Facing climate change: Environmental evaluation of gypsum-like CO₂ utilization Mg-based materials

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Abstract. The product environmental assessment quantifies possible further improvements during the life cycle of a product, from flue gas extraction, through adsorption, carbonation, rinsing, activation and utilization. In this study, the carbon footprint, water footprint and energy footprint of magnesium carbonate product (MCC) has been estimated, following the life cycle assessment method. Though the analysis, the species of alkali, efficiency of alkali using, seawater desalination technology and substitution ratio have strongly influenced on the overall CO₂ footprint, water footprint and energy footprint balance of the CO₂ mineralization process. Several scenarios using ammonia or waste alkali would produce a negative carbon footprint MCC material, to substitute plasterboard. Energy consumption for scenarios with 100% substitution is -2 MJ to 14 MJ per kg of final MCC for scenarios using waste alkali.

Keywords: Magnesium Carbonate; CO₂ Absorption; CO₂ Footprint; Water Footprint; Energy Footprint

1. Introduction

Greenhouse gas emission (GHG) reduction has become one of the most relevant global challenge and research hotspots. In 2017, China’s carbon dioxide emissions reached 9.1 Gt, almost 1% higher than their 2014 level; and the global energy-related CO₂ emissions grew by 1.4%, reaching a historic high of 32.5 Gt, a resumption of remarkable growth after three years remaining stabilized[1]. The building materials manufacturing sector is one of the largest CO₂ emission sector around the world, especially for the cement industry etc.. With China’s continuous development in infrastructure and fixed assets, 2.18 Bt of cement products were produced by 1682 NSP clinker production lines of China’s cement industry in 2018, accounting for nearly 60% of global cement[2]. Cement industry is a typical resource and energy consumption industry, in which a large amount of limestone, coal and power resources are consumed in the clinker calcination processes. The decomposition of limestone, combustion of coal and consumption of power could cause direct or indirect CO₂ emission. Therefore, cement industry has become the second largest source of CO₂ emission in the manufacturing sector, with the rise in the proportion of total CO₂ emission. We must be open for all means contributing to a Low Carbon Future.

CO₂ Capture, Storage and Use technologies (CCSU) is becoming the conduit and gaining attention for a new energy economy and enabling the decarbonisation of carbon-intensive industry[3]. According to the IEA Roadmap 2050(which was shown in Figure 1), CO₂ reduction targets can only be achieved by using Carbon Capture and Storage (CCS)/ Carbon Capture Storage and Utilization (CCSU) technology. CCSU involves multiple multiphase processes, including CO₂ capture, separation, transport,
storage, utilization and post monitoring [4-5]. Captured CO₂ from traditional industrial process streams can be stored and captured through numerous approaches, including ocean storage below sea-level beds, geologic storage, biological storage, chemical storage, and mineral carbonation [6].

In 1990, mineral carbonation of CO₂, or mineral sequestration is one promising and feasible route, as it offers permanent CO₂ storage, which was proposed by Seiftriz at first. The reaction is to form thermodynamic stable and insoluble solid carbonates, e.g. CaCO₃ or amorphous MgCO₃, through the gas-solid two-phase reaction between CO₂ and metal cations such as Mg²⁺/Ca²⁺, which is close to the natural weathering process[7]. Natural minerals and rocks, alkaline industrial wastes, high-salinity brines and new binders are available for use in CO₂ sequestration. The energy state of CO₂ is 400 kJ/mol higher than that of mineral carbonate (60-180 kJ/mol), as shown in Figure 2 [8]. The mineral carbonates produced are environmentally stable, these make mineral sequestration of CO₂ as one long-term, leakage free and large sequestration capacity CCSU method [9].

