Reusing coffee ground waste in manufacture of novel sustainable product

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Abstract: Coffee is one of the most important commodities in the world. Every year the coffee industry is responsible for generating a large amount of wastes, mainly Spent Coffee Grounds (SCGs). The traditional disposal of this residue into the environment should be avoided due to its toxicity and organic character. Because of the decrease in non-renewable natural resources, society has been making a huge effort to valorize and reuse several types of wastes in the production of novel sustainable products. In this regard, construction is considered one of the most energy-intensive sectors. As a consequence, the goals of sustainability and energy efficiency must be prosecuted to achieve the results expected by the recent European directives and national regulations. The present paper aims at providing further knowledge on wastes recycling, analyzing the influence of the SCG incorporation as an aggregate in construction materials. To this purpose, the produced mortar specimens are firstly characterized. Afterwards, engineering properties as well as environmental and economic aspects are taken into account to rank the considered mixtures by a multi-criteria approach. The performed analysis highlights how the addition of the considered industrial wastes is strongly recommended to improve the performance of materials intended for various applications in construction.

Keywords: Sustainability, waste valorisation, multi criteria decision making, coffee

1.Introduction

Over the last 50 years, the exponential increase in population has internationally impacted on the economic, social, and infrastructural tolerances of countries. As a consequence, the global wastes production has never been worst, with a global solid waste forecast of 27 billion tonnes by 2050 (Tang et al., 2020). The coffee industry is responsible for generating a large quantity of residues, mainly Spent Coffee Grounds (SCG) (Mussatto, et al., 2011). Approximately 6 million tons of SCGs are generated in the world every year (Getachew and Chun, 2017). The traditional disposal of this residue into the environment should be avoided due to its toxicity and organic character (Ktori et al., 2018; Massaro and Ferreira, 2019). From this perspective, the focus on the development of various industries have been side tracked towards sustainable as well as renewable, eco–friendly and cheap resources from SCGs, following the circular economy paradigm (Karmee, 2018; Son et al., 2018; Nguyen et al., 2019; Dattatraya Saratale et al., 2020). By the way, circular economy could be strongly applied towards the management of food waste biomasses. Particularly referring to SCG, it can be subjected to a re-cycling process for the production of a wide range of bio–products, e.g. the extraction of sugars and oils to produce renewable biofuels, isolating the remaining phenolics and antioxidants to use them as nutraceutical supplements, or combining SCG with other substances to develop novel materials (McNutt and He, 2019). So far, biodiesel production from SCG has been one of the most popular research topics. In addition, one of the most valuable property of SCG is its high antioxidant and phenolic compounds content such as chlorogenic acid, caffeine, and flavonoids. Therefore, a lot of literature contributions have been focused on the isolation of these compounds through various extraction methods.

As concerns the construction sector, more and more attention has been paid by researchers and industries on the utilization of renewable resources to produce sustainable materials alternatively to the Portland cement. By-product wastes have great potential for use in the construction industry, so that oil palm shell (Khankhaje et al., 2017), bamboo leaf ash (Villar-Cocina et al., 2011), rice husk ash (Rahgozar et al., 2018), periwinkle and cockle shell (Umoh and Olusola, 2013; Othman et al., 2013), wood waste (Ijaz et al., 2020), date seed (Adefemi et al., 2013), coconut shell (Gunasekaran et al., 2012), banana leaf ash (Kanning et al., 2014), corn cob ash (Adesanya and Raheem, 2009), and vegetable fibers (Pacheco-Torgal and Jalali, 2011) have been recently evaluated by researchers. These applications can both preserve the limited availability of natural resources and reduce the overall carbon emission so contributing to less solid wastes production (Li et al., 2019).

