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Sustainable Cement Manufacturing: Carbon Injection into Soils to Reduce Footprint

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Abstract— **The increasing production in cement manufacturing industries results in combustion that emits high levels of carbon dioxide, which is the primary greenhouse gas responsible for climate change. This paper addresses the escalating environmental challenges generated by these industries, particularly its significant contribution to global carbon emissions, which account for approximately 8% of the world's total CO2 production. This problem is mainly related to two Sustainable Development Goals (SDGs) of the United Nations. These are number 9 and number 11, which aim to modernize industries and reduce the environmental impact of urbanization. Given the industry's reliance on solid fuels and its impact on climate change, this paper explores sustainable methodologies to mitigate these effects, focusing on the innovative technique of soil carbon injection. This method requires capturing CO2 from cement production and injecting into the soil. The paper is structured to first explain the sources and impacts of CO2 emissions in cement production, followed by an analysis of CO2 capture and soil injection techniques, and an evaluation of the project's viability and benefits. This paper is expected to contribute to raising awareness towards a low carbon future of cement industry and what it represents in terms of pollution, in the context of the Net Zero Emissions by 2050.**

Keywords: **cement manufacturing, sustainable cement manufacturing, carbon capture, CO2 injection**

Resumen— **El aumento de la producción en las industrias de fabricación de cemento da como resultado combustión que emite altos niveles de dióxido de carbono, que es el principal gas de efecto invernadero responsable del cambio climático. Este trabajo aborda los crecientes desafíos ambientales generados por estas industrias, en particular su importante contribución a las emisiones globales de carbono, que representan aproximadamente el 8% de la producción global de CO2. Esta problemática está relacionada principalmente con dos Objetivos de Desarrollo Sostenible (ODS) de las Naciones Unidas. Estos son el número 9 y el número 11, que apuntan a modernizar las industrias y reducir el impacto ambiental de la urbanización. Dada la dependencia de la industria de los combustibles sólidos y su impacto en el cambio climático, este trabajo explora metodologías sostenibles para mitigar estos efectos, centrándose en la técnica innovadora de inyección de carbono en el suelo. Este método requiere capturar CO2 de la producción de cemento e inyectarlo en el suelo. Este trabajo está estructurado para explicar primero las fuentes y los impactos de las emisiones de CO2 en la producción de cemento, seguido de un análisis de las técnicas de captura de CO2 e inyección en el suelo, y una evaluación de la viabilidad y los beneficios del proyecto. Se espera que el mismo contribuya a crear conciencia sobre un futuro con neutralidad de carbono en la industria del cemento y lo que representa en términos de contaminación, en el contexto de las emisiones netas cero para 2050.**

***Palabras clave*: fabricación de cemento, fabricación de cemento sostenible, captura de carbono, inyección de CO2**

I. Introduction

The increasing demand for construction work leads to a rise in production within cement manufacturing industries. Cement is used in construction to bind other materials together. It is mixed with sand, gravel and water to produce concrete. Over 10 billion tonnes of concrete are used each year, which makes it the most used construction material in the world. These industries depend on solid fuels such as fossil fuels, charcoal, and animal waste, resulting in combustion that emits high levels of carbon dioxide (from now on, CO2), which is the primary greenhouse gas responsible for climate change. Consequently, carbon emissions from cement production are escalating globally, presenting significant environmental challenges.

Addressing this issue is crucial through sustainable methodologies, given that the cement manufacturing industry ranks among the top contributors to CO2 emissions. Total emissions from cement production "are approximately 2.8 billion tons of CO2, this is around 8% of the world's total CO2 production" [1]. Within this framework, this paper aims to explore a method to achieve sustainable practices in cement production, decreasing the impact of CO2 emissions. The central thesis of this paper is that, through the adoption of an innovative technique, substantial reductions in the carbon footprint of the cement manufacturing industry can be achieved.

This problem is mainly related to two Sustainable Development Goals (SDGs) of the United Nations. These are number 9 and number 11. SDG 9 focuses on building resilient infrastructure and sustainable industrialization [2]. One of its targets is 9.4, whose goal is to "modernize infrastructure and industries so that they are sustainable, using resources more efficiently and promoting the adoption of clean technologies and industrial processes" [2, p.44]. In turn, SDG 11 is about making cities and human settlements safe, resilient and sustainable [2]. One target of this SDG related to the problem of this project is 11.6, which aims to "reduce the adverse environmental impact per capita of cities, paying special attention to air quality" [2, p.52].

