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Life Cycle Analysis of Light Weight Artificial Aggregates for Sustainable Construction

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Abstract **-** This article focuses on a comprehensive life cycle analysis (LCA) of granules derived from fly ash, marble sludge, and cement in various proportions, with the aim of evaluating their viability as a sustainable resource in the construction activities. The investigation delves into the environmental and economic implications of incorporating artificial granules into construction materials, examining their entire life cycle from production to disposal. Encompassing extraction of resources, building, transporting, manufacturing procedures, and end-of-life circumstances, the analysis sheds light on key factors such as energy consumption and resource depletion. In recent years, the construction sector has increasingly embraced recycled materials, with lightweight artificial aggregates emerging as a promising alternative to traditional concretes. This study introduces a selection model for lightweight artificial aggregates through experimental processes, considering economical, ecological, and technological elements. Three distinct mixtures, incorporating cement and industrial waste such as fly ash from a municipal waste incineration plant and marble sludge, were prepared. With a consistent 75% fly ash inclusion, varying percentages of marble sludge (10%, 15%, 20%) and cement (15%, 10%, 5%) were employed. This approach facilitated a comprehensive evaluation of the economical, ecological, and mechanical features of every lightweight artificial aggregate blend. The paper identifies preferred scenarios among the three mixtures, aiming for convergence and compliance in terms of environmental impacts (assessed through Life Cycle Assessment), economic considerations (assessed utilizing Life Cycle Costing), and technical-functional aspects. The findings underscore that the optimal solution for sustainable lightweight artificial aggregates involves a composition of 75% fly ash, 15% marble sludge, and a higher cement content of 10%. This outcome emphasizes the practicality of making environmentally conscious choices in selecting lightweight artificial aggregates for construction applications, aligning with the industry's shift towards sustainability.

Keywords**:** life cycle analysis, life cycle costing, granules, construction and demolition waste, cold-bonding process.

1. Introduction

Global warming and climate change are critical issues, with human activities, particularly carbon emissions, playing a significant role [1]. Europe, as a significant contributor to carbon emissions, is under increasing pressure to mitigate its environmental impact. The construction industry, accountable for a substantial share of carbon emissions and resource consumption, offers a distinctive opportunity for emission reduction. About 40% of global resource consumption is attributed to the construction sector, generating 36% of total CO2 emissions and 35% of global waste annually [2]. While the challenges are undeniable, the construction industry holds immense potential for emissions reduction. Construction and demolition waste (CDW), comprising materials such as concrete, brick, tile, wood, and glass, constitutes a significant portion of the construction industry's environmental footprint [3]. Europe generates an annual half to 1 billion tons of CDW, with approximately 70% being demolition waste [4, 5]. However, the disposal of demolition waste presents challenges, employing methods like reuse, recycling, landfill, and dumping [6]. Despite recycling efforts, a substantial amount of demolition waste is still buried rather than repurposed, highlighting gaps in current waste management policies and industry standards. Recycling, a pivotal strategy for waste management, aims to produce recycled aggregate to replace natural aggregate. In Europe, economic feasibility becomes a concern due to higher production costs for recycled aggregate compared to natural aggregate. These cost considerations encompass energy consumption and machinery expenses [7]. Further studies are imperative to evaluate the economic viability of producing recycled aggregate, a crucial aspect for fostering sustainable waste management practices.

Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) stand out as powerful tools for evaluating the environmental and economic impacts of products or systems. LCA comprehensively assesses inputs, outputs, and potential environmental impacts throughout a product's life cycle [8]. Meanwhile, LCC determines the total costs associated with an asset, covering acquisition, installation, operation, maintenance, refurbishment, and disposal [9]. While previous studies often segregated environmental and economic assessments, integrating LCA and LCC offers a more holistic view, preventing the overlooking of interconnected issues [10, 11]. Prior research on CDW frequently analyzed environmental and economic impacts independently. Environmental assessments, utilizing LCA, highlighted various issues, such as the adverse impact of CDW on road construction [12]. Economic assessments explored cost-benefit analyses, examining the potential economic benefits of recycling construction waste [13]. An integrated approach, leveraging both LCA and LCC, is indispensable for a comprehensive evaluation of demolition waste disposal methods. This ensures a more nuanced understanding of the environmental and economic implications, avoiding the pitfalls of narrowly focused analyses [10, 11]. This study bridges the gap between environmental impact and economic benefits by incorporating carbon trading mechanisms into LCC analysis. This paper presents a methodological advancement, introducing the design of various mixtures (three in present case) for generating LWAs through solo-phase cold bonding pelletization (S-CBP). This method serves as an eco-friendly substitute for natural aggregates. The primary objective is to propose an integrated methodology alongside Life Cycle Costing and Life Cycle Assessment methodologies. The methodology employed in this investigation is novel in that it is applied to a laboratory material envisioning its potential for large-scale utilization. In this specific case, the study addresses the challenge of aligning sustainability principles with technological performance requirements.

2. Methodology

LCA was utilized primarily to examine carbon emissions in this investigation, with environmental impacts not being considered. Consequently, determining the primary contributors to carbon emissions across various demolition waste management scenarios constituted the objective of the LCA. There were different steps involved in the methodology, which are shown below in the form of the figure (see Figure 1).

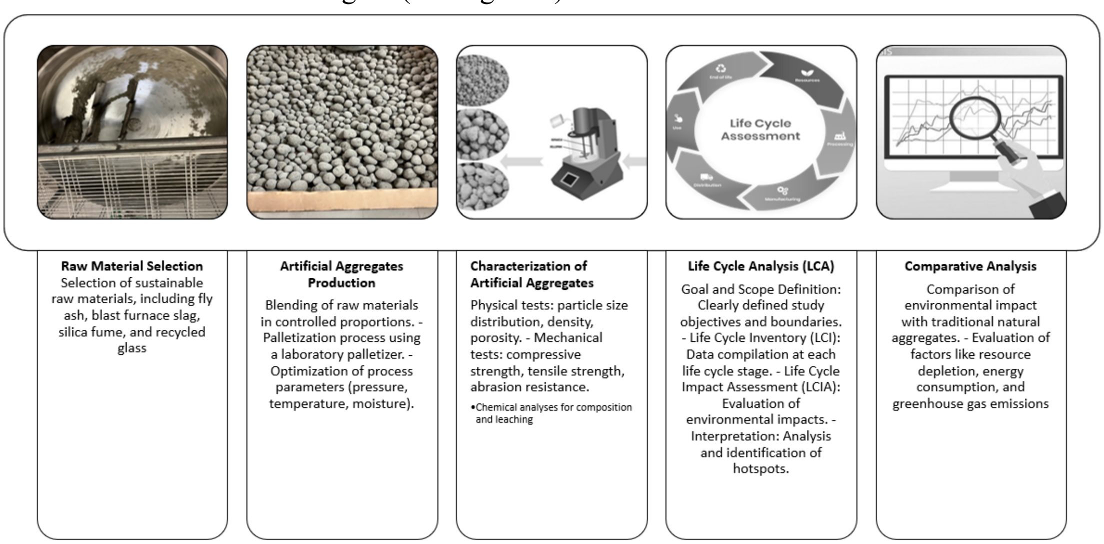

Figure 1 Steps to carry out the investigation.

2.1 Marble sludge (MS)

The extraction and refining of rock material generate significant quantities of waste materials of various types [14]. The accumulation of materials is the primary issue with mining, as it degrades the environment and alters the landscape. Marble sludges are byproducts of the industries that process marble. Academic study has established that wastewater marble is utilized in the manufacturing process of both ordinary and special concretes [15]. Principal benefits of reutilization are associated with the following qualitative constants: chemical composition, diminutive size, and absence of heavy metals.