Recent studies demonstrate that multi-criteria approaches may represent a valid decision aiding support tool to assess the development of new sustainable construction materials (Kurda et al., 2019; Sciortino et al., 2019). Actually, the need to consider controversial and often uncertain technological, environmental and economic aspects in the selection of new materials makes the multi-criteria approach particularly suitable (Janssen, 1992; Micale et al., 2017). Therefore, the present paper aims to assess the physical and mechanical proprieties as well as the technological viability of different mortar formulations obtained by incorporating various amounts of SCG as aggregate. In the attempt to evaluate the industrial feasibility of the proposed solutions both from an environmental and economic point of view, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is applied to rank the considered mixtures.

2. Materials and methods

2.1 Materials

In this study, mortars employing Natural Hydraulic Lime (NHL) as hydraulic binder and various percentages of SCG are considered (Figures 1 and 2). NHL is produced by Axton and furnished in powder. On the other hand, the aggregate consists of a mixture in various proportions of a commercial natural sand (calibrated 0.5 mm) and SCG, being the latter a domestic waste deriving from ordinary *Moka* Italian coffee machine. The main characteristics of the used NHL-mortar are summarised in Table 1.

Table 1: property of NHL mortar (reference)

Property	Measured value
Consistency (spread by flow table) [cm]	21
Water: solid ratio	0.155
Bulk density [Kg/m^3]	1706
Sorptivity by immersion [%]	11.1
Coefficient of capillarity [kg/(m^2·min$^{0.5}$)]	1.57
Compressive break point [MPa]	2.82±0.18
Bending resistance [MPa]	1.25±0.02

Figure 1: NHL

Figure 2: SCG

The foreseen use of NHL-mortars manufactured with different SCG waste quantities is a plastering application for architectural finishing with innovative insulating performances. By adding increasing quantities of SCG in substitution of the traditional sand, mortars mix are designed in order to improve the material performance, along with its sustainability. In this regard, the aggregate is prepared by substituting increasing quantities of sand by SCG (i.e. 5 %, 10 %, 17.5 % in volume) until the material does not become too viscous to be appropriately mixed (cfr. flow table test). Four different formulations are considered as listed in Table 2.

NHL-mortars are produced by mixing the lime with water for 30 seconds. According to UNI EN 1008:2003 and UNI EN 206-1: 2006, water is taken from the municipal aqueduct. Afterwards, the aggregate (i.e. sand or sand+SCG) is added and mixed for other 210 seconds. The slurry is then poured in standard metallic moulds, vibrated for 2 minutes, sealed for 7 days (2 days in the mould and 5 days un-demoulded). Specimens are then cured for other 28 days until testing (Figure 3).

Table 2: formulation of NHL mortars

N.	ID	Substitution [volume %]	Mix design - aggregate volume [%]		Mix design - aggregate part	
			sand	coffee	sand	coffee
1	NHL_0	0	100	0	3	0
2	NHL_5	5	95	5	2.85	0.15
3	NHL_10	10	90	10	2.7	0.3
4	NHL_17.5	17.5	82.5	17.5	2.475	0.525

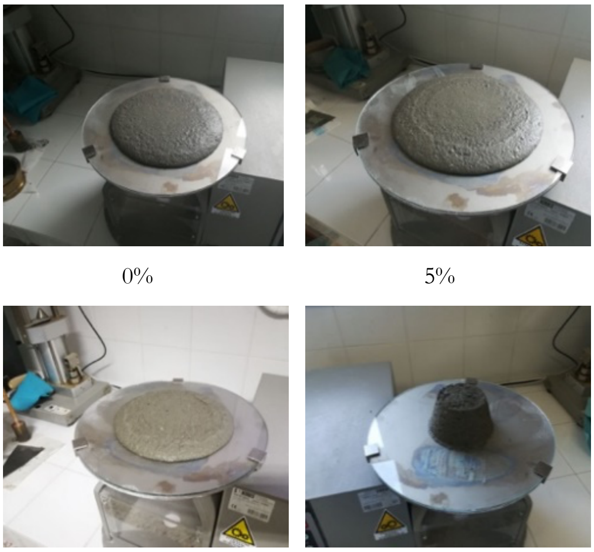
Figure 3: NHL mortars specimens

2.2 Evaluation criteria

Aiming to select the best SCG quantity to substitute the sand, properties and performance of NHL-mortars manufactured with different SCG waste quantities are here analysed, compared and ranked by TOPSIS. Different evaluation criteria are taken into account depending on the particular application which they are intended for (Saeli et al., 2020).

