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CO₂ Capture and Storage in Solid Waste and Low-Carbon Reactants for Sustainable Construction Composites

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Abstract

CO_2 capture and storage, exploitation of industrial solid waste and low-carbon materials, and reducing greenhouse gas emissions have global attention for achieving some of the sustainable development goals. There is a great practical significance to using these materials to get improved construction materials with enhanced characteristics. Here, we outline the process of gas capture by several types of solid waste containing calcium silicates. Furthermore, the curing behavior and the mechanism of silicate during the accelerated carbonization reaction are discussed. The main reason for the enhanced mechanical and physical properties is the stable calcium carbonate precipitated during carbonization by reacting the leached calcium cations with carbonate anions. Finally, the paper highlights the deficiencies in the related work and recommends some perspectives on the process of hardening solid waste and silicates using waste gas to form useful and sustainable construction materials.

Keywords: Construction materials; Solid waste, CO_2 capture and storage; Carbonization, Low-carbon materials.

1. Introduction

The large number of concrete waste and industrial solid waste, such as steel slag, fly ash, crushed aggregate, gypsum, red mud, blast furnace etc. are regularly produced in huge amounts which increases environmental problems [1,2]. In addition, increasing the greenhouse gas emissions has become the focus of global attention. Among of these gases, CO_2 has received the most attention because its concentration in the air is continues to increase [3,4]. Basically, the Ordinary Portland cement (OPC) is one of the most important raw cementitious materials for structural and building applications. However, consumption of high energy and emission of heavy exhaust during manufacturing are considered as harmful environmental issues, those may hinder the development of traditional Portland cement in the near future. In addition, manufacturing of traditional cement materials is considered as a highly CO_2-emitting process. The international man-made emission of CO_2 has reached 8% of the total emitted gas; the cement industry causes around 7% of the total anthropogenic CO_2 gas [5,6]. So minimizing this percentage is the aimed environmental impact. Furthermore, the lower alkalinity of traditional cement that leads to corrosion of reinforcing steel bars is another disadvantage. Some other types of cement are recommended, such as calcium silicate (CS), dicalcium silicate (C_2S), and tricalciumdisilicate (C_3S_2), as new proposed clinkers. These minerals have about lower 250 °C sintering temperature, 30% energy consumption and 70% gas emissions, compared with the traditional cement, in addition to the improved mechanical and physical properties upon carbonation curing. The carbonation mechanism is related to the transfer of concentrated CO_2 gas into silicate pores, and formation of stable carbonate. Therefore, it is of great significance to

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explore the benefit of low-carbon and solid waste materials for producing applicable building materials [7,8]. Because this approach has salient "environmental-friendly" features with the short-time process of accelerated carbonization reaction, neither by-products nor safety hazards can be obtained [9,10]. Furthermore, the usage of different solid waste and recycled materials in recognizing environmental issues is targeted in many applicable products [11,12]. With more focus on the different types of cement materials, the phase of hardened traditional cement is CSH gel, formed by hydration and then carbonation. However, the main product of non-hydraulic cement is carbonate-silica intermix [13], which still more needs study. This new technique can be applied with some kinds of low-energy and low-carbon starting materials for reducing greenhouse gas emissions [14,15]. CO_2 gas could react with either non-hydraulic cement, e.g. C_2S and C_3S, or hydraulic products, e.g. $Ca(OH)_2$ and CSH, though converting gaseous phase to solid carbonate and CSH [16]. The accelerated carbonization reaction for non-hydraulic calcium/magnesium silicate is still a new approach for preparing precast concrete and cement; this technology achieves a bundle of properties such as economic cost, permanency and gas uptake. With that mechanism, the pressured CO_2 in the presence of humidity can precipitate the stable carbonate which is the sources of improved mechanical effect; such mechanism prevents further release of CO_2 gas in air and reduces carbon footprint. Because of the non-hydraulic nature of C_2S, C_3S_2 and CS silicates types, they give mostly anhydrous phases during carbonation without hydration products [17]. Based on the above ideas, this paper analyzes and summarizes the research progress on the possibility of utilizing solid waste for making improved and sustainable construction materials for reducing greenhouse gas emissions. The accelerated carbonization reaction is highlighted for curing the silicate reactants. The gas uptake in the carbonized product is another environmental feature.

2. Principles of carbonization
2.1. Dissolution of CO₂

To start the reaction of carbonization, the carbon dioxide gas should be dissolved firstly in water depending on pressure and temperature. In the "CO_2-H_2O" system, CO_2 dissolves and reacts with H_2O to form carbonic acid (H_2CO_3) by a physically diffusion

under controlled temperature and pressure [18]. After that, the formed carbonic acid is ionized to protons and carbonate ions, as in Equation 1.

$$CO_{2(g)} + H_2O_{(aq)} \rightarrow H_2CO_{3(aq)} \rightarrow 2H^+_{(aq)} + CO_3^{2-}_{(aq)} \quad (1)$$
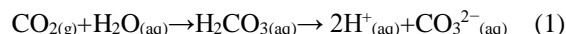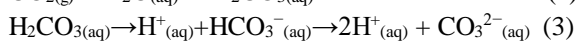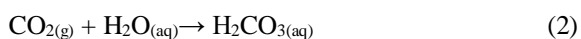
A lot of studies were studied reaching the maximum solubility and equilibrium phases with different temperatures and pressures. ATR spectroscopy has been used at different conditions reaching the equilibrium state; FTIR was also used for measuring the solubility of H_2O [19]. Also, ion and gas chromatography, volumetric and Raman analytical methods have been applied [20,21]. A summary for some related work is given in Table 1 that concludes the applied pressures and temperatures. From that table, we can state that the dissolution of carbon dioxide in liquid solutions is a pressure/temperature-dependent process, and each condition has its equilibrium point and solubility extent. Dissolution in the CO_2-H_2O system results in carbonic acid, which finally forms active carbonate anions.

Table 1: A summary of applied parameters for CO_2 dissolution.

Temperature range applied (K)	Pressure range applied (MPa)	References
273.2 to 573.2	10 to 120	Guo et al. [22]
283.4 to 351.3	0.3 to 5.2	Chapoy et al. [23]
283 to 363	0.3 to 12.1	Carvalho et al. [24]
288 to 398.2	6.1 to 20.3	King et al. [25]
293.2 to 375.2	2.5 to 14.7	Sander [26]
296.7 to 369.7	1.6 to 8.3	Bermejo et al. [27]
303.2 to 333.2	10 to 20	Bando et al. [28]
313.2 to 343.2	4.3 to 18.3	Han et al. [29]
323.1 to 373.1	2.1 to 20.2	Koschel et al. [30]
323.2 to 413.2	5 to 40	Yan et al. [31]
333.2 to 373.2	0.1 to 21.3	Mohammadian et al. [32]
348.2	10.3 to 15.3	Sako et al. [33]
352.9 to 471.3	2.1 to 10.2	Nighswander et al. [34]
374	7.2 to 27.3	Tong et al. [35]
374.2 to 393.2	2.3 to 70.3	Prutton and Savage [36]
393.2	11.3 to 33.7	Savary et al. [37]

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2.2. Ions equilibrium of CO₂ in water

As provided in Equations 2 and 3, the dissolution of CO_2 gas in water gives carbonic acid, depending on pH value indeed, that separated into carbonate and bicarbonate anions needed for neutralizing of carbonic acid. The constants for the corresponding equilibrium at room temperature ($K_a=10^{-6.3}$ and $K_b=10^{-10.3}$) can be written as in Equations 4 and 5, respectively [38,39]. The equation for the moles balance of formation of carbonic acid is given in Equations 6, where C_T is for the concentration of total carbon. Furthermore, Equations 7-9 are three formulas where α_0, α_1 and α_2 those are governed by pH values [40].

$$CO_{2(g)} + H_2O_{(aq)} \rightarrow H_2CO_{3(aq)} \tag{2}$$
$$H_2CO_{3(aq)} \rightarrow H^+_{(aq)} + HCO_3^-_{(aq)} \rightarrow 2H^+_{(aq)} + CO_3^{2-}_{(aq)} \tag{3}$$
$$K_a = [H^+][HCO_3^-]/[H_2CO_3] \tag{4}$$
$$K_b = [H^+][CO_3^{2-}]/[HCO_3^-] \tag{5}$$
$$C_T = [H_2CO_{3(aq)}] + [HCO_3^-_{(aq)}] + [CO_3^{2-}_{(aq)}] \tag{6}$$
$$[H_2CO_{3(aq)}] = \alpha_0 . C_T, \ \alpha_0 = [H^+]^2/([H^+]^2 + K_a[H^+] + K_aK_b) \tag{7}$$
$$[HCO_3^-_{(aq)}] = \alpha_1 . C_T, \ \alpha_1 = K_a[H^+]/([H^+]^2 + K_a[H^+] + K_aK_b) \tag{8}$$
$$[CO_3^{2-}_{(aq)}] = \alpha_2 . C_T, \ \alpha_2 = K_aK_b/([H^+]^2 + K_a[H^+] + K_aK_b) \tag{9}$$

It can be concluded that the carbonizationreaction and its products are strongly influenced by pH value. More content of CO_3^{2-} is produced with more basic medium, higher content of H_2CO_3 can be obtained with neutral conditions, and more HCO_3^- is produced with acidic conditions. We can say that the basic medium is the best for the carbonizationreaction; in that case the rich-carbonate substrate is utilized with improved characteristics. Also, the carbonizationprocess is influenced by the pressure provided where higher content of CO_2 gas can be diffused and sequestrated under higher pressure. The pressure factor itself can be influenced by temperature where they are proportional to each other and govern the carbonizationcuring extent [41,42].

2.3. Ions equilibrium in alkaline ions

Basically, the carbon dioxide gas is dissolved in the aqueous phase giving aqueous carbonic acid and then dissociated to carbonate anions, as summarized in this section in Equation 10. The calcium/magnesium-containing silicate material or solid waste is being dissolved (leached). This dissolution is provided with the help of the formed carbonic acid to give calcium/magnesium ions with raising the pH to high basic value ~11.4 [43]. Respectively as shown in Equations 11-14, the solid larnite (Ca_2SiO_4),

rankinite($Ca_3Si_2O_7$), wollastonite ($CaSiO_3$) and lime (CaO) are dissolved and leached into calcium cations. Finally, a nucleation reaction between calcium cations and carbonate anions is occurred resulting in precipitation of calcium carbonate, as given in Equation 15 [44,45].
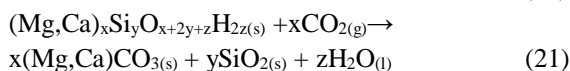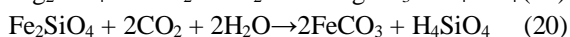
$$CO_{2(g)} + H_2O_{(aq)} \rightarrow H_2CO_{3(aq)} \rightarrow 2H^+_{(aq)} + CO_3^{2-}_{(aq)} \tag{10}$$
$$Ca_2SiO_{4(s)} + 4H^+_{(aq)} \rightarrow 2Ca^{2+}_{(aq)} + SiO_{2(s)} + 2H_2O_{(l)} \tag{11}$$
$$Ca_3Si_2O_{7(s)} + 6H^+_{(aq)} \rightarrow 3Ca^{2+}_{(aq)} + 2SiO_{2(s)} + 3H_2O_{(l)} \tag{12}$$
$$CaSiO_{3(s)} + 2H^+_{(aq)} \rightarrow Ca^{2+}_{(aq)} + SiO_{2(s)} + H_2O_{(l)} \tag{13}$$
$$CaO_{(s)} + 2H^+_{(aq)} \rightarrow Ca^{2+}_{(aq)} + H_2O_{(l)} \tag{14}$$
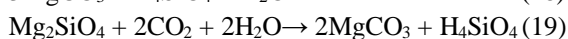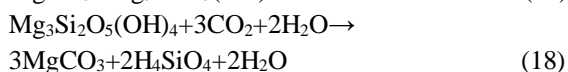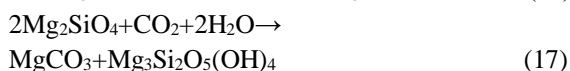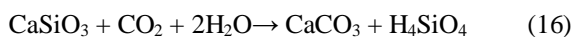$$Ca^{2+}_{(aq)} + CO_3^{2-}_{(aq)} \rightarrow CaCO_{3(s)} \tag{15}$$
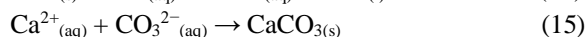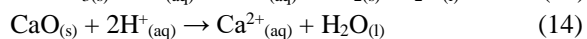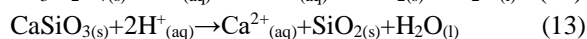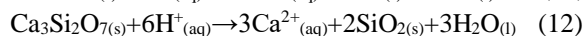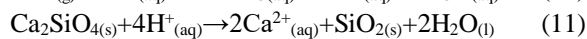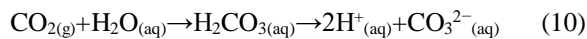
As a summary, the carbon dioxide gas is diffused in the aqueous phase to form carbonic acid till reaching the equilibrium phase at the end. At the same time, the solid waste or silicate material is leached and releases calcium cations which neutralize the formed acid to produce the hard calcium carbonate.

2.4. Carbonization mechanism

The mechanism of carbonization reaction is based on the chemical interaction between silicates and CO_2 gas getting carbonated and carbonized (hard) materials. In the recommended carbonizationprocess, CO_2 gas is diffused inside the microstructural of silicates and converted from the gaseous phase to the solid phase, as the form of generated silica gel (SiO_2) and calcite ($CaCO_3$) [46,47]. These obtained materials are responsible for the stiffness of the cured product. So, carbonizationis considered as a permanent sequestration process for CO_2 in silicate minerals.Taking into consideration of the industrial waste residue that contains a lot of calcium and magnesium silicates, so this solid waste is considered as a silicate-rich source. Consequently, it is possible to utilize these industrial residues in sequestration of CO_2 gas through the carbonizationreaction. In fact, it is known that the normal "weathering carbonization" could hold some disadvantages, such as low durability and corrosion sensitivity, which already present in the normal types of cement like OPC. Subjection of silicates for carbonizationreaction using high-pressured CO_2 gas in humid and warm closed system which is called "accelerated carbonization", can serve with avoiding those disadvantages. This mechanism provides a fill carbonizationreaction within shorter time, compared with the weathering carbonizationtype [48,49].Basically, the reaction of

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CO_2 with the cementitious materials has the same carbonization mechanism of the reaction of CO_2 gas with different calcium/magnesium/iron silicates in presence of water, such as wollastonite ($CaSiO_3$) olivine (Mg_2SiO_4), fayalite (Fe_2SiO_4), rankinite ($Ca_3Si_2O_7$) and belite (Ca_2SiO_4). In addition to industrial alkaline waste that contains much contents of calcium/magnesium/iron silicates and oxides, which can be exploited as reactants for carbonization process [50,51]. As shown in Equations 16-20, the carbonization requires water for hydration, and the carbonization reaction yields carbonate/silica intermixes. An overall carbonization reaction for calcium/magnesium silicate is summarized in Equation 21. Theoretically, the final product contains silica, but it is difficult to find this silca as pure phase in the resultant materials [52,53].

$$CaSiO_3 + CO_2 + 2H_2O \rightarrow CaCO_3 + H_4SiO_4 \quad (16)$$
$$2Mg_2SiO_4 + CO_2 + 2H_2O \rightarrow$$
$$MgCO_3 + Mg_3Si_2O_5(OH)_4 \quad (17)$$
$$Mg_3Si_2O_5(OH)_4 + 3CO_2 + 2H_2O \rightarrow$$
$$3MgCO_3 + 2H_4SiO_4 + 2H_2O \quad (18)$$
$$Mg_2SiO_4 + 2CO_2 + 2H_2O \rightarrow 2MgCO_3 + H_4SiO_4 \quad (19)$$
$$Fe_2SiO_4 + 2CO_2 + 2H_2O \rightarrow 2FeCO_3 + H_4SiO_4 \quad (20)$$
$$(Mg,Ca)_xSi_yO_{x+2y+z}H_{2z(s)} + xCO_{2(g)} \rightarrow$$
$$x(Mg,Ca)CO_{3(s)} + ySiO_{2(s)} + zH_2O_{(l)} \quad (21)$$

Basically, the normal curing of cement materials is based on hydration followed by weathering carbonation reactions, where the main product is CSH. However, the proposed carbonation curing is based on purging concentrated CO_2 gas in presence of humidity and warm conditions for a short period; a side hydration reaction may be occurred. Consequently, the carbonate particles are precipitated in the silicate sued, and cause improved characteristics [54,55]. As a summary for this section, the carbonization process can be concluded as the sequestration and conversion of CO_2 gas in silicate microstructures into calcite and silica gel. Accelerated carbonization is applied to make a complete carbonization in a shorter time compared with weathering carbonation. The industrial residues can be used as a silicate-rich source.

3. CO₂ capture and storage

3.1. Gas uptake targeted in silicate/solid waste

The amount of solid carbon can be maximized through the proposed carbonization reaction. It increases the CO_2 uptake in silicate reactants. This can be achieved by the accelerated carbonization reaction through exposure of silicates or solid waste to a concentrated CO_2 gas. Accelerated carbonization is supported with higher pressure