With the aim of reducing the environmental impact by means of the adoption of clean technologies in the cement industry, the purpose of this paper is to identify and analyse a method known as soil carbon injection. This method reduces CO2 emissions by capturing it from the cement industries [3] and injecting it into the soil, typically in agricultural fields or degraded lands. This technological option involves more sustainable practices in relation to global development.

To reach this objective, this paper is divided into four parts. Firstly, a description of some concepts of the production of CO2 in the cement manufacturing industry are accomplished so as the reasons and impacts of CO2 release to the atmosphere. Secondly, an efficient way of capturing CO2 is described. Also, a technological technique of carbon injection into soils is presented. Thirdly, the viability and benefits of the project are stated. Finally, the conclusion is related to the discussion of the relevance of the issue. This paper is expected to contribute to raising awareness towards a low carbon future of cement industry and what it represents in terms of pollution, in the context of the Net Zero Emissions by 2050.

II. Traditional method of manufacturing cement

Cement was first developed by Joseph Aspdin in 1824. He patented his creation as Portland cement due to its similarity to a stone located in the Isle of Portland. Aspdin was a businessman British stonemason, who heated a mix of ground limestone and clay in his kitchen stove and then pulverized the concoction into a fine powder. This was the first hydraulic cement that solidifies when mixed with water [4]. Although some components changed and new technologies were incorporated, the basic process remains the same as it was two centuries ago, and these traditional steps, that release CO2 into the environment, are going to be developed in the following section.

A. Process of cement production and CO2 releasing into the environment

Portland cement, a form of hydraulic cement, is by far the most common type of cement in general use around the world [5]. Its manufacturing involves a series of steps that transform the raw material into a usable product, and they are described below, following [6].

First, raw materials are extracted, the main one being limestone, and the others are different clays and other minerals. These materials are extracted from quarries by blasting or heavy machinery.

Secondly, the extracted materials are transported to the cement plant. There, through a crushing process to reduce their size, it is ensured that the materials have a uniform consistency for further processing.

Third, the crushed raw materials are mixed in the correct proportions and stirred until a homogeneous mixture is achieved. This mixture is called raw powder.

Fourth, the raw mixture is preheated using hot gases from the oven. This process seeks to eliminate moisture and begin the chemical transformation of the material.

Fifth, calcination occurs. In this step, the preheated raw mixture is calcined in the oven. The mixture is heated to temperatures of around 900°C.

Sixth, the calcined raw limestone and clay enter the rotary kiln, where they are heated to about 1400 °C, as shown in Fig. 1. At this temperature, the materials partially melt and form clinker nodules that are small, hard, and spherical in shape. In order to reach these temperatures, a large quantity of fuel is used.

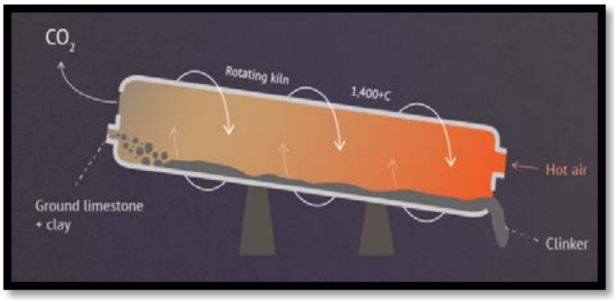

Fig. 1. Rotary kiln in clinker formation. [7]

Seventh, the hot clinker is cooled quickly using room temperature air. This helps to stabilize the minerals formed during the heating process. In this cooling process, heat is recovered, which is used to preheat another mixture.

Finally, the cooled clinker is mixed with gypsum and other additives in crushing machines where it is ground to a fine powder. This final product is known as Portland cement.

These traditional cement manufacturing stages are widely used globally. However, it has a significant environmental impact. Once the production process is stated, the reasons and consequences of CO2 emissions are going to be analysed. This is an important part to address a solution.

B. Carbon dioxide emissions in cement manufacturing industries

A crucial aspect of the cement production is the energy consumption. According to [8, p.3], "Traditional kilns primarily use fossil fuels like coal, oil, or natural gas, which release substantial CO2 emissions during combustion. This energy-intensive process significantly contributes to the industry's overall carbon footprint. After clinker production, the resulting clinker is finely ground with gypsum and additives to produce cement". While the grinding process itself does not produce CO2 emissions directly, it requires a substantial amount of energy, which is frequently supplied by power plants that rely on fossil fuels [8].

