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The cement industry in accordance with the UN Sustainable Development Goals through the C-S-H seeds technology – A critical review

A indústria do cimento de acordo com os Objetivos de Desenvolvimento Sustentável da ONU através da tecnologia das sementes C-S-H - Uma análise crítica

La industria del cemento conforme los Objetivos de Desarrollo Sostenible de la ONU mediante la tecnología de semillas C-S-H - Una revisión crítica

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Abstract: The United Nations (UN) has stablished several goals and actions in order to mitigate climate change and reduce its consequences. As one of the main responsible of global anthropogenic carbon emissions, cement industry has a great potential on collaboration to achieve such goal. New solutions are studied to decrease the environmental impact caused by cement production. Clinker content replacement by Supplementary Cementitious Materials (SCM) is indicated as the more feasible one. Despite the environmental benefit offered by the action, the composition modification of the binder leads to initial performance issues. Cementitious materials with lower clinker content and presence of SCM presents higher setting time and lower early strength, which limits the application of the measure regardless of its environment advantage. The use of C-S-H (calcium silicate hydrate) seeds additive can overcome such effect, since it accelerates cement hydration, improving its initial performance. Therefore, such additional input enables the vaster application of low carbon cements. Nonetheless, the manufacture of C-S-H seeds also emits greenhouse gases with environmental impacts comparable to cement production. Hence, the objective of this study is to analyse and discuss the contribution of the use of C-S-H seeds on the

potential carbon footprint reduction of cementitious materials and if this measure could help to achieve the goals stablished by the UN. The reviewed papers pointed the additive as a feasible solution to low carbon cements production which allays technical and environmental requirements. Therefore, it was concluded that C-S-H seeds can effectively contribute to achieve the UN stablished goals towards climate change mitigation.
Keywords: nanoparticles, low carbon cement, supplementary cementitious materials, clinker reduction, carbon footprint.

Resumo: A Organização das Nações Unidas (ONU) estabeleceu vários objetivos e ações para mitigar as alterações climáticas e reduzir as suas consequências. Sendo um dos principais responsáveis pelas emissões antropogênicas globais de carbono, a indústria cimenteira tem um grande potencial de colaboração para atingir esse objetivo. Novas soluções vêm sendo estudadas para diminuir o impacto ambiental causado pela produção de cimento. A substituição do teor de clínquer por Materiais Cimentícios Suplementares (MCS) é apontada como a mais viável. Apesar do benefício ambiental oferecido por essa ação, a modificação da composição do ligante leva a problemas iniciais de desempenho. Materiais cimentícios com menor teor de clínquer e presença de MCS apresentam maior tempo de pega e menor resistência inicial, o que limita a aplicação da medida, independentemente de sua vantagem ambiental. O uso do aditivo de sementes de C-S-H (silicato de cálcio hidratado) pode contornar esse efeito, pois acelera a hidratação do cimento, melhorando seu desempenho inicial. Portanto, esse insumo adicional possibilita a aplicação mais ampla de cimentos de baixo carbono. No entanto, a fabricação de sementes de C-S-H também emite gases de efeito estufa com impactos ambientais comparáveis aos da produção de cimento. Assim, o objetivo deste estudo é analisar e discutir a contribuição do uso de sementes de C-S-H na redução potencial da pegada de carbono de materiais cimentícios e se esta medida pode ajudar a atingir as metas estabelecidas pela ONU. Os trabalhos analisados apontaram o aditivo como uma solução viável para a produção de cimentos de baixo carbono, que atende a requisitos técnicos e ambientais. Concluiu-se, portanto, que as sementes de C-S-H podem contribuir efetivamente para alcançar os objetivos estabelecidos pela ONU para a mitigação das alterações climáticas.
Palavras-chave: nanopartículas, cimento baixo em carbono, materiais cimentícios suplementares, redução de clínquer, pegada de carbono.