During the past decades, alternative cementitious materials for CO₂ sequestration have been reported. Solidia and LafargeHolcim [10] have developed a new low-CaO clinker (SLC for short) in the cement kiln using common raw materials (limestone, siliceous material and other correcting materials), which comprises the low CaO/SiO₂ calcium silicate minerals as rankinite (C₃S₂) and wollastonite(CS). SLC cement is too unreactive to harden by common hydration method. And it can only be cured rapidly in
an atmosphere of pure CO₂, with controlled relative humidity far below 100%. SLC cement have recently been commercialized in early-stage for manufacturing certain non-reinforced precast cement-based products, and the CO₂ used for curing currently can come from industrial carbon dioxide gas suppliers. In addition, MgO-based cements (MBC for short) made from magnesium silicates could be with greater CO₂ sequestration through the carbonation-curing approach; in this case the raw materials contain minerals without CO₂ emission. For example, Novacem cement is a type of MgO-based cement, which is made by a British company and won the Material of the Year Award from Material ConneXion[11]. One novel development to make binders derived from the use of magnesium(Mg) and calcium(Ca) from hard brine is the Calera process [12]. The novel process focuses on the precipitation of carbonates, e.g. CaCO₃, amorphous MgCO₃, or magnesium-hydroxyl-carbonate-hydrate phases. Results show that these carbonates can be filler for lightweight aggregate, bricks and drywall materials. In special, some results [13] show these products of carbon dioxide capture can be prepared as useful self-cemented building products (MCC for short) with strength. Consequently, these low carbon Mg-cements (MCC) has drawn increasing interests widely as well. An estimate of the environmental profile of so-called Mg-cements gives an overview of the contribution to facing with the climate changes. It is necessary to identify environmental evaluation in the product chains and thereby address the environmental impact in the most efficient way. However, can Mg-cements (MCC) really reabsorb CO₂ as to be one type of low carbon cement in the life cycle as researchers expected? Only limited technical research study has been published. This issue is needing to be theoretically or thoroughly assessed.

In this article, the purpose of this study is to evaluate environmental impact potential based on current technological knowledge and further improvements, to the global sustainability targets outlined in IEA’s 2050 roadmap. It was discussed through Life Cycle Assessment (LCA) to assess the environmental impact of MCC with CO₂ capture and mineralization process using the aqueous waste (hard water) in alkaline buffers in the life cycle.

2. Methodology

Given the characteristics of CO₂ absorption to produce the low carbon cement to be environmentally assessed, Life Cycle Assessment (LCA) is the suitable methodology. And LCA, which is defined in the ISO 14040[14] and 14044 standards[15], is a method to assess environmental aspects and potential impacts (use of resources, the environmental consequences of releases, etc.) associated with a product, process or service, throughout the life cycle from raw material acquisition, production, use, end-of-life treatment, recycling, and final disposal (from cradle to grave). From a research and development point of view, LCA is used as a tool in making decision for product design improvement and innovation. From an industrial point of view, LCA can therefore also be used in making decision for technology investments, innovation systems, etc. However, a simplified LCA assessment is decided to be executed, as the results that there is lack of commercial industrial process producing the final construction material.

2.1. Research Goal

The research goals of the paper are to quantify the environmental footprint of the absorption CO₂ process using hard water to produce MCC, which are summarized below:

i) to provide the overall research framework for evaluation the magnesium carbonate construction materials produced from CO₂ absorption;

ii) to evaluate CO₂ balance, resource consumption and energy consumption associated with the CCUS process, to quantify the potential environmental highlights of the CCUS process;

iii) to evaluate critical boundary conditions, sensitivity analysis and uncertainty sources under different scenarios;

iv) to provide important recommendations for future development of the CCUS process technology.

2.2. Research Scope and Data Collection
The research scope is defined on the initial parts of LCA, from the cradle-to-gate perspective. Because such CO₂ absorption to produce construction materials has not exist yet at a commercial scale.

For MCC cement, according to material flows from cement manufacturing, the environmental footprints can be assessed by carbon footprint, water footprint, energy footprint. Also, those environmental indicators can be used to measure the sustainability.

The MCC cement based construction materials could be used for replacing gypsum plasterboard and the subsequent materials application processes. There is limited information available concerning the lifespan of such construction materials using hard water to capture CO₂. Therefore, a broadened scope focusing on the subsequent application processes would be much more complex and it appears to be a common choice to apply a cradle-to-gate perspective in the LCA studies of the process of CO₂ absorption using hard water to produce construction materials. The research scope contains CO₂ capture, carbonation, activation and production of Mg-based construction materials, see Figure 3. This assessment does not include generation, transport or storage of CO₂, and is only focused on analyzing the CO₂ capture, absorption and utilization. Meanwhile, the LCA studies focuses on the CCUS process and related construction materials commercialization; therefore, the transport, end-of-life treatment, recycling and final disposal of the product are considered to be out of the research scope.