Another cause of the CO2 release is the decomposition of calcium carbonate. Following [8, p.4], "[i]n clinker production, which is a key stage in cement manufacturing, CO2 emissions are primarily generated from the calcination process, where limestone (calcium carbonate) is heated to produce lime (calcium oxide) and big amounts of CO2". This critical chemical reaction is a fundamental contributor of carbon footprint. The 8% of global carbon emissions mainly come from the production of clinker, which is the primary source of concrete [9]. In other words, reducing CO2 emissions is important to cut down the carbon footprint.

C. Environmental impact of carbon dioxide emissions

The global environmental impact of the carbon emissions is the priority to decrease to achieve a carbon-neutral cement sector. In this sense, the aim is to create a more sustainable and resilient future, mitigating the adverse effects of climate change on the environment, economy, and society, especially for the next generations. "These emissions significantly contribute to global warming and climate change, resulting in detrimental environmental effects including altered precipitation patterns, extreme weather events, and rising sea levels" [8, p.5].

The biggest consequence is that this industry is one of the most polluting on the planet. In this sense, addressing the cement industry's significant carbon emissions is critical in mitigating these impacts and working towards global sustainability.

III. Carbon Capture and Its Injection into Soil

The cement industry has identified different methods to reduce the carbon footprint like energy efficiency, reduction of the clinker factor and the use of alternative fuels. However, there is a limit to the amount of emissions that can be mitigated using these methods. Given the limited potential of these methods it is clear that carbon capture and sequestration (CCS) will play a crucial role.

A. Carbon capture and sequestration

CCS refers to a method that captures CO2 emissions from large industrial sources, such as power plants and cement factories, and stores the captured CO2 in a variety of ways. According to [10] currently there are three main methods to achieve CCS. These are pre-combustion, oxy-combustion and post-combustion.

The pre-combustion method utilizes gasification technologies to produce syngas, which serves as the primary fuel source for the plants. Following [10], the main drawback of this approach is that only the CO2 from the syngas fuel will be captured while the CO2 released by the calcination of limestone will not. Moreover, a new generation of burner technology and cement kiln lines will be required.

According to [10], another method is oxy-combustion, where purified oxygen is used in the cement kiln for combustion to produce nitrogen-free combustion gases. After condensation, this process yields a stream of pure CO2, making its capture easier. However, the use of this combustion will require major modifications in the design of the burner, the furnace and the configuration of the plant. This shows that several investments must be made in this sector to be more sustainable.

The remaining method described in [10], known as post-combustion, involves the separation of CO2 from the gases emitted by the clinker kiln. The main advantage of this approach is that it captures CO2 produced both from fuel combustion and calcination. Additionally, this technique can be implemented in new and existing cement plants. This requires less investment than the previous methods, so post-combustion CO2 capture appears to be the simplest retrofit in a cement plant.

Within post combustion there are many methods to capture CO2, but emphasis will be placed on the use of membranes, which are proven technologies made of polymers to separate industrial gases with non-hazardous materials, following [10]. According to [11], membrane separation is increasingly implemented in recent years due to low capital and operating costs, low energy consumption and space requirements, easy operation, simple equipment, high flexibility, safety and an absence of possibly toxic or harmful wastes.

The use of membranes in post-combustion described in [11] works by applying a pressure differential. In this way, flue gas from the plant, which contains CO2, is passed through a special membrane that selectively captures the CO2, as shown in Fig. 2. Then, these molecules of gas are collected on the permeate side, resulting in a gas stream that is enriched with CO2. This gas stream can then be further processed to purify the CO2 for utilization in some applications or storage, such as underground geological formations.

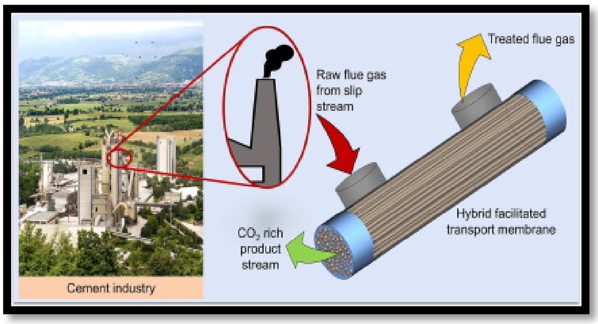

Fig. 2. Membrane for CO2 capture. [11]

B. Carbon injection into geological formations

There is a series of considerations when determining the injection place, such as characteristics, execution time and cost. The places where the use of this technique is usually used and evaluated according to [10], are the following:

1. Oil and gas reservoirs:

Following [10], oil and gas reservoirs are ideal for CO2 storage due to their proven ability to retain gases over millions of years. Also, existing infrastructure facilitates CCS project implementation and captured CO2 can be used for enhanced oil recovery, increasing oil production. However, potential complications include monitoring, verification, and accounting challenges for CCS sites and interference with subsurface oil and gas mineral recovery.