2.2 MSWI-FA

MSWI- fly ash is a byproduct generated during the combustion of municipal solid waste to produce energy. Comprising fine particles and heavy metals, MSWI fly ash necessitates careful management due to its potential environmental impact. Commonly rich in elements such as lead, cadmium, and zinc, it poses a risk of leaching into the surrounding environment if not properly treated. As a result, effective containment and disposal methods are essential to prevent soil and water contamination. Additionally, ongoing research explores innovative approaches, including recycling and beneficial reuse, to mitigate the environmental concerns associated with MSWI fly ash [16].

2.3 OPC

Another material which has been used in this article is OPC, though as stated above the OPC is the only one which has not been derived from the waste, hence has been purchased from the local market. OPC is the is one of the most important constituents for preparation of the aggregates as it serves as the binder. Ordinary Portland Cement (OPC) is a widely used type of cement renowned for its versatility in construction. Comprising primarily clinker, gypsum, and small proportions of other additives, OPC is manufactured through a controlled process of grinding and blending raw materials. Its strength and durability make it a cornerstone in the construction industry for various applications, including concrete production. OPC is classified into different grades based on compressive strength, with common types such as OPC 33, OPC 43, and OPC 53. Its ubiquitous presence in construction projects underscores its significance as a fundamental binding agent, contributing to the structural integrity of buildings and infrastructure [17].

2.4 Mix Design for Solo-phase (Cold Bonding) Pelletization

For the solo-phase cold bonding pelletization, three mixtures were prepared, involving OPC and processed MSWI-FA. The mix design features a constant MSWI-FA content (75%) and varying proportions of marble sludge (10%, 15%, 20%) and OPC (15%, 10%, 5%) (see Table 1). These mixtures result in the production of Solo-phase Lightweight Aggregates (S-LWAs), subsequently subjected to an additional cold bonding pelletization process. This work only involves single phase cold bonding palletization process. Sense the literature reported that the dual cold bonding process can also be carried out which has not been presented in the present case due to the restriction of the length of the article, but the extended version of this article will be consisting of dual cold bonding process in future.

2.5 (Solo-phase) Cold Bonding Pelletization Process (S-CBP)

The S-CBP process entails the accumulation of an ingredient comprising primary powder particles (OPC, marble sludge, MSWI-FA) utilising a granulation liquid. The fluid, in this case, water, is non-toxic and volatile, ensuring its removal during the drying phase. The pilot-scale CBP involves the use of an 80 cm in diameter granulator featuring an inclined and rotating plate. Operational parameters include a rotation speed of 40 rpm and an inclination angle of 40◦. From an operational perspective, the powder precursors are introduced into the granulator, and water is gradually added to facilitate the formation of S-LWAs (Fig. 3).

The S-CBP process has been previously studied for environmental sustainability (Colangelo et al., 2021) and was replicated for the purposes of this study.

2.6 Artificial Lightweight Aggregates

In this study, three distinct mixtures have been formulated, incorporating three precursors: Portland cement (OPC), MSWI-FA and MS. All precursors, with the exception of OPC, are industrial byproducts, strategically employed within a circular economy framework as materials for secondary use. MSWI-FA, which is classified as a potentially dangerous waste due to the presence of heavy metals, sulphates, and chlorides, must undergo a pre-treatment procedure to increase its capacity for inertia within a cement matrix. This ensures that the Lightweight Aggregates (LWAs) retain their optimal qualitative properties. Pretreatment is divided into dual phase cleansing process utilizing water. Ensure that the liquid-to-solid ratio is maintained at 3.5:1 and that each phase is retained for a duration of 1.5 hours. After the washing procedure is completed, the materials are dried in a furnace at 45°C for a duration of 24 hours.

