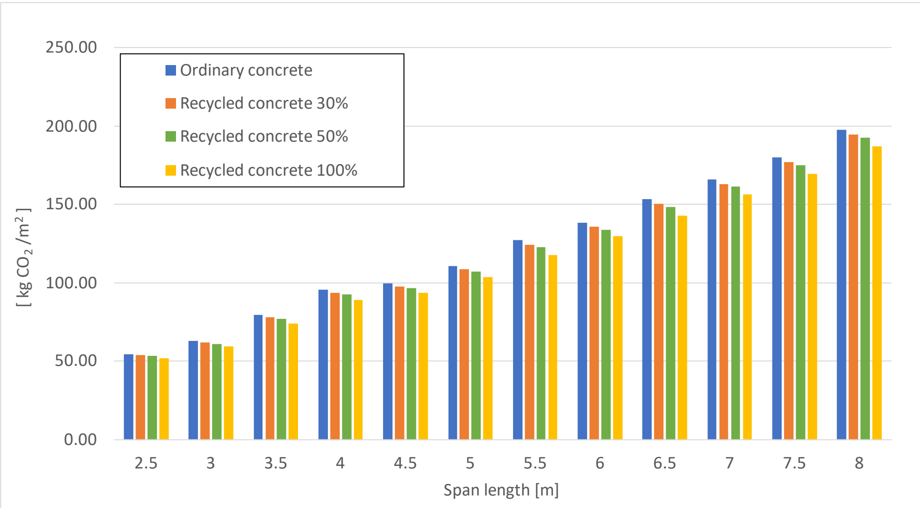

Figure 6: CO_2 emissions of composite slabs as a function of span length for service load Qk1=6 kN/m^2

The graphs of carbon dioxide emissions for different service load values (Figure 3, Figure 5, Figure 6) present an approximately linear trend, showing an increase in the amount of CO_2 produced as the size of the span length increases. As previously mentioned, upon analyzing the ultimate and serviceability limit states of the structural element, it is observed that the critical aspect of this construction system is the longitudinal bonding strength at the interface between the steel sheet and concrete. In these analyses, no additional elements were considered to increase the mechanical bonding between the metal sheet and concrete. Such low values of bonding strength do not allow for the optimal use of the material mechanical performance, resulting in the need for larger quantities of both steel and concrete, leading to increased carbon dioxide emissions. Therefore, to further reduce CO_2 production, additional methods and elements can be employed to improve the steel-concrete bonding and achieve better optimization of the composite section's performance.

3.2 Economic costs

The economic costs of the composite slabs have been evaluated for different loading conditions and span length. As explained before the design have been developed minimizing the quantities of materials necessary to satisfy all the ultimate and serviceability limit states required by Eurocode 4 [15].

Figure 7 presents the economic costs of composite slabs as a function of span length for service load equal to 2 kN/m^2. It should be noted that there are very small variations between the cost composite slab made with ordinary concrete and the ones realized with recycled aggregates. The cost reductions using recycled aggregates varies from a minimum of 0.1 €/m^2 for a 2.5 m slab with replacement percentage of 30%, up to a maximum of 1.1 €/m^2, in the case of 8 m span and with 100% replacement percentage.

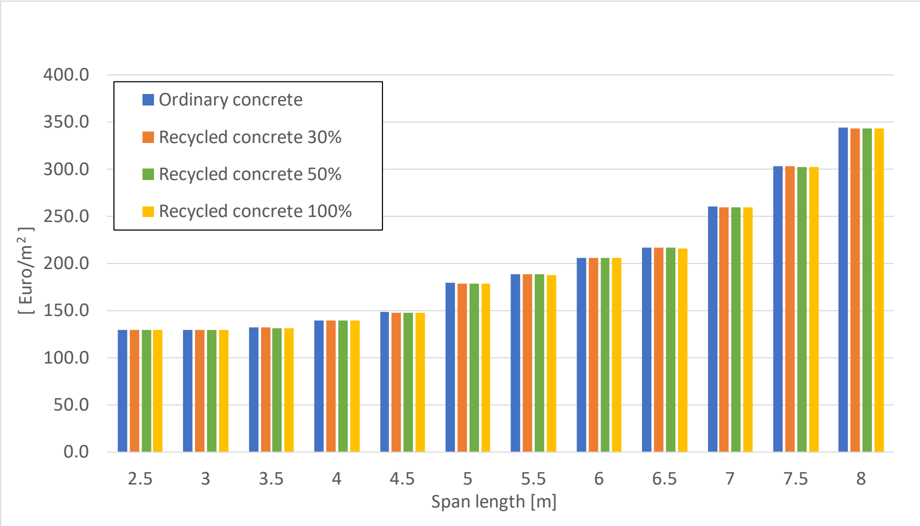

Figure 7: Economic costs of composite slabs as a function of span length for service load Qk1=2 kN/m^2

