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Life cycle analysis of innovative building materials based on circular coffee ground supply chain

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Abstract

The construction sector is widely recognized as one of the most polluting mainly due to its intensive exploitation of natural resources and large energy consumption to produce traditional building materials. In the last years, alternative building materials have been developed with the aim to reduce the environmental burden of this sector. In particular, the use of geopolymer mortars as alternative cementitious materials is gaining increasing acceptance among scientists. Numerous laboratory studies demonstrate their suitability for construction applications, highlighting the potential environmental benefits that can be obtained from their large-scale production. This study aims to perform a preliminary evaluation of the environmental performance of a geopolymer mortar, whose production includes the reuse of a food waste: Spent Coffee Ground (SCG). By using the Life Cycle Assessment (LCA) approach, an environmental comparison with a traditional production of cement mortar was carried out on the basis of the Global Warming Potential (GWP) indicator.

Keywords: Life Cycle Assessment; Circular economy; Food waste; Spent Coffee Ground.

1. Introduction

Nowadays, the construction industry is one of the least sustainable sectors, being responsible of several adverse environmental effects, such as large consumption of energy, high use of non-renewable raw materials, greenhouse gas emissions, and dust pollution (Murmu and Patel A., 2018; Saeli et al., 2019). Accordingly, the European Green

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Deal (A European Green Deal European Commission, 2020) refers to construction as one of the key sectors for the green transition of European countries, meaningfully contributing to the carbon neutrality that must be achieved by 2050 (New Circular Economy Action Plan, 2020). In particular, the building materials production represents a huge environmental problem due to the great impact caused by their manufacturing processes. In this regard, some researcher investigated the production of alternative construction materials to mitigate the environmental impacts of the construction sector (De Carvalho Araújo et al., 2019; Saeli et al., 2020b). Among these, the Geopolymers (GP) demonstrated good mechanical properties and interesting environmental performances, when used as alternative cementitious materials (Nguyen et al., 2018; Saeli et al., 2020a).

With this recognition, the present study aims to evaluate the carbon footprint of the GP mortar production system developed at industrial scale by La Scalia et al. (La Scalia et al., 2021), in which increasing quantities of Spent Coffee Ground (SCG) were used as additional aggregate material. In recent years, the practice of reusing SCG has grown in many sectors, thus avoiding both their combustion in waste-to-energy plants and disposal in landfill (He and McNutt, 2019; Ma et al., 2019). The SCG potential can be understood analyzing its composition. They generally consist of polysaccharides, such as cellulose and hemicellulose (about 50% of the dry mass), lignin and proteins (about 20% of the dry mass), and oils (about 15% of the dry mass). There are also other minor components such as caffeine, ash, minerals and phenolic compounds (Ballesteros et al., 2014). This mix of substances makes the SCG suitable for many applications and functional for the production of different bio-products. In particular, Kamil et al. (Kamil et al., 2020) investigated the potential use of SCG for biodiesel production by exploiting their oil content. Despite the lower calorific value obtained compared to traditional fuels, biodiesel showed better environmental performance in terms of polluting emissions of CO, CO2 and HC. Itten et al. (2011) studied the conversion of SCG into organic briquettes for heating, comparing them to other biomass sources such as olive pomace or horse dung. The results obtained showed a good potential in terms of heating, lower than fossil fuels but higher than wood. On the other hand, Murthy and Naidu (2012) proposed an interesting application of the SCG in the food sector. The authors have in fact investigated the possibility of obtaining glucose from the cellulose content and exploiting it to produce feed, biscuits and snacks. As regards the construction sector, a few studies that use SCG as an alternative raw material are present in the literature. For example, Muñoz Velasco et al. (2015) have carried out a study on the insulating performance of clay bricks with the addition of increasing amounts of SCG. The obtained results showed a reduction in thermal conductivity of up to 50% for samples with 17.5% of SCG.