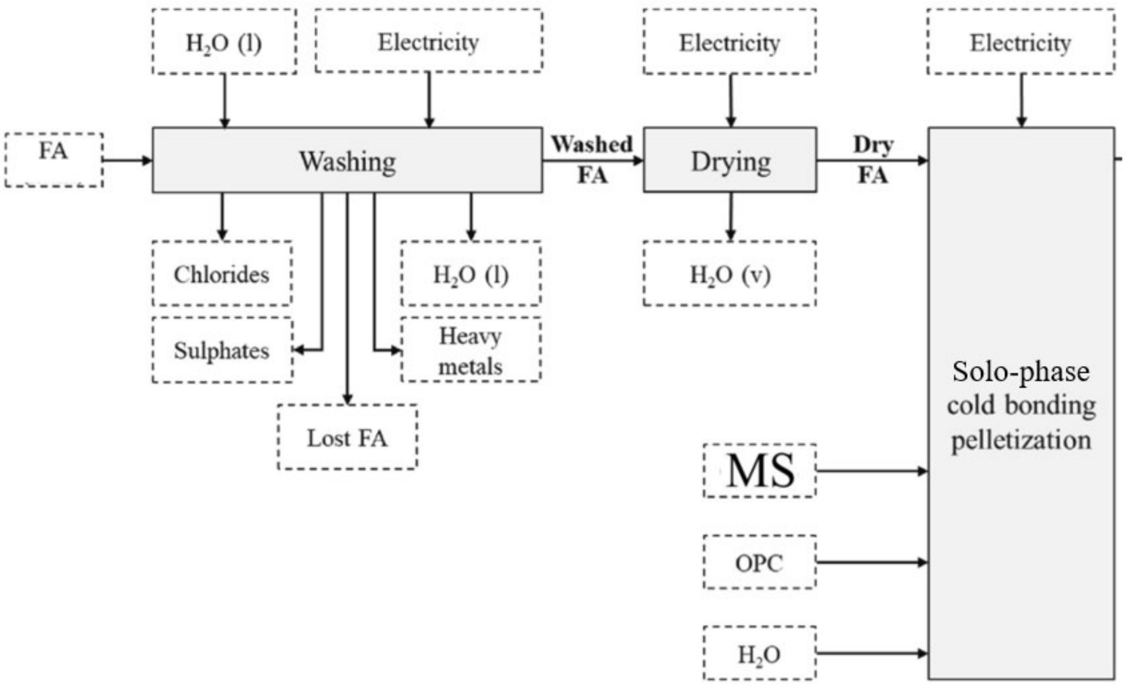

Figure 2 Followed methodology

Table 1 Composition (wt%) of S-LWAs

Composition	OPC	MS	MSWI-FA
A	5	20	75
B	10	15	75
C	15	10	75

A rotating, inclined plate (d = 80 cm) is incorporated into the granulator. The coordinates of the rotational speed (40 rpm) and the angle of inclination (40°C) were entered. From a practical standpoint, the particle constituents were contained within the granulator while water was systematically introduced in order to facilitate the development of the S-LWAs (see Figure 3). An investigation was conducted in a prior study that focused on the ecological viability of S-LWAs, which are LWAs derived from solo-phase cold bonding pelletization. To conduct this research, the pelletization procedure utilizing solo-phase cold bonding was duplicated. The process of preparation of the granules have been show in the Fig. 3.

Figure 3 Process of obtaining granules by palletization process

2.7 Crushing test

The crushing tests adhered to the ISO 12620-4 standard and were conducted on S-Lightweight Aggregates (S-LWAs) with a 12.5 mm diameter, by employing the A080KIT aggregate impact value instrument within a laboratory setting. The outcomes of the impact strength experiments conducted on aggregates exhibited variability dependent upon the composition of the composites. A notable rise in the crushing test values was observed as the amount of cement utilized in pelletization procedures increased. This is consistent with prerequisites, given that the percentage of the blend is a crucial factor that influences the outcome of aggregate crushing experiment.