Resumen: La Organización de las Naciones Unidas (ONU) ha establecido varios objetivos y acciones para mitigar el cambio climático y reducir sus consecuencias. Como uno de los principales responsables de las emisiones antropogénicas globales de carbono, la industria cementera tiene un gran potencial de colaboración para alcanzar dicho objetivo. Se están estudiando nuevas soluciones para reducir el impacto medioambiental causado por la producción de cemento. La sustitución del contenido de clínker por Materiales Cementosos Suplementarios (MCS) se señala como la más factible. A pesar del beneficio medioambiental que ofrece la acción, la modificación de la composición del aglutinante conlleva problemas iniciales de rendimiento. Los materiales cementantes con menor contenido de clínker y presencia de MCS presentan mayor tiempo de fraguado y menor resistencia inicial, lo que limita la aplicación de la medida independientemente de su ventaja medioambiental. El uso de aditivo de semillas C-S-H (silicato de calcio hidratado) puede superar tal efecto, ya que acelera la hidratación del cemento, mejorando su rendimiento inicial. Por lo tanto, esta aportación adicional permite una aplicación más amplia de los cementos bajos en carbono. No obstante, la fabricación de semillas C-S-H también emite gases de efecto invernadero con impactos ambientales comparables a la producción de cemento. Por lo tanto, el objetivo de este estudio es analizar y discutir la contribución del uso de semillas C-S-H en la reducción potencial de la huella de carbono de los materiales cementosos y si esta medida podría ayudar a alcanzar los objetivos establecidos por la ONU. Los artículos revisados señalaban el aditivo como una solución viable para la producción de cementos bajos en carbono que satisface los requisitos técnicos y medioambientales. Por lo tanto, se concluyó que las semillas C-S-H pueden contribuir eficazmente a alcanzar los objetivos establecidos por la ONU para mitigar el cambio climático.

Palabras clave: nanopartículas, cemento bajo en carbono, materiales cementantes suplementarios, reducción de clinker, huella de carbono.

INTRODUCTION

The environmental impact caused by human activities is a global concerning issue and the urgency of finding feasible solutions to decrease it is continuously growing. In order to discuss possible measures to achieve this goal, after an event with representatives of all the members of the United Nations (UN) in 2015, it was adopted the 2030 Agenda for Sustainable Development (UN, 2015a). In this plan of action, 17 Sustainable Development Goals (SDGs) were established to present the needed efforts to attend the goals agreed by the UN members. With the SDGs it is aimed to find a global plan to achieve: (1) no poverty; (2) zero hunger; (3) good health and well-being; (4) quality education; (5) gender equality; (6) clear water and sanitation; (7) affordable and clean energy; (8) decent work and economic growth; (9) industry, innovation and infrastructure; (10) reduced inequalities; (11) sustainable cities and communities; (12) responsible consumption and production; (13) climate action; (14) life below water; (15) life on land; (16) peace, justice and strong institutions; and (17) partnerships for the goals. The SDGs are presented in the Figure 1.

Figure 1: UN Sustainable Development Goals.

Source: UN (2015a).

In order to enable the goals to be accomplished, changes in the productive sectors of all UN countries must be made. The construction industry plays a key role in this action, since it is responsible for a considerable part of the greenhouse gas emissions worldwide (IEA, 2023). According to the 2021 Global Status Report for Buildings and Construction (United Nations Environment Programme, 2021), the energy spent for edification construction was responsible for the generation of 37% of global carbon emissions in the year 2020.

The latest report of the Intergovernmental Panel on Climate Change (IPCC), the Sixth Assessment Report (AR6), indicates the potential of construction sector to mitigate the Greenhouse Gas (GHG) emissions. According to the document Climate Change 2022: Mitigation of Climate Change, which contributed to AR6 elaboration, one of the key actions to accomplish such goal would be through the decarbonization of the buildings (IPCC, 2022).