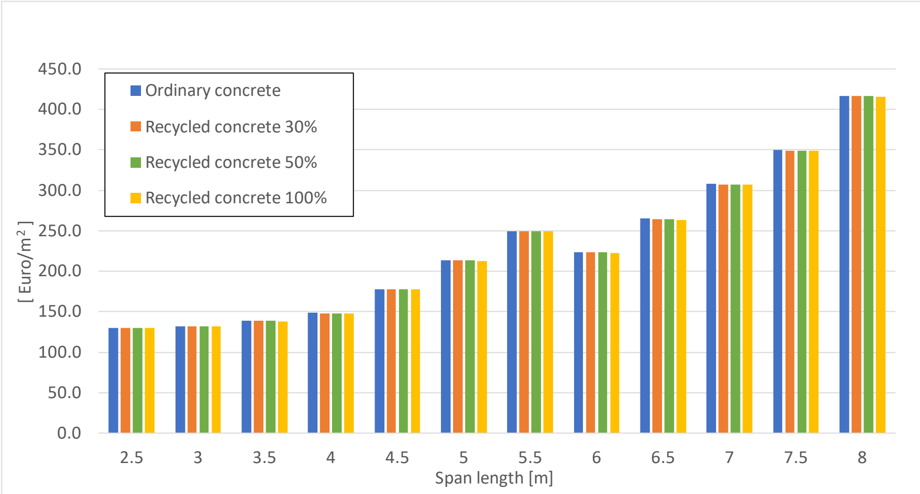

Figure 8: Economic costs of composite slabs as a function of span length for service load Qk1=4 kN/m²

Figure 8 presents the variations of specific economic costs of composite slabs subjected to 4kN/m² for different span length. Also, in this case there is an oscillation between 5.5 and 6.0 m span lengths due to the changing of the metal sheets necessary to optimize the costs followed by a usual increasing trend. Compared to the composite slab made with ordinary concrete, the construction costs of composite slabs present a small reduction from a minimum of 0.1 €/m² for a 2.5 m span composite slab with a percentage of replacement of recycled aggregates of 30%, up to a maximum of 1.3 €/m², in the case of 8 m span and with the complete replacement of aggregates (100%).

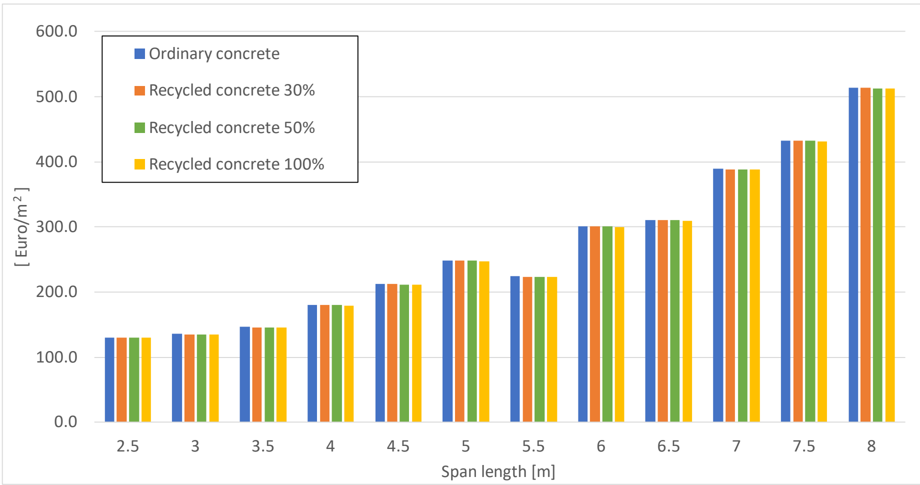

Figure 9: Economic costs of composite slabs as a function of span length for service load Qk1=6 kN/m²

Similar results and trends are shown by Figure 9 for composite slabs subjected to service load equal to 6kN/m^2.

Based on the analysis of Figure 7, Figure 8 and Figure 9, it is evident that the economic benefits of using recycled concrete in comparison to ordinary concrete are nearly unaffected by the percentage of aggregates replaced in the mixture. For instance, considering a span of 5.5 m, the maximum economic saving is 0.80 €/m^2 when 100% of the aggregates are substituted considering the heaviest load configuration Qk_1=6 kN/m^2. This outcome can be explained by examining the costs of the individual components that constitute the composite slabs. Excluding the cost of steel sheet metal and electro-welded mesh, which remains constant for all cases, the cost of each kilogram of cement (0.279 €/kg) is significantly higher (by two orders of magnitude) than that of both natural and recycled aggregates (0.0096 €/kg and 0.0082 €/kg, respectively).

Despite aggregates accounting for 75% of the mass in a cubic meter of concrete mixture, with the remaining 25% being divided between cement and water, the substantial cost disparity between binder and aggregates implies that the difference in cost between constructing the same composite slab with ordinary concrete versus recycled concrete is minimal, even for 100% replacement percentage. Indeed, the difference in price between natural and recycled aggregates is only 0.0014 €/kg. Furthermore, the majority of the cost of concrete is attributed to cement and labor, while the cost of aggregates has a negligible impact on the final expense.

4 Conclusion

This paper analyzed the environmental impact and the economic aspects of the use of concrete with recycled aggregates for composite steel-concrete slabs.

Previous researches [4-11] proved that recycled aggregates can be used in structural concrete, even at high percentages of replacement of natural aggregates, reducing carbon dioxide emissions without increasing construction costs for companies. However, a network of plants for the treatment and recycling of construction and demolition waste must be appropriately spread throughout the territory otherwise transportation costs can become important.

With regards to sustainable development, the findings of this work suggest the following observations to reduce concrete impact on the environment:

- Using recycled aggregates in concrete for structural purposes reduces carbon dioxide emissions by more than 10 kg/m^2, which could lead to significant benefits if applied on a large scale.
- An update of the international standard is necessary to use of mixtures containing higher percentages of replacement of recycled aggregates.
- Encouraging the spread of treatment and recycling plants for waste materials from demolition and construction is crucial for having recycled aggregates available on the market at competitive prices.

- In steel-concrete composite structures, particularly in the construction of slabs, maximizing the bonding resistance is essential to obtain the best performance of the two materials and thus obtain reduced sections and lower CO_2 emissions.

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