Table 2 Crushing test results

S. No	Mixture	Crushing strength (MPa)	CO_{2Gem} (kg CO_2 eq.)	*WACG* (m3)	*Costs (€)*
1	S-LWA A	1.75	29.34	0.21	30.25
2	S-LWA B	4.95	21.23	0.17	21.55
3	S-LWA C	10.04	28.35	0.21	29.56

The introduction of a cement notably enhanced crushing resistance, with 1,2, and 3 showing values 1.75, 4.95, and 10.04. Hence, it can be inferred that artificial aggregates with a higher cement content in the mix-design exhibit superior mechanical properties, exemplified by a crushing strength value of 10.04 MPa. For a comprehensive analysis of the crushing strength of aggregates manufactured via solo-phase granulation procedures, refer to Table 2.

4. Life cycle assessment

The evaluation of CO_2 emissions and WAC for LWAs was conducted through the computation of the granulator's material (OPC, MS, MSWIFA), water, and electrical consumption throughout the aggregates manufacturing phases. In accordance with prior research, the unit of 1 kg of LWAs was determined, taking into account the limitations of the cradle-to-gate method system in the prototype laboratory. Consequently, the extraction of raw materials, refining of materials, and producing aggregates were all incorporated. The procedures proposed for the solo-phase cold bonding pelletization process are illustrated in Fig. 2 of section 2.6. The materials utilized in the solo-phase cold bonding pelletization were taken into account during the inventory phase. An inventory of data was compiled using sources such as the datasets, laboratory, and literature. The processes involved in the fabrication of the materials listed in the databases require electricity, cement, and water. MS and MSWI-FA were taken from a prior study. Cement is the only process for which European regionalization was taken into account; all others are subject to Italian regionalization. The impact assessment was conducted in accordance with the Recipe 2016 method, which is consistent with other construction-related literature reviews. Furthermore, the selection of the Recipe 2016 method aligns with prior research that investigates the solo-phase cold bonding pelletization process. The computation was specifically performed at the midpoint level from a A hierarchical viewpoint, which is the norm in the scientific community. The midpoint level conducts a comprehensive examination of the impacts, and the findings acquired are indicative of the specific impacts in issue.

4.1 Carbon dioxide emissions (CO_2)

In assessing the CO2 emissions associated with manufactured aggregates, a thorough computation of the energy, material, and water usage to produce three distinct mixtures is performed. The gross CO_2 emitted (CO_{2Gem}) during the manufacturing process of aggregates was estimated using Eq. (1):