Cement is the main construction material used and its production represents a great part of this amount of GHG emissions on the construction sector. The cement plants activity has been pointed as one of top four industries in global CO_2 emissions in 2018 by International Energy Agency (IEA) (2023). As a key material to the construction sector, the growth of the building activities leads to a higher production of the binder, especially in developing countries (USGS, 2023).

In this context, an effort is being made to find feasible solutions in order to obtain low carbon cements. This goal can be found in several research and reports such as in Provis (2014), Park, Jang and Lee (2018), Visedo and Pecchio (2019), Adesina (2020) e Benhelal, Shamsaei and Rashid (2021), which focused on the change of cement composition to reduce its environmental impact. One of the main strategies to decrease the binder emissions is to replace the clinker content by mineral additions, such as pozzolanas and slags (Kanchanason & Plank, 2019; Zhou, Sofi, Liu, Li, Zhong & Mendis, 2021b; Li, Bizzozero, & Hesse, 2022).

Despite clinker being the most important component of cement, responsible for its main properties, it also emits the great part of carbon dioxide throughout the cement production process (Mehta & Monteiro, 2014; Visedo & Pecchio, 2019; Benhelal, Shamsaei & Rashid, 2021). Nonetheless, the clinker reduction in cement composition can affect the material properties, decreasing the reactivity of the binder, as proved by Kanchanason and Plank (2019) and Juenger, Snellings and Bernal (2019). This performance modification could highly limit the effort to reduce the cement environmental impact, since it can affect the main properties of the binder, such as mechanical strength and setting time (Szostak & Golewski, 2020; Zhou et al., 2021b; Chen, Wu, Xia, Cai & Zhang, 2021).

However, a recent and innovative field of research brings a technology called by C-S-H seeds as a possible solution to overcome this problem, as seen in Land and Stephan (2018), Li, Zhang, Xu and Monteiro (2020); Pedrosa, Reales, Reis, Paiva, and Fairbairn (2020), John (2022) and Pizon, Piekarczyk & Miera (2022). Because of the low content of this additive, its environmental impact and additional cost is considered negligible (Land & Stephan, 2015; John, Epping & Stephan, 2019; Li et al., 2020). Therefore, the main objective of this paper is to analyse and discuss the contribution of the use of C-S-H seeds on the potential carbon footprint reduction of cementitious materials and if this measure could help to achieve the goals stablished by the UN.