2. Unmineable coal seams:

The use of unminable coal seams is an efficient and large space where CO2 can be deposited, as it is said in [10, p.2721], "Utilization of unmineable coal seams (those coal deposits which are too deep to be conventionally mined) as a CCS site via coal-bed methane recovery methods (CBM) was also considered. Because this particular CCS site would require methane gas recovery systems in addition to the CO2 injection systems". This means CO2 injection can displace methane, allowing for its recovery but this requires additional systems for methane recovery, complicating and increasing costs, especially in short-duration projects.

3. Deep saline formations:

They contain large volumes of saline water at significant depths, making them ideal for CO2 storage. These deep formations are abundant and widely distributed geographically, and according to [10], this abundant presence and its depth is the essential factor for the final evaluation and election.

Furthermore, deep saline formations are considered the most suitable option for CO2 injection. This affirmation is based on [13, p.3], which mentions that "Deep saline aquifers are large underground rock formations that contain briny water and are found deep beneath the Earth's surface. These aquifers are typically several thousand feet deep and can stretch for hundreds of miles. Due to their geological characteristics, they have been identified as one of the most promising and economically viable options for the long-term storage of carbon dioxide (CO2) produced by industrial processes". Also, these reservoirs already have existing wells and pipelines that can be adapted for CO2 injection and storage, potentially cutting down the cost and time needed to set up a new storage facility, as stated in [13]. In this sense, deep saline formations generally offer a stable and practical solution for CO2 injection and storage, minimizing risks of leakage and operational problems.

IV. Viability Assessment and Benefits of Carbon Dioxide Footprint Reduction

Economic viability and benefits are some considerations when evaluating and running CO2 technologies in the cement industry. These technologies aim to reduce carbon emissions, enhance sustainability, and align with the SDGs, according to [8].

The post-combustion by membrane capture of CO2 method [11] and the deep saline injection [10] offer a highly effective option to the ongoing and growing problem of the CO2 footprint in the cement industry. Although they do not reduce the amount of CO2 produced overall, this approach proposes a method by which the amount released into the environment can be highly reduced. This represents a step towards achieving Sustainable Development Goals such as 9 and 11. In relation to SDG 9, infrastructure for sustainable industries, such as the cement industry, could be developed. These advantages can be achieved with small changes in a working cement plant since they do not require major modifications, making the implementation of this method to be quick and at a low cost. SDG 11 is not strictly related to the cement industry, but one of its targets would be positively affected since the adverse environmental impact per capita would be reduced, especially in cities where big cement industries are located.

In terms of benefits, reducing the CO2 footprint is important to combat climate change in a transition towards sustainability. Also, according to [13], the use of membrane technologies for CO2 capture is likely to grow in the future, giving this proposal advantages such as reduced capital and operating costs, minimal space requirements, great variety to opt depending on the amount needed to be treated, and ease of operation.

The implementation of carbon injection into soils may vary depending on the economic possibilities, geographical location and availability of materials to carry out the modifications. Another factor to take into account is that the implementation must be carried out carefully by qualified labour, as injecting the captured CO2 incorrectly could make the entire process ineffective.

V. Conclusion

The urgency of addressing carbon emissions in cement production cannot be overstated. As the demand for infrastructure and construction materials continues globally growing, so does the industry's carbon footprint. The need to decarbonize cement production is underscored, highlighting the wide implications of its carbon emissions on climate change, to achieve the involved SDGs previously mentioned.

In this paper, the process of cement production is first stated and then the reasons and consequences of CO2 emissions are identified. As a result of this, an optimal CCS method such as post-combustion is proposed and chosen, among the other ones mentioned (pre-combustion and oxy-combustion), to capture the CO2 from the cement industry. Consequently, the CO2 injected through pipes to the most reliable and practical geological formation as they are deep saline formations.

If carried out, this proposal could have the potential to greatly decline the arising greenhouse gases emissions. With the ongoing research on the fields of membranes and it could be an easy, inexpensive and efficient method to implement and mitigate the carbon dioxide emissions. Also, this proposal has a direct impact on the current situation of the environment today, but more importantly, it also affects the situation of the environment in the future.

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