$$CO_{2Gem} = CO_{2Wash} + CO_{2Dry} + CO_{2S-CBP} + CO_{2D-CBP} \tag{1}$$

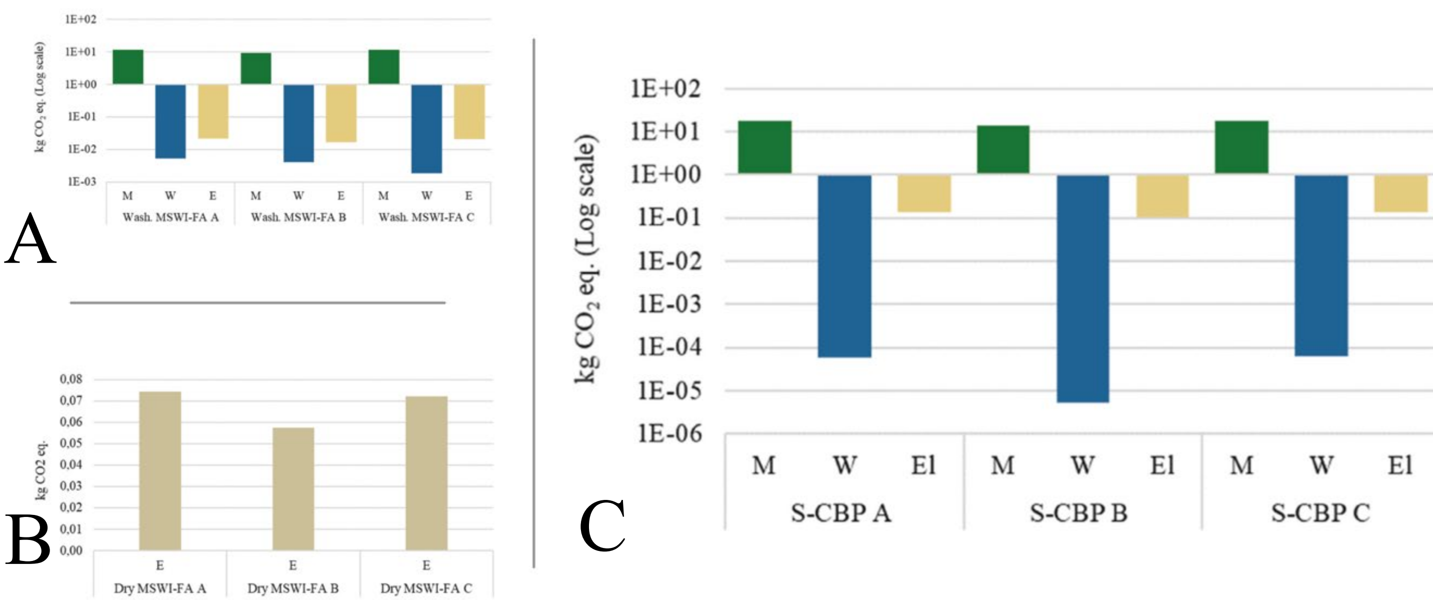

Figure 4 A) emission for washing process B) emission for drying process C) emission for S-CBP process

In Eq. (1), CO_2 emissions were computed for aggregates derived from, S-CBP, washing and drying of MSWI-FA.

As detailed in a study by researchers [18], S-LWA production involves three processes: washing, drying, and S-CBP. The previous LCA analysis revealed that S-LWA B has the least impact. Washing primarily affects CO_2 emissions for mixture A, while drying, carried out in an oven, shows lower CO_2 emissions for mixture B. The results indicate that S-CBP B is less impactful, with S-CBP A being the most critical. S-CBPs show that materials (MSWI-FA, MS, and OPC) significantly contribute to CO_2 emissions, with MSWI-FA being the most impactful (see Fig. 4).

5. Conclusion

A case study was conducted using the proposed model to compare various compositions of S-LWAs containing industrial waste, including MSWI-FA and MS stabilized with cement binder. S-LWAs were generated through the process of solo-phase cold bonding pelletization, commencing with aggregates acquired via this method and supplemented with a blend of fly ash, marble sludge (MS), and cement (OPC). The purpose of this mixture was to augment the quantity of repurposed waste (marble sludge), which was employed to augment the layer thickness of the aggregates and enhance their technological characteristics. The analysis was conducted on the basis of these presumptions to aid in the selection of a control option that optimizes the objectives while adhering to the imposed constraints. It is evident that the allocation of relative weights impacts the configuration of alternatives and is contingent upon the judgment of the specialists consulted with regard to the particular instance being examined. In analysing the production of S-LWAs, the experimental model emphasized environmental, technological, and economic factors. The technological superiority of the S-LWA C was attributed to its superior mechanical performance values. Indeed, the crushing crushing strength that has been computed for S-LWA C represents the maximum value derived from the compression testing. Conversely, the resistance of S-LWA A is measured to be a mere 2 MPa, representing the minimum value acquired. This value is notably different to the remaining values. S-LWA C exhibits a substantial percentage deviation in performance when compared to S-LWA A and S-LWA B. S-LWA B is arguably the most beneficial aggregate from a sustainability perspective, with respect to both water resource consumption and CO_2 emissions into the environment (0.16 m3 and equivalent to 23 kg CO_2 respectively). The observed values are a direct result of the mix design. Further composition B comprises 10% OPC and MS on average while the quantity of additional material remains consistent throughout the granulation process. This indicates that an equilibrium exists between OPC and MS, which is reflected in enhanced performance in the environment. In conclusion, when considering the economic aspect, it can be observed that S-LWA A and S-LWA-C account for an equivalent amount of 30 € in total costs incurred by the analytical laboratory. In contrast, S-LWA B demonstrates economic benefits at a cost of approximately 22 €.

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