The Life Cycle Assessment (LCA) approach was used to evaluate the carbon footprint of the production system under consideration. In addition, the environmental performance of the GP mortar production system was compared with that of a traditional cement mortar. LCA is a useful technique to assess the potential environmental impacts of an industrial process to make decisions aimed at improving its sustainability (International Organization for Standardization (ISO), 2006). Moreover, LCA has already been demonstrated a useful tool to compare traditional and new processes in several industrial sectors, as construction industry (Salas et al., 2018).

The remainder of this paper is organized as follow. Section 2 summarizes both the methodological approach used for the environmental analysis and the inventory data. Section 3 shows the results of the analysis, while in section 4 the conclusions are reported.

2. Materials and methods

This section aims to provide the basic assumptions and inventory data of the LCA analysis of the production systems under consideration. The LCA methodological approach was used in accordance with the ISO guidelines 14040/14044 (International Organization for Standardization (ISO), 2006), and the analysis was carried out with the help of Simapro software (https://simapro.com/). The inventory phase was based both on Ecoinvent database (https://ecoinvent.org/the-ecoinvent-database/) and literature contributions for background data. The adopted life cycle impact assessment method was based on the single-issue indicator of Global Warming Potential (GWP), which allowed to compare the climate effect of different emissions based on the kg CO_2 eq.

2.1 Goal and scope definition

The environmental comparison between GP mortar and cement mortar was based on the functional unit (FU) of 1 ton of mortar produced. As regards the system boundaries, the cradle-to-gate approach was considered, that includes the raw materials extraction or production, the transport operations to plant and the manufacturing processes. Figures 1 and 2 show the system boundaries of the GP mortar and the cement mortar respectively. Since the production system analyzed includes the reuse of wastes (i.e., Biomass Fly Ash (BFA) and SCG), the "cut-off system model" was used as multi-functional processes approach, which considers the wastes or recyclable materials cut off from the primary production system and free from environmental burdens.

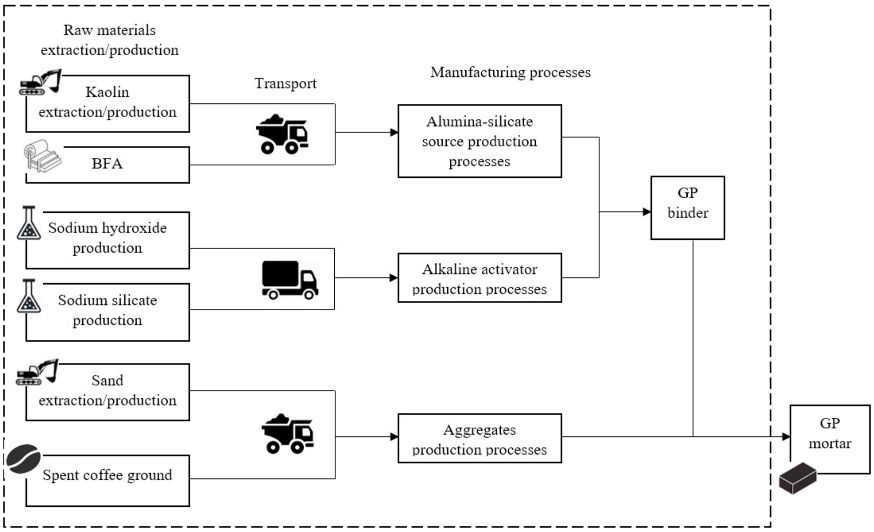

Fig.1. System boundaries of the GP mortar production and supply system.