For the considered application, evaluation criteria are described as follows.

- Workability [cm] (W): according to EN 1015-3:1999, it is estimated by the flow table test and expressed in terms of spread. It indicates the consistency of the produced slurry so returning the product attitude to be mixed until reaching the homogeneity required to be conveniently used. It is strictly related to the slurry fluidity (or conversely viscosity) and the specific application. Figure 4 shows the test conducted on the 4 considered specimens.
- Bulk Density [kg/m^3] (BD): it represents the geometric mean value calculated for three different specimens cured for 28 days.



0% 5%

10% 17.5%

Figure 4: workability test

- Uniaxial Compressive Strength [MPa] (UCS): it indicates the maximum resistance by compression. According to EN 998-2:2016, it is measured by using a universal testing machine (Shimadzu, AG-25TA), equipped with a 250 kN load cell running at 0.5 mm/min displacement rate (Figure 5). Mean values are calculated from three tests performed on specimens cured for 28 days.

Figure 5: UCS test

- Axial Strain [%] (AS): it is the strain at rupture by compression (cf. UCS) calculated as the quotient of the displacement at maximum strength and the initial length of the specimen.
- Flexural Strength (FS): it indicates the maximum resistance by pure flexion under an external load applied perpendicularly to the longitudinal axis of the specimen. According to EN 998-2:2016, it is calculated by using a universal testing machine (Shimadzu, AG-25TA), equipped with a 20 kN load cell running at 0.5 mm/min displacement rate. Mean values are calculated from three tests performed on specimens cured for 28 days (Boresi et al., 1993).
- Bending Deflection (B): it represents the degree to which the simply-supported specimen (10 cm distance) is displaced under the load applied in the centre.
- Water Absorption by immersion [%] (WAI): it indicates the quantity of water - by weight variation ($\Delta P/P$ %) - absorbed by a specimen after a full immersion in water. The value is the average from three tests.
- Thermal Conductivity [W/m·K] (TC): it indicates the rate of the heat transfer through the specimen. According to ISO 6946:2017, it is measured by a spectrometer.
- Sustainability (S): it is intended as the reduction of the environmental and economic impact in terms of waste disposal. The higher the amount of SCG used in the material, the lower the costs for its disposal and raw materials (the less the sand usage). This criterion is expressed in the range [1; 10].

2.3 TOPSIS Technique

Developed by Hwang and Yoon in 1981, TOPSIS is a Multi-Criteria Decision making (MCDM) method to deal with choice and ranking problems of alternatives in the presence of multiple evaluation criteria. By the method, the best compromise solution is the one having the shortest distance from the Positive Ideal Solution (PIS) and the longest distance from the Negative Ideal Solution (NIS). TOPSIS has been already applied to rank alternatives related to new building materials derived from waste reuse (Bisikirske et al, 2019; Saeli et al., 2020; Rashid et al., 2020). Actually, the method provides some advantages in dealing with MCDM problems of materials selection because it allows to include several independent and conflicting criteria, taking into account both quantitative and qualitative attributes (Arukala et al., 2020).

In the present paper, alternatives to be ranked by TOPSIS are NHL mortars with different SCG quantities as aggregate, whereas criteria are the ones introduced in Section 2.2. As input data, the method requires the rating g_{ij} of every alternative $i|i=(1,\ldots,n)$ against the criterion $c_j|j=(1,\ldots,m)$ so obtaining the decision matrix of Table 3. A further input data is the relative importance of every criterion w_j.