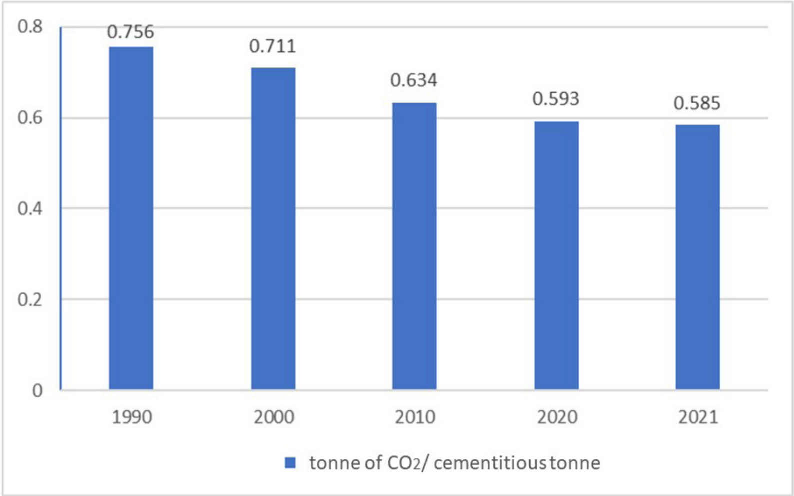
THE ROLE OF CEMENT INDUSTRY ON CLIMATE ACTION

Portland cement (PC) is the main component of concrete, the most used man-made material on the planet (ABCP, 2023; GCCA, 2023). The Common PC is mainly composed by a great amount of clinker mixed with gypsum and calcined clay (Mehta & Monteiro, 2014; GCCA, 2023). According to the Brazilian standard NBR 16697 (ABNT, 2018), the sum of clinker and calcium sulphates can reach over 90-100% of cement composition. To obtain this component, the raw materials, basically limestone, clay and iron oxide, must pass through the pre-calcination and calcination processes, which requires a high temperature of over 1450°C, as mentioned by Mehta and Monteiro (2014), Salas, Ramirez, Rodríguez, Petroche, Boero and Duque-Rivera (2016) and Visedo and Pecchio (2019). Those heating steps will lead to the chemical reaction of transformation of calcium carbonate ($CaCO_3$) into calcium oxide (CaO), which releases great amounts of CO_2. After this process, the final clinker composition is ready, reaching levels between 45–70% of tricalcium silicate (C_3S), 10–30% of dicalcium silicate (C_2S), 5–10% of tricalcium aluminate (C_3A) and 5–10% of tetracalcium aluminoferrite (C_4AF). Once mixed with water the anhydrous silicates will form the calcium hydrate (CH) and calcium silicate hydrate (C-S-H), main responsible for cement's properties, such as mechanical strength (Newman & Choo, 2003; Mehta & Monteiro, 2014; Neville, 2015).

According to the World Business Council for Sustainable Development (WBCSD) (2016) and International Energy Agency (IEA) (2023) the cement industry is responsible for 7-8% of global anthropogenic carbon emissions. In 2018, near 4100 million tonnes of cement were produced, which leaded to an emission of 2378 million tonnes of carbon dioxide. The ratio of 0.58 tonne of CO_2 per tonne of cement continued stable in 2021, when 585 kilograms of carbon dioxide per tonne cementitious were generated through the production of 4374 million tonnes of the binder (IEA, 2023; GCCA, 2023). This achievement was reached through measures regarding the production process and cement composition. The main implemented actions were fossil fuel substitution by alternative fuels and biomass waste, energy optimization during production processes, new technologies investment and cement composition modification (UN Environment, Scrivener, John & Gartner, 2018; Benhelal, Shamsaei & Rashid, 2021; IEA, 2023).

The implementation of such actions resulted in environmental advances by the cement industry, which leaded to a decrease of near 23% in net CO_2 emissions per tonne cementitious, reduction of 18% in fossil fuel consumption and improvement of 19% in energy efficiency regarding the year of 1990, with the kilogram CO_2 per cementitious tonne ratio decreasing from 0.756 (1990) to 0.585, in 2021 (GCCA, 2023), as presented in Figure 2.

Figure 2: Environmental advances by the cement industry according to GCCA (2023).



Source: Adapted from GCCA (2023).

Although some advances were achieved by the cement industry, the numbers not yet reached the threshold required to accomplish the global goals to mitigate climate change. During the United Nations Climate Change Conference in Glasgow (COP26), which took place from 31 October to 12 November 2021, the Paris Agreement (UN, 2015b) statements were reinforced (UN, 2022a), when the participating countries reaffirmed their commitment of limiting the increase in the global average temperature to well below 2°C and pursuing efforts to limit it to 1.5°C (UN, 2022a). Brazil was one of the event members to sign the Glasgow Pact (UN, 2022b) and reassumed its engagement during the UN Climate Change Conference COP27, which took place in Sharm el-Sheikh (Arab Republic of Egypt) from 6 to 20 November 2022. In the conference, the urgency of taking more serious and effective measures to accomplish the 1.5°C goal was stated. It was declared that a reduction of 43% in GHG emissions by 2030 is mandatory to achieve a net zero scenario in 2050, which, according to UN (2022c) is when GHG emissions are decreased as much as possible, and any remaining emissions are reabsorbed (UNFCCC, 2023).