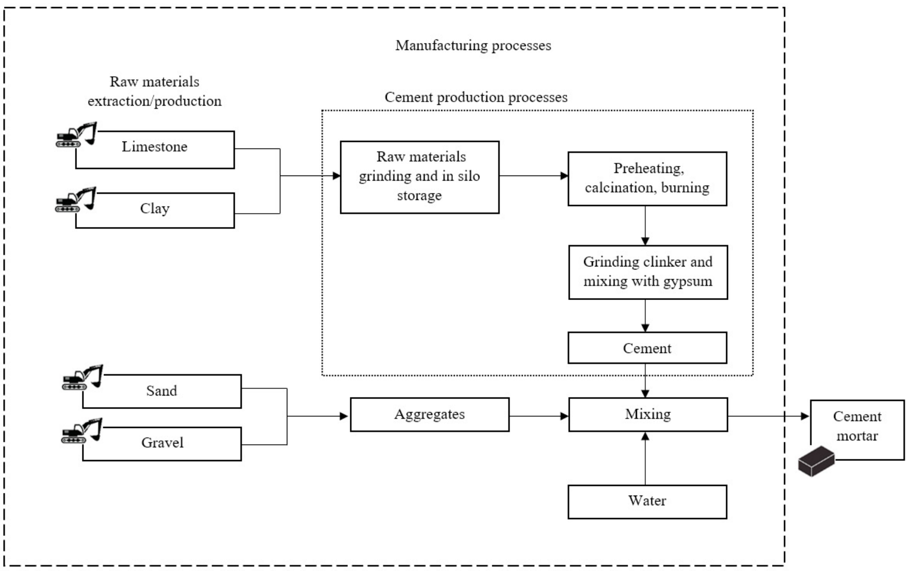

Fig.2. System boundaries of the cement mortar production

2.2 Mix Design

Five different formulations of GP mortars were analyzed, which differ in the composition of the aggregates. In particular, from the reference formulation (1) up to the fifth, an increasing percentage of spent coffee ground has been added to replace the sand. Table 1 summarizes in detail the composition of the five formulations considered.

Table 1. Mix design of GP mortars analyzed.

Formulation n.	Alumino-silicate source	Activating solution	Binder/ aggregate ratio	Wastes used as filler typology	wt%
REF - 1	70% wt. BFA + 30% wt. MK	25% wt. Na hydroxide + 75% wt. Na silicate	1:3	-	0.0%
2				SCG	5%
3				SCG	10%
4				SCG	15%
5				SCG	17.5%

2.3 Life cycle inventory (LCI) phase

The LCI of the GP mortar production system refers to the industrial scale up data, developed by La Scalia et al. (2021) from a referenced laboratory production system proposed by Saeli et al. (2020a). While the LCI of cement mortar was based on an average cement LCI contained in Ecoinvent and adapted to a European scenario (e.g., the italian mix for electricity generation was considered).

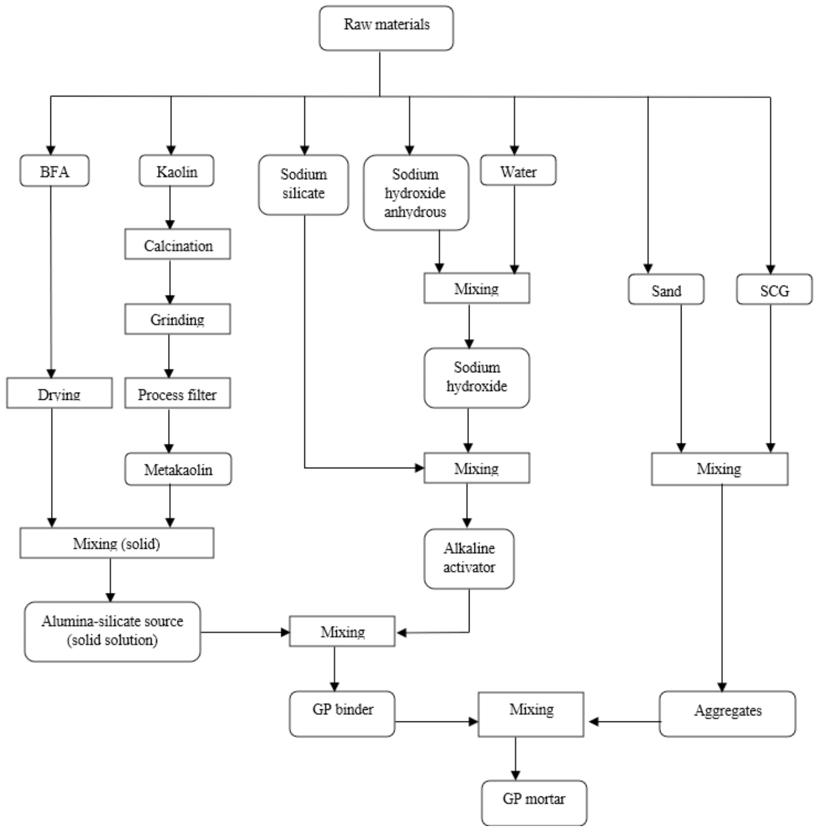

Fig. 3. Flow chart of the GP mortar production and supply system (La Scalia et al., 2021).