Table 3: decision matrix

ALTERNATIVES	CRITERIA			
	c_1	c_2	…	c_m
a_1	g_{11}	g_{12}	…	g_{1m}
a_2	g_{21}	g_{22}	…	g_{2m}
…	…	…	…	…
a_n	g_{n1}	g_{n2}	…	g_{nm}

The TOPSIS method is performed through the following steps.

step 1 – calculation of the normalized decision matrix where the generic element z_{ij} is obtained by the equation (1).

$$z_{ij} = \frac{g_{ij}}{\sqrt{\sum_{i=1}^{n} g_{ij}^2}} \quad \forall i, \forall j \tag{1}$$

step 2 – calculation of the weighted normalized decision matrix, where the generic element u_{ij} is obtained by the equation (2).

$$u_{ij} = w_j \cdot z_{ij} \quad \forall i, \forall j \tag{2}$$

step 3 – calculation of the positive (i.e. Azimuth) (A^*) and negative (i.e. Nadir) (A^-) ideal solutions. Indicating by I' and I'' the sets of benefit and cost criteria respectively, PIS and NIS are computed by equations (3) and (4).

$$A^* = \left(u_1^*, \ldots, u_n^*\right) = \left\{\left(\max_i u_{ij} \mid j \in I'\right), \left(\min_i u_{ij} \mid j \in I''\right)\right\} \tag{3}$$

$$A^- = \left(u_1^-, \ldots, u_n^-\right) = \left\{\left(\min_i u_{ij} \mid j \in I'\right), \left(\max_i u_{ij} \mid j \in I''\right)\right\} \tag{4}$$

step 4 – calculation of distances between every alternative and the positive/negative ideal solutions (eqs. 5 and 6 respectively).

$$S_i^* = \sqrt{\sum_{j=1}^{m} \left(u_{ij} - u_j^*\right)^2}, \forall i \tag{5}$$

$$S_i^- = \sqrt{\sum_{j=1}^{m} \left(u_{ij} - u_j^-\right)^2}, \forall i \tag{6}$$

step 5 – calculation of the closeness coefficient related to every alternative i (i.e. C_i) by the equation (7).

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^*} \qquad 0 \le C_i^* \le 1 \qquad \forall i \tag{7}$$

step 6 – ranking the alternatives according to descending values of C_i^*.

3. Results and discussions

In the present paper, criteria weights (Table 4) are obtained by the Delphi technique (Delbecq et al., 1975), where a panel of experts in the field under investigation is iteratively queried by means of questionnaires until an agreement is achieved. In this study, three experts are selected (i.e. a material scientist, expert in the area of materials processing; a construction technologist, expert in novel materials and technologies; an architectural engineer, expert in the application of novel materials) that have the appropriate knowledge and expertise in the field of innovative materials for constructions.

Table 4: criteria weights

Criterion	Weight
W	0.105
BD	0.100
AS	0.095
UCS	0.117
B	0.099
FS	0.119
WAI	0.098
TC	0.111
S	0.156

Among criteria, workability, uniaxial compressive strength, flexural strength and sustainability have to be maximized (i.e. benefit criteria), whereas the others have to be minimized (i.e. cost criteria). The decision matrix of Table 5 shows ratings of alternatives (i.e. different NHL mortar formulations) against criteria. As regards the score against the workability criterion, it takes a value equal to 1 if the measurement x ranges in the interval [18; 22], whereas the following equations have to be considered for the intervals [10; 18[and]22;30] respectively.

$$(x - 10)/8 \quad 10 \le x < 18 \tag{8}$$

$$(30 - x)/8 \quad 22 < x \le 30 \tag{9}$$

When the value is lower than 10 or bigger than 30, the score is equal to 0.

Table 5: Decision matrix

Criterion	NHL 0%	NHL 5%	NHL 10%	NHL 17.5%
W	23.0	20.3	15.0	10.0
BD	1832	1794	1739	1648
AS	2.65	2.88	1.92	0.59
UCS	21.66	18.67	20.83	10.63
B	0.46	0.43	0.34	0.27
FS	4.08	3.64	3.23	2.58
WAI	13.00	13.43	13.83	16.49
TC	575.0	568.0	521.0	470.0
S	8.00	8.50	9.00	9.75

Table 5 show that the use of coffee waste increases water absorption (WAI) while the bulk density (BD) decreases. The incorporation of coffee waste produces a mechanical strength reduction (UCS). The technological properties are more promising than those obtained in the literature for other types of wastes. An excellent improvement in thermal insulating properties is also obtained. In fact, even the addition of just 5% coffee waste produces a decrease in the thermal conductivity coefficient (TC).