Brazil has been pointed by the Emissions Gap Report 2022 as one of top seven countries which were responsible of half global GHG emissions in 2020 (UN, 2022d). The cement industry is one of the main contributors to such position and therefore should be a direct responsible for decreasing the CO_2 generation, as pointed out by sector representatives SNIC (2022) and ABCP (2021). As mentioned, the latest report of IPCC, the AR6, shows the potential role of construction sector in climate change mitigation mainly through building decarbonization (IPCC, 2022). Visedo and Pecchio (2019) reports the Brazilian cement industry capacity, by 2050, of reducing 33% of carbon emissions. The authors, together with Li et al. (2020), Benhelal, Shamsaei and Rashid (2021) and Bumanis, Korjakins and Bajare (2022), indicated clinker content reduction on cement composition as the most economical and technological feasible measure that enables such scenario.

While clinker plays a key role in cement properties development, its manufacture also represents the main carbon generation phase in cement plants. Approximately 63%

of the total CO_2 emitted during Brazilian cement production is due to clinker obtention, generated by the high temperatures and chemical reactions in calcination process (Salas et al., 2016; Visedo & Pecchio, 2019; Benhelal, Shamsaei & Rashid, 2021). Thus, in order to accomplish the agreed UN climate goals, it was recommended to gradually reduce the clinker/cement ratio from 68%, in 2014, to 59%, in 2030, to finally a maximum of 52% in 2050 (IEA, 2018; Visedo & Pecchio, 2019).

CLINKER CONTENT REDUCTION: THE ROLE OF THE C-S-H SEEDS TECHNOLOGY

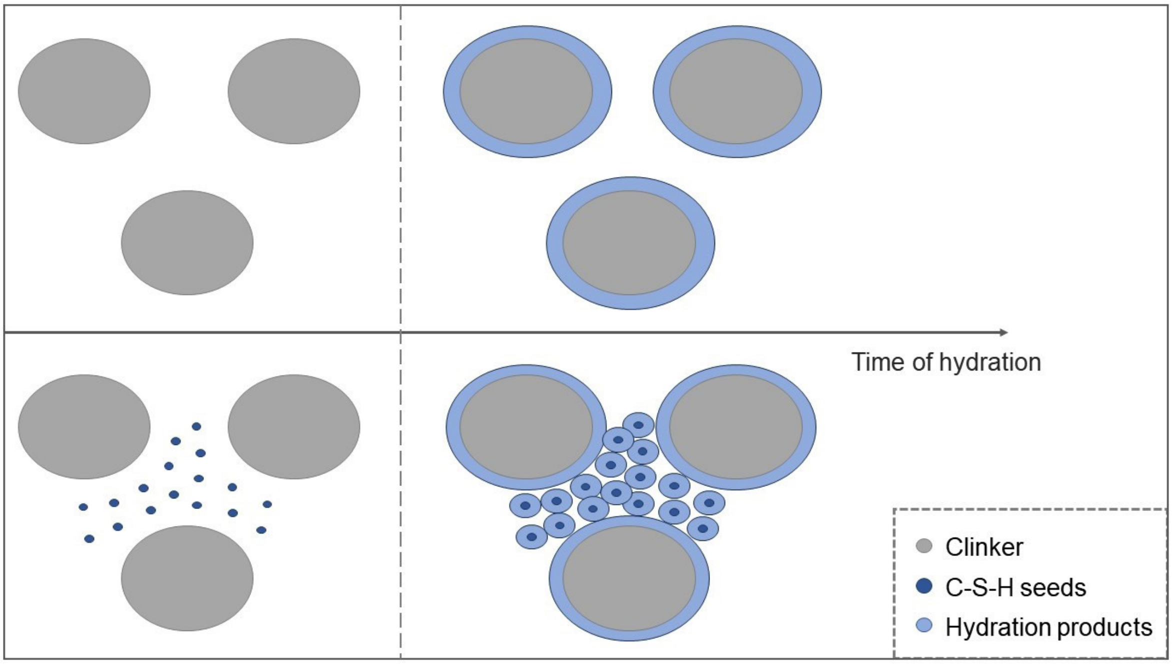
Clinker can be replaced by Supplementary Cementitious Materials (SCM) with a reaction mechanism similar to cement hydration. The main clinker substitutes are limestone filler, fly ashes, slags, silica fume and metakaolin (Lothenbach, Scrivener & Hooton, 2011; Juenger, Snellings & Bernal, 2019). According to Panesar and Zhang (2020), a large part of these mineral additions are industrial wastes, such as fly ashes, from combustion of pulverized coal in electric power plants, and blast furnace slags, from iron manufacturing industry. The Brazilian standard NBR 16697 (ABNT, 2018) allows limits of up to 75 and 50% of cement composition by granulated blast furnace slags and pozzolanic materials, such as fly ashes. Nonetheless, the availability of these types of SCM is decreasing due environmental matters, therefore new waste sources of such materials are being evaluated as in Juenger, Snellings and Bernal (2019) and Afrin, Huda and Abbasi (2021). The clinker substitution by SCM represent a great environmental advantage. Besides the decrease of CO_2 emission during cement production, the use of SCM can improve the solid waste management by preventing its disposal in landfills, as indicated by Acordi, Luza, Fabris, Raupp-Pereira, De Noni and Montedo (2020), Ighalo and Adeniyi (2020) and Afrin, Huda and Abbasi (2021). The lower pressure to select new zones destinated to receive such residues also represents an environmental and social benefit, since it would decrease natural compromised areas and land conflicts, which is aligned to the SDG.