With reference to the figure 1, the alumino-silicate source is produced mixing of 70wt% BFA and 30wt% Metakaolin (MK). Metakaolin is obtained from the calcination process of kaolin, which is a heat treatment performed at 750°C for 15h. The alkaline activator is composed by 25wt% of a sodium hydroxide solution and 75wt% of sodium silicate respectively. Then the alumino-silicate source and the alkaline activator are mixed in a ratio of 0.78 in order to obtain the GP binder, which is finally mixed with the aggregates. Figure 3 shows the flow chart of the GP mortar production system, where materials and processes are represented by rectangular boxes with or without rounded edges respectively. For more details on the process parameters, the reader is referred to the authors' previous paper (La Scalia et al., 2021).

Processes involved in the GP mortar production system can be classified in two categories. The first one includes processes that need heat (i.e., calcination and drying), while the second one refers to mixing, grinding and filtering processes where mechanical energy is necessary. Only the calcination process is powered by the heat generated by the combustion of natural gas; the remaining processes are powered by electricity. The heat required for the calcination and drying processes are computed according to the heat transfer theory, that suggests the equation (1) for the process
heat computation.

$$Q_p = Q_{heat} + Q_{keep\ temp} \tag{1}$$

Q_{heat} and $Q_{keep\ temp}$ are the required heat to reach the process temperature and to keep the needed temperature throughout the process respectively. Q_{heat} and $Q_{keep\ temp}$ are calculated according the equations (2)-(3).

$$Q_{heat} = c_p \cdot M_c \cdot \left(T_p - T_o\right) \tag{2}$$

$$Q_{keep\ temp} = \frac{A \cdot k \cdot \left(T_p - T_o\right)}{s} \cdot t_p \quad , \tag{3}$$

where T_p and T_o are the process temperature and the room temperature respectively, while M_c and c_p are the mass and the specific heat of the material heated. A, k and s are parameters related to the specific oven: in particular A is the surface area, k is the thermal conductivity of the insulation material and s is the insulation thickness. In this study, the assumption of using a rotary oven with a diameter of 0.70 meters and a length of 3 meters was considered. Finally, t_p is the process time. Table 2 shows the parameters used for the calcination and drying processes.

Table 2. Parameters used for the calcination and drying processes

Parameters	Unit	Calcination (Kaolin)	Drying (BFA)
T_p	°C	750	105
T_o	°C	20	20
M_c	kg	1000	1000
c_p	kj/kg°C	1.024	1.246
A	m^2	6.597	6.597
k (glass fiber)	W/m°C	0.042	0.042
s	m	0.075	0.075
t_p	h	15	1
Q_p	kWh	247	30

The energy values required for the remaining processes have been estimated based on the suitable machineries plate data. As regard the transport inventory, it was assumed to locate the production plant in the Po Valley, the most industrialized area of Italy. Therefore, an average distance with the main producers of raw materials was assumed using google maps. Table 3 shows the data respectively of the average distance and of the type of vehicle considered.

Table 3. LCI of the transport

Raw materials	Average distance	Unit	Transportation vehicle
Kaolin	400	km	lorry 16-32 metric ton
BFA	300	km	lorry 16-32 metric ton
Sodium hydroxide	300	km	light commercial vehicles
Sodium silicate	300	km	light commercial vehicles
Sand	100	km	lorry 16-32 metric ton
SCG	0	km	-

As regards the cementitious mortar, a typical production system (schematized in figure 2) is considered. Limestone (90%) and clay (10%) are crushed before being stored. This mixture is then further crushed and ground in order to obtain the appropriate particle size. The raw flour obtained is introduced into an oven where it is preheated to be then introduced into a rotating oven, where the temperature reaches 1450 °C. The result of this process is the clinker which is then cooled, ground and mixed with gypsum and additives to obtain the commercial cement mixture. For the present analysis, the mix of Italian electricity generation was considered. The LCI of the cement mortar is based on the inventory data of an average cement mortar production, in which the Italian energy mix was considered.