![Figure 3. Research scope of CO₂ absorption process using hard water to produce construction materials.](image)

For achieving the assessment goals, the functional unit was defined as one kilogram of final solid product cement-magnesium carbonate product (MCC), which was recognized as negative or neutral carbon footprint. Because the raw material providing Mg/Ca, that is concentrated seawater, is defined as a product waste, with zero footprint associated with its generation. The reference functional unit is provided to that the collecting data are normalized.

According to system boundary, the data should be collected is comprised of concentrated seawater acquisition data, alkali acquisition data, heat or electricity data, desalinated water acquisition data, flue gas acquisition data. This choice was also indispensable to be able to realize the research goal and assessment. Raw material acquisition data has been collected from published literatures and other tools. In order to collect relevant information and data, these acquisition data have been investigated by several industry experts and used to calculate as mean values.

3. **Inventory analysis**

The inventory analysis, as the key part of LCA, quantifies objectively the environment load of product processes throughout the life cycle based on data collection and experiment data, including CO₂, water, energy, emission.

3.1. **Water footprint**

Water is required in two processes as rinsing the intermediate product and rehydrating to form final product: the former process is specially designed to remove soluble substances (such as NaCl, KCl etc.) from carbonate solids; the latter process is the necessary method to promote cementation and form final solids (MCC) through rehydrating the dehydrated products[19]. In actual fact, the benchmark of
minimum water intensive of rinsing could be designed at 3 cubic metres per t of product when using three-stage counter-current rinsing system or other new rinsing system, the benchmark of maximum intensive of washing could be designed at 10 cubic metres per t of product, which can raise CO₂ emission depending on the actual desalination technology[16]. The activation process of intermediate product, nesquenonite and hydromagnesite, to form final solids has the similar mechanism to that of gypsum to produce plaster, in which molecules of water is first released by thermal activation method, and then molecules of water is again react with the solids to cementing the final solid product. In actual fact, average water consumption for rehydration range from 0.7 to 1.4 cubic metres per t of solid product[16], that can raise CO₂ emission depending on the actual desalination technology.

Direct water footprint \( (m^3/kg) = W_W + W_R \)

Where,
- \( W_W \) water volume consumed in the washing the intermediate product process, in m³ per kg of solid carbonates (MCC), values in 0.003 to 0.01[16];
- \( W_R \) water volume consumed in the rehydration process, in m³ per kg of solid carbonates (MCC), values in 0.0007 to 0.001[16];

\[
\text{Indirect water footprint (m}^3/\text{kg}) = \frac{\alpha \beta M_A}{138.3} W_A - SW_s
\]

Where,
- \( \alpha \) molar ratio of alkali to fed CO₂;
- \( \beta \) absorption efficiency (mol/mol), considered equal to 1;
- \( M_A \) molar mass of the alkaline substance’s molecule, in g/mol, e.g. the value of NaOH at 39.996;
- \( W_A \) the water footprint associated with the alkaline sources, in cubic metres per kg of alkaline sources, e.g. 0.06 m³/kg NaOH[17];
- \( S \) the substitution ratio of plasterboard (it is a conventional construction materials), in kg/kg, values in 0 to 1[17];
- \( W_s \) the water footprint associated with the substituted construction material-plasterboard, 0.001 m³/kg[18].

3.2. Energy footprint

The thermal activation of intermediate product requires an energy consumption, coal or heavy oil as fuel. Assuming the similarity of activation process to that of gypsum to produce plaster[17] in some respects, fluidized bed furnace can be used to activate the intermediate product, through the pneumatic conveying method, which is widely used in plaster producers. An energy consumption of 10-12 kJ/g water[18], and an energy efficiency of 50%, the overall energy consumption per kg of carbonate(MCC), \( Z_T \), would be 1200MJ per t of MCC.

\( \text{Mg}^{2+} \) originates from desalination brines, and desalination process is an energy intensive process, which is designed to supply drinking water for the requirements of residential water consumption and boiler filled water. Multistage flash, Multi effect distillation and reverse osmosis are the mainstream types of desalination technology. Multistage flash (MSF) and multi effect distillation (MED) consume thermal energy as main source of energy based on steam evaporation, while reverse osmosis (RO) consumes electricity as main source of energy. Desalination water to feed brine ratio, as \( X_D \), is 0.1-0.25 for MSF technology, 0.25-0.35 for MED technology, 0.40-0.45 for RO technology. For MSF, MED and RO technologies, electricity consumption, in kWh per m³ water, is respectively 3-6, 1.5-2.5, and 2.5-4. Concentration of Mg²⁺ in desalinated brines ranges 1.35 - 1.85 g/L for MSF plants, 1.8 - 2.1 g/L for MED plants, and 2.1 - 2.65 g/L for RO plants[21].

The use of alkali additives depends on the OH/CO₂ ratio (i.e. \( \alpha \)), CO₂ adsorption efficiency (i.e. \( Y \)). Precipitation of 1 molecule of MgCO₃·3H₂O needs to capture 1 molecule of CO₂, through \( \alpha Y \) molecule of caustic soda. \( Z_A \), the energy consumption per kg of caustic soda, is 15 megajoule [20].

Assuming that MCC could compete directly with plasterboard, the average associated energy consumption of plasterboard is 4.3MJ per kg.

Direct energy penalty (MJ/kg) = \( Z_T \)
Where,  
$Z_T$ the heat required for the thermal activation, in MJ/kg, 1.2MJ/kg for magnesium carbonate(MCC);  
Indirect energy penalty (MJ/kg) = water footprint $\times Z_w + \frac{\alpha \beta M_A}{138.3} Z_A - SZ_s$

Where,  
$Z_w$ the associated energy of desalinated water production, in megajoule /cubic meters, 1134-1494 MJ/m$^3$ for MSF technology, 85 MJ/m$^3$ for RO technology, 80 MJ/m$^3$ for MED technology[21];  
$Z_A$ associated energy of the alkaline sources, in MJ/kg alkali, 15 MJ for NaOH produced by ionic membrane method[17];  
$Z_s$ associated energy of the plasterboard substituted, in MJ/kg, 4.3 MJ/kg[20].

3.3. CO$_2$ footprint

CO$_2$ emissions about the capture and utilization process are indirect emissions from the alkaline resources, activation energy and desalinated water. There are five main contributions: the alkali used to capture CO$_2$, the desalinated water to clean the intermediate products and rehydrate to form final products, thermal activation consumption of intermediate products, carbon dioxide saved by alkali capture and replacing of plasterboard (traditional construction product).

The solubility of CO$_2$ in desalinated brine is quite low at 25°C and 1 atm. Therefore it needs the alkaline additives, to enhance the pH of desalinated brines over a basic pH of 9.0, and finally in order to promote the precipitation of carbonates. Eqs. (1) shows the using of alkali to increase the dissolution of CO$_2$ forward the neutral balance. The absorption capacity of CO$_2$ in the alkali medium depends on the OH/CO$_2$ ratio, called as $\alpha$, ($2x+y)/(x+y)$. According to the function evaluation and chemical reactions, the range of OH/CO$_2$ ratio could be 1.0 - 2.0. If OH/CO$_2$ ratio is 2.0, i.e. y=0, sodium carbonate is formed; if OH/CO$_2$ ratio is 1.5, i.e. $x=\frac{1}{2}$, the mixture of sodium carbonate and sodium bicarbonate is formed; if OH/CO$_2$ ratio is 1.0, i.e. $x=0$, sodium bicarbonate is formed. The OH/CO$_2$ ratio has the notable influences on CO$_2$ dissolving capacity and efficiency of the capture process. For achieving more xMg(OH)$_2$,$y$MgCO$_3$$\cdot$$z$H$_2$O phases, the pH condition could be kept far from near-neutral condition, therefore, bicarbonate amount in the solution could be controlled in an accurate way. When only pure bicarbonate is formed, xMg(OH)$_2$$\cdot$$y$MgCO$_3$$\cdot$$z$H$_2$O phases does not appear. Therefore, consideration must be given to both the CO$_2$ capture efficiency and precipitation of xMg(OH)$_2$$\cdot$$y$MgCO$_3$$\cdot$$z$H$_2$O phases; in actual fact, the optimal OH/CO$_2$ ratio lies 1.5 - 2.0, as shown in Figure 4. The CO$_2$ emissions associated with the alkali additions, is around 1.125 kg CO$_2$ per kg caustic soda [22-24].

\[\Delta H_{588} = (-66.5y-107.7x)kJ/mol CO_2\]

\[
\text{CO}_2^{\text{aq}} + \text{HCO}_3^{\text{aq}} + \text{Mg}^{2+} \rightarrow \text{xMg(OH)}_2\cdot\text{yMgCO}_3\cdot\text{zH}_2\text{O} \quad (2)
\]

Water is required in two processes as washing the intermediate product and rehydrating to form final product, which can add CO$_2$ emission depending on the actual desalination technology. The CO$_2$ emissions associated with the desalination technology, $E_{d}$, in kg CO$_2$ per m$^3$ of water, which depends on the desalination process, 5.5, 4, and 1.2 to 1.8 respectively for MSF hybrid CCGT power plant, MED hybrid CCGT power plant, RO power plant.

The thermal activation adds CO$_2$ emission, which is from fossil fuel combustion. It is assumed as 88.83 g CO$_2$ per megajoule (from coal combustion) [25].

1 molecule of CO$_2$ could be captured by caustic soda to precipitate 1 molecule of MgCO$_3$$\cdot$3H$_2$O, therefore with average CO$_2$ emission savings of 318 g per kilogram of final product.

For further simplified assessment, it is appropriate to assume that magnesium carbonates would entirely substitute for traditional gypsum plasterboard, with associated CO$_2$ emissions of 360g per kilogram of gypsum product[18].

\[\text{CO}_2 \text{ emission (kg CO}_2/\text{kg)} = 0.32 \times \left(\frac{\alpha \beta M_A}{44} - 1\right) + W \times E_W + Z_T E_T - E_s S \quad (3)\]

Where,
0.32  molecular weight ratio of CO₂ to MgCO₃·3H₂O;

\[ E_A \]  carbon dioxide emissions of alkali, in kgCO₂/kg alkali, 1.125 kg CO₂ per kg NaOH[18];

\[ E_W \]  associated CO₂ emission of 1 m³ desalinated water, in kgCO₂/m³ desalinated water, 5.5, 4, and 1.2 to 1.8 respectively for MSF hybrid CCGT power plant, MED hybrid CCGT power plant, RO power plant[18];

\[ E_T \]  CO₂ emissions of the thermal activation, in kgCO₂/ megajoule , 0.089 kgCO₂ per MJ for coal combustion[18];

\[ E_s \]  CO₂ emissions of the plasterboard replaced, in kgCO₂/kg, 0.36kgCO₂/kg plasterboard[18].

4. Result and discussion

Basically pursuing the simplest understanding, the base case situation is designed as the production of final MgCO₃·3H₂O solids as the full substitution of gypsum plasterboard by using concentrated brine from a RO plant, CO₂ from a cement plant, caustic soda from ionic membrane method and 2.0 of OH/CO₂ ratio. As discussed above, substitution ratio can be divided into 0, 1.0; alkali sources can be divided into caustic soda, ammonia, waste alkali, which is the key factor for environmental assessment; OH/CO₂ ratio can be set as 1.5, 2.0; concentrated brine can be sources from a RO plant, MSF plant or MED plant. Therefore, 36 scenarios would be assessed.

Table 1. Emission results for base case situation. MCC environmental footprint (calculated per kilogram of product).

| Process      | CO₂ footprint, kg CO₂/kg | Direct water consumption, m³/kg | Indirect water consumption, m³/kg | Direct energy penalty, MJ/kg | Indirect energy penalty, MJ/kg | Water footprint, m³/kg | Energy footprint, MJ/kg |
|--------------|--------------------------|---------------------------------|-----------------------------------|-----------------------------|-------------------------------|------------------------|--------------------------|
| Absorption   | 0.39                     | 0.00                            | 0.03                              | 0.00                        | 11.63                         | 0.03                   | 11.63                    |
| Rinsing      | 0.02                     | 0.01                            | 0.00                              | 0.00                        | 0.85                          | 0.01                   | 0.85                     |
| Activation   | 0.11                     | 0.00                            | 0.00                              | 1.20                        | 0.06                          | 0.00                   | 1.26                     |
| Substitution | -0.36                    | 0.00                            | 0.00                              | 0.00                        | -4.39                         | 0.00                   | -4.39                    |
| Total        | 0.15                     | 0.01                            | 0.03                              | 1.20                        | 8.15                          | 0.04                   | 9.35                     |

Table 1 shows the calculated results in the base case situation, per kilogram of MCC. Base case situation is competent to produce nesquehonite-based solids embodying around 0.15 kg CO₂ per kg of final products when concentrated brine from the RO plant, caustic soda and OH/CO₂ ratio of 2.0 used as a 100% replacing plasterboard. The direct and indirect energy penalty is around 9.35 MJ per kg of final product, which is higher than that of plasterboard (6 MJ per kg). The high values of energy footprint resources from indirect sources, the embodied energy of alkalis for example. The total water footprint is around 0.04 m³ per kg of final product, which is also higher than that of plasterboard.

It is certain that absorption process is the largest contributor to CO₂ reduction in all the processes, the using of alkali in the absorption process. And the substitution of plasterboard process is the largest contributor to mitigation of carbon emission, although which is partly compensated by the use of alkaline. The water footprint in rinsing and activation processes is confirmed to be a focal point and would be never neglected.

This result confirms the clear optimized pathways for process improvement: less alkaline and less water consumed. Less alkaline should be consumed, and alkaline with low environmental impacts should be considered, such as soda residue, kiln dust and others. Water consumption reduction should be considered, though the water with low environmental impact, the new rinsing process and the water recovery process. For instance, the rinsing process can be divided into multiple stages, the initial one using low-quality water. If the adsorption process reduce the alkaline by 40%, the CO₂ emission in the adsorption process can be cut by 46%, all the CO₂ footprint can be cut by 30% - 70%, the water footprint by 19.1% - 19.5%, the energy footprint by 19% - 31%. If water from MSF technology is used, the total carbon footprint would be increased by 26% than that of MED, 117% than RO; the energy footprint would be increased by 545% than that of MED, 529% than that of RO.
In order to consider the influences from different technological change, the assessment is extended to 36 scenarios: the seawater desalination technology, the species of alkalis, and the efficiency of alkalis using, the substitution ratio. Figure 4, 5 and 6 show the analysis results of carbon emission, water footprint and energy footprint for the assumed 36 scenarios. These reveals the significant influence of the alkaline resources, substitution ratio, efficiency use and desalination technology, in the final MCC product footprint.

![Graph showing carbon dioxide emission per kg of produced MCC in different scenarios, kgCO2/kg.](image)

**Figure 4.** Carbon dioxide emission per kg of produced MCC in different scenarios, kgCO₂/kg.

From the results in Figure 4, the remarkable reduction of carbon footprint for all scenarios, when OH/CO₂ (efficiency of alkali use) is reduced from 2.0 to 1.5, which means the lower the OH/CO₂ rate, the more efficient the absorption step and lower CO₂ emission is. From the results in Figure 4, 5 and 6, And when ammonia or waste alkali is used in the absorption process, the related CO₂ footprint, water footprint and energy footprint get significantly reduced. However, several scenarios using ammonia or waste alkali could cut carbon footprint MCC, to substitute plasterboard.

From Figure 6, energy consumption for these scenarios with 100% substitution ratio is 5 MJ - 64 MJ per kg of final MCC for scenarios using caustic soda, 5MJ to 26MJ per kg of final MCC for scenarios using ammonia, -2 MJ to 14 MJ per kg of final MCC for scenarios using waste alkali, while only 6MJ per kg of plaster. Only certain scenarios can reach a zero or negative energy footprint materials when waste alkali is assumed in the process assessment. The absorption and rinsing processes are the major contributors to water footprint.
Figure 5. Associated water footprint in different scenarios, m³/kg produced MCC.

Figure 6. Associated energy footprint in different scenarios, MJ/kg produced MCC.

5. Conclusions
Using the cradle-to-gate method, the CO₂ footprint, water footprint and energy footprint balance have been calculated and analyzed for the CO₂ capture and mineralization process route. The processes
involve the use of aqueous Mg-rich high-salinity brine, the use of flue gas containing CO₂, forming the magnesium carbonates precursor such as Mg₂CO₃·3H₂O and hydro-magnesite, and then forming plaster-like MCC product through activation method. LCA Analysis reveals the remarkable influence of the alkaline, substitution ratio, efficiency use and desalination technology, in the final MCC product footprint. Several scenarios using ammonia or waste alkali would cut carbon dioxide, and make the MCC with negative carbon footprint, to substitute plasterboard. Energy footprint in these scenarios with 100% substitution ratio is -2 MJ to 14 MJ per kg of final MCC for scenarios using waste alkaline. Beyond that, searching an ideal alkali waste, and developing an appropriate water recycling method are important to provide useful information for further development of MCCs with less CO₂ emission/ and less energy consumption.

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