According to Panesar and Zhang (2020), despite the evident environmental benefit of clinker replacement by SCM, the measure can only be feasible and sustainable if the cement performance is maintained or even improved. Studies as Lothenbach, Scrivener & Hooton (2011), Benhelal, Shamsaei and Rashid (2021) and Lazik and Garrecht (2021) indicate benefits regarding mechanical strength, chemical resistance and durability indicators, on cementitious materials by using SCM. Nevertheless, several researchers have pointed an underperformance at initial phases in the presence of such materials (Juenger, Snellings & Bernal, 2019; Yun, Rahman, Phing, Chie & Bakri, 2020). Chen et al. (2021) explain that materials chemical reaction varies according to its granulometry and composition. The hydration mechanism in pastes with lower clinker content and higher presence of SCM is modified, leading to a slower hydration rate, as mentioned by Snellings (2016) and Benhelal, Shamsaei and Rashid (2021). The late formation of hydrates will affect the initial performance of cementitious materials, which will present a delayed setting time (when cement begins to lose its plasticity and start hardening) and lower early age strength. As pointed by Das, Ray, and Sarkar (2020) and Zhou, Pan, Mi, and Zhan (2021) the increase of demand for more reactive binders, mainly in specific applications, as in precast concrete and concrete screed, may limit market implementation of the lower clinker content cements (materials with lower initial performance and production speed).

One possible solution to overcome this issue is the seeding technology, which is the addition of external nuclei on cementitious system in order to optimize its hydration process, as mentioned by Wang, Kong, Jiang and Wang (2020). After evaluation of other nanomaterials, as studied by Lee and Kurtis (2010), Oltulu and Sahin (2011) and Kong, Du, Wei, Zhang, Yang and Shah (2012) and Adesina (2020), C-S-H seeds have been pointed as the most effective material for this goal (Wang et al., 2020; Szostak & Golewski, 2020). This additive is formed by artificial calcium silicate hydrates of nanometric dimensions and is added to cementitious materials to accelerate the kinetics of its chemical reactions (Szostak & Golewski, 2020; Wang, Lü, He, Wang, & Hu, 2021). The performance of C-S-H seeds is influenced by properties of the additive, such as its chemical stoichiometry and surface area, and mixing design, such as water content, cement composition and additive content (Nicoleau, 2011; John, Epping & Stephan, 2019; Kanchanason & Plank, 2019).