Processes modeling on Simapro software has been carried out through a "bottom up" approach. With reference to figure 1, first the production/extraction processes of raw materials were modeled. Then, the processes of the higher level were created up to the GP mortar. The tab of each process is identified by the output of the specific process and by its quantity. Therefore, each tab was filled with all inputs and outputs, consisting of the mass and energy flows (e.g, semi-finished products, electric energy, transport) needed to produce the given output.

3. Results and discussion

Table 4 shows the results of the LCI relating to the mass and energy flows required to produce the functional unit (i.e., 1 ton) of the GP mortar. These data result from the flows aggregation provided by Simapro. For example, to produce the functional unit of the GP mortar, 48.8 kg of kaolin are required with a natural gas consumption equal to 43.3 MJ for the calcination of this quantity of kaolin. The remaining processes are powered by the electricity and the total amount of electric energy needed is 19.1 MJ per ton of GP mortar. A relevant part of this value consists of the electric energy used to dry the 98 kg of BFA (about 10.6 MJ per ton of FU). Table 4 also shows that it is possible to save up to 131 kg of sand per ton of GP mortar with the fifth formulation. This is a great result in terms of saving of natural resources. In fact, assuming an annual production of 200,000 tons of the third formulation (i.e., with 10% of SCG), which has shown the best laboratory performances (La Scalia et al., 2021b), it would be possible to save 15,000 tons of sand.

Table 4. LCI parameters to produce 1 ton of GP mortar

Life cycle phase		Quantity	Unit/ FU	Source
Raw materials	Kaolin	48.8	kg	Ecoinvent
	BFA	98	kg	Burden free
	Sodium hydroxide	27.5	kg	Althaus et al. (Althaus et al., 2007)
	Sodium silicate	82.5	kg	Fawer et al. (Fawer et al., 1997)
	Sand	750	kg	Ecoinvent
	SCG	0 37.5 75 112.5 131.25	kg	Burden free
Manufacturing processes	Electricity, medium voltage {IT}	19.1	MJ	Ecoinvent
	Heat, district or industrial, natural gas {RER}	43.3	MJ	Ecoinvent

Once the boundaries of the systems to be analysed are defined (see figures 1 and 2), Simapro allows to evaluate the related equivalent CO_2 emissions, applying a "characterization factor" to all emissions to the environment. This one is a conversion factor that returns the kg of CO_2 equivalent for each emission. In this way the software manages to sum the effects of different emissions in order to obtain the single indicator of the GWP. Figure 3 shows the results about the GWP indicator of the compared production systems, in reference to 1 ton of mortar produced.

The production of the GP mortar generally allows a reduction of 43.3% of greenhouse gas emissions (about 98 kg of CO_2 eq less). However, the GWP scores of the five formulations do not show any significant difference. In fact, the amount of SCG used to replace the sand is minimal compared to the functional unit. However, as already said, the environmental benefit of reusing SCG should be considered in large scale production, where the quantity of sand saved becomes significant.

It is worth to note that the provided comparison entails limitations due to the uncertainty represented by the characterization of cement within the LCI of cement mortar. As mentioned in Section 2.3, an average cement LCI was considered and the result could be affected by the given clinker to cement ratio, that is equal to 0.9 in the presented analysis. Therefore, the present analysis is valid only under the conditions of the present study. In order to identify the most critical processes of the GP mortar production system a contribution analysis was performed. Once the overall environmental impact of a system has been obtained, the software allows to evaluate the fraction of environmental burden caused from each process through the contribution analysis. Figure 5 presents the results of the contribution analysis, in which an exclusion threshold value of 1% was regarded.