The weighted normalized matrix (Table 6) and the resulting Azimuth and Nadir values (Table 7) are then calculated. According to steps 4 and 5 of the TOPSIS procedure, distances from PIS and NIS are finally obtained for every alternative, as well as the final ranking (Table 8).

Table 6: weighted normalized matrix

Criterion	NHL 0%	NHL 5%	NHL 10%	NHL 17.5%
W	0.063	0.072	0.045	0
BD	0.052	0.051	0.050	0.047
AS	0.057	0.062	0.041	0.013
UCS	0.069	0.059	0.066	0.034
B	0.060	0.056	0.044	0.035
FS	0.071	0.063	0.056	0.045
WAI	0.045	0.046	0.048	0.057
TC	0.060	0.059	0.054	0.049
S	0.071	0.075	0.079	0.086

Table 7: PIS and NIS

Criterion	A^*	A^-
W	0.072	0
BD	0.047	0.052
AS	0.013	0.062
UCS	0.069	0.034
B	0.035	0.060
FS	0.071	0.045
WAI	0.045	0.057
TC	0.049	0.060
S	0.086	0.071

Table 8: Final ranking of mortar formulations

Ranking	NHL mortar formulations	C_i^*
1	NHL 10%	0.591
2	NHL 0%	0.583
3	NHL 5%	0.580
4	NHL 17.5%	0.409

Results show that the mortar with 10% of added SCG is the best solution, whereas the worst one is the NHL 17.5%. To assess the robustness of the obtained solution, a sensitivity analysis is also performed by changing criteria weights by ±20%. In Table 9, only scenarios leading to a different ranking are reported. Obtained results confirm that the mortar with 10% of SCG always takes the first position, while it takes the second position in FS +20% and B -20% and the third one in AS -20%. The analysis therefore demonstrates the sufficient stability of the solution obtained and then the robustness of the proposed approach.

Table 9: Sensitivity analysis

Ranking	UCS -20%	AS -20%	FS +20%	FS -20%	B +20%	B -20%
1	10.0%	5.0%	0.0%	10.0%	10.0%	0.0%
2	5.0%	0.0%	10.0%	5.0%	5.0%	10.0%
3	0.0%	10.0%	5.0%	0.0%	0.0%	5.0%
4	17.5%	17.5%	17.5%	17.5%	17.5%	17.5%

Summing up, the mixtures in the right proportions of SCG give to mortars proper workability features and are capable of industrial processing. In some cases, the incorporation of such waste could improve the mechanical properties. Based on these preliminary results, it can be concluded that coffee waste can be added as aggregate for the production of finishing with acceptable physical and mechanical performance and low thermal conductivity. As a way of reducing the use of non-renewable natural resources, coffee waste could hence be reutilized as a secondary raw material to develop adequate finishing with a high thermal insulation capacity, which could reduce the energy consumption of a building.

4. Conclusions

The present study proves the feasibility of the use of significant amounts of coffee waste as additive in mortar manufacturing for construction purposes.

To date, most of the available literature on recycling SCG in construction materials does not consider mortar-based applications and multi-criteria approaches. Therefore, our study proposes itself as an innovative track solution to food waste management lowering the employment of non-renewable natural resources and the costs associated to construction materials production. At the same time, a novel and innovative way of waste disposal is suggested, pursuing the sustainability and substantially reducing the environmental impact of construction and building materials. This study is a fundamental step in assessing the real potential and applicability of our designed and produced materials for a massive industrial scale production.

Future research developments may concern the analysis of other sets of construction materials to evaluate their possible usage, also including further criteria. Furthermore, the uncertainty related to the measured criteria could be also considered to make the presented approach a valid decision-making support tool useful for real situations.

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