C-S-H seeds act mainly through the nucleation mechanism, which increase the available sites for hydration precipitation, leading to an early crystal formation on cementitious matrix, as noticed by Szostak and Golewski (2020). Additionally, because its similarity to cement hydration product, the chemical composition of the additive optimizes its effectiveness, creating an ideal substrate to hydrates formation, as pointed by Nicoleau (2011) and Land and Stephan (2012). This whole mechanism will optimize cement hydration process, with hydrates formation in the pore structure (Figure 3).

Figure 3: Scheme of hydration of cement with and without C-S-H seeds.



The enhance of chemical reactions caused in the presence of C-S-H seeds will lead to higher crystal formation, which will accelerate the setting time and early age strength of cementitious materials. In order to obtain this benefit, small amounts of the materials are required. Considerable effects on cement performance were achieved by using a range of 0.5 to 2.0%, as in Wang et al. (2021). More than just raise common Portland cement initial performance, the C-S-H seeds have shown a great impact over cementitious pastes with SCM, presenting an especial affinity to granulated blast furnace slags as evidenced by Kanchanason and Plank (2019) and Li, Bizzozero and Hesse (2022).

Some of the reviewed performance improvements (setting time, measured in hours and early strength, measured in MPa) in the presence of C-S-H seeds are presented in Frame 1, which summarises the outcomes (compared to references of same composition, without additive) of C-S-H content (referred to cement mass) in cementitious materials with SCM (type and content referred to cement mass):

Frame 1: Performance improvements of cementitious materials with C-S-H seeds noticed by the cited studies.

SCM	C-S-H seeds (%)	Property	Outcome (approximated value)	Reference
Calcined clay (35%)	2.0	Early compressive strength (24h)	Increase of 100%	Kanchanason and Plank (2019)
Ground granulated blast furnace slag (35%)	2.0	Early compressive strength (24h)	Increase of 100%	Kanchanason and Plank (2019)
Ground granulated blast furnace slag (50%)	1.0	Early compressive strength (24h)	Increase of 50%	Xu, Li and Yang (2020)
Fly Ash (60%)	1.0	Setting time	Acceleration of 60%	Zhou et al. (2021b)
Fly Ash (60%)	1.0	Early compressive strength (24h)	Increase of 20%	Zhou et al. (2021b)
Ground granulated blast furnace slag (50%)	1.5	Early compressive strength (24h)	Increase of 110%	Li, Bizzozero and Hesse (2022)
Ground granulated blast furnace slag (95%)	1.5	Early compressive strength (24h)	Increase of 105%	Li, Bizzozero and Hesse (2022)

ENVIRONMENTAL ANALYSIS OF C-S-H SEEDS

The initial performance improvement of cementitious materials in the presence of C-S-H seeds overcomes the hydration delay caused by the use of SCM. Although indicating a possible environmental benefit, the sustainability of the C-S-H seeds must also be evaluated. Despite the additive being composed of natural and non-toxic materials (Land & Stephan, 2015; John, Epping & Stephan, 2019) there is a potential environmental impact during its manufacture process.

There are different methods to obtain C-S-H seeds, but the most currently adopted are through pozzolanic, sol–gel, and precipitation reactions (John, Matschei & Stephan, 2018). Li et al. (2020) indicated manufacturing of seeds by hydrating C_3S and/or C_2S as the best technique regarding economic and environmental aspects. In the study, the authors analysed the Life Cycle Assessment (LCA) of C-S-H seeds prepared by diluted C_3S hydration. The cradle-to-gate model considered raw material extraction, production/ processing, transportation to concrete plant and paste mixing/batching.

It was calculated that the production of seed precursors (C_3S) leads to an energy consumption and GHG emissions 7% and 12% higher than those of cement manufacturing, respectively (Li et al., 2020). Because of the low additive content in evaluated pastes, the cementitious mixtures' impact with and without additives remained the same. Nonetheless, after analysing the CO_2 emissions normalized through the compressive strength, the authors noticed a value of CO_2-eq 30% lower to seeded pastes at 28 days.

Similarly, Nassiri et al. (2023) studied the LCA of the production of C-S-H seeds from the tobermorite (TOB) and foshagite (FOS), two crystalline C-S-H seeds produced by the hydrothermal method in a sealed autoclave from $CaO–SiO_2–H_2O$ mixtures (with lime and SiO_2 slurry), and the production of mortar mixtures with the additive. The cradle-to-gate model considered comprises raw material production, transportation, and mixture production. The authors calculated that the environmental impact of the studied C-S-H seeds production can be decreased 62-84% if recycled steam is used instead of newly produced steam. In this scenario, the environmental impacts of seeded mortars are up to 8% higher than the control. When producing seeds with recycled steam, the total Global Warming (GW) contribution of the additive in mortars is only 3-5% while the Portland cement represents an amount of 82-97%. One of the main contributions of this study is to recognize the increase of environmental performance of C-S-H seeds, once recycled steam is incorporated during its manufacture process. After normalizing the GW with compressive strength, which was called carbon intensity, the difference is even more evident (Nassiri et al., 2023). The analysis of Nassiri et al. (2023) data enables to conclude the higher environmental efficiency when recycled steam is used in the seed production. By using this method, the seeded mortars reach a reduction of almost 30% in carbon intensity compared to the unseeded ones.

DISCUSSION

By reviewing the presented studies, it was possible to verify the C-S-H seeds effect of increasing initial performance of cementitious materials. This benefit can be achieved by using low additive contents, which represents low-cost increase. It also enables a wider application of low carbon cements since it mitigates the SCM addition effects of delaying setting time and decreasing early age strength of cement pastes. In addition, LCA studies have shown that C-S-H seeds use reduces normalized environmental impact regarding the compressive strength. The sustainable potential of seeded mixtures can be even greater considering the use of wastes during the production process of the additive and further use of residues and by products as SCM.

Therefore, the production of special materials with C-S-H seeds enables to combine 5 SDGs: 8 (Decent Work and Economic Growth), 9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production) and 13 (Climate Action). The fabrication of the additive will not represent a health risk to workers since it represents low inhalation risks, low toxicity and no health hazards other than drying out/desiccation of skin as pointed out by Nassiri et al. (2023). This is also an innovative industrial solution which contributes to more sustainable buildings and structures, which can ally performance and environmental impact reduction. Additionally, C-S-H seeds use enables the higher adhesion to cement pastes with SCM, which can be residues and by-products. The environmental benefits also represent a feasible solution to reduce the carbon emissions caused by cement use, which contributes to the UN goals towards a net zero scenario by 2050.

CONCLUSION

The aim of this study was to analyse and discuss the contribution of the use of C-S-H seeds on the potential carbon footprint reduction of cementitious materials and if this measure could help to achieve the goals stablished by the UN.

The analysis of the reviewed papers proved that C-S-H seeds can be a feasible solution to achieve such goals, especially regarding GHG emission reduction. Through the consideration of performance aspects, required content, environmental impact and sustainable potential of C-S-H seeds, the use of this additive can lead to the application of low carbon cements without great negative environmental and social impact, while the materials performance is maintained. As the availability of the most common SCM materials decreases, more studies are required to evaluate the C-S-H seeds performance on cement pastes with new SCM sources. Also, we need a more robust study of environmental impacts of the additive once used in low carbon cements. It was noticed the potential of process modification during manufacture of C-S-H seeds leading to lower environmental impacts during the process. Therefore, it is recommended to increase the studies on production process and precursors of the additive in order to obtain an even higher environmental performance.

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