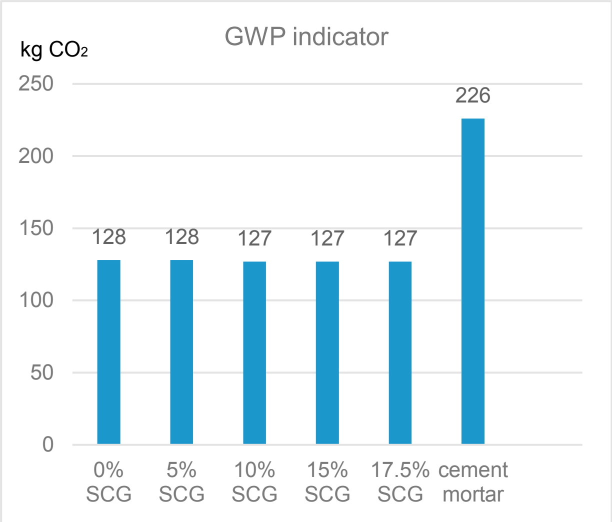

Fig.4. GWP indicators of the two mortar productions

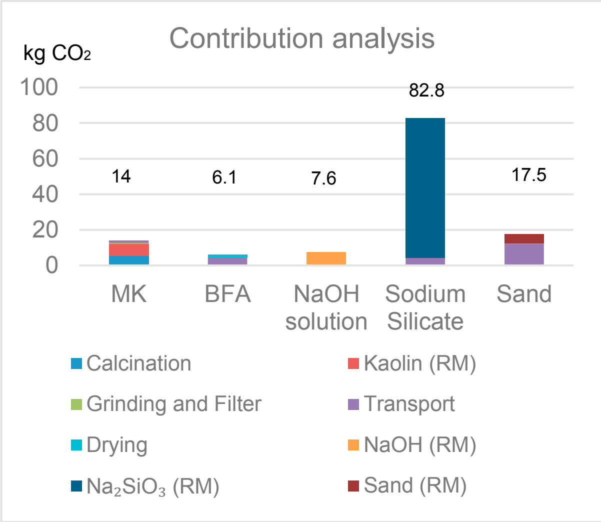

Fig.5. Contribution analysis results

The sodium silicate production represents the most contribution to the overall environmental load with a GWP value of 82.8 kg of CO_2 eq, consisting of 64.7% of the total. This result is consistent with many previous studies (Salas et al., 2018), which identified the main environmental limitation of GP mortar production in the use of large quantities of alkaline activator. The use of sand and MK roughly generate the same environmental burden, with a GWP values equal to 17.5 kg of CO_2 and 14 kg of CO_2 respectively, confirming that the consumption of natural resources is one of the most critical issues of the construction sector. The environmental impact of transport is particularly significant for the production/extraction of sand and BFA. It represents 70% on overall sand impact and 78% on overall BFA impact respectively, while it affects the environmental load of the other raw materials to a lesser extent.

It's clear that environmental impact of the production processes depends on the process parameters and the nature of the raw materials. On the other hand, the environmental burden of the transport phase is based solely on the location of the plant and on logistical considerations. In fact, locating the plant in an industrial district, whose production sites are strongly interconnected through several routes helps to reduce the impact caused by transport. Conversely, an area poorly interconnected and poor in industrial plants useful for production could make transport the critical phase of the life cycle, reducing the environmental advantage obtained with GP mortar production.

4. Conclusions

The LCA analysis performed on different formulations of GP mortar highlighted the potential environmental benefits they offer compared to the traditional cement mortar. In particular, the results showed a reduction of 43.3% of the carbon footprint. However, no differences about the GWP scores of the five formulations were obtained, when referring to the functional unit. In fact, the advantages offered by the reuse of SCG must be considered in large-scale production, where the use of 10% of SCG in the aggregates could lead to a saving of several tons of sand. In this way, the industrial production of innovative formulations of GP mortars would mean both a lower extraction of sand and the reuse of an organic waste, which would otherwise be disposed in landfill or burned in waste-to-energy plants. Therefore, the results of this study confirm that the waste management aimed at their reuse, according to the principles of the circular economy, is a winning strategy to improve the sustainability of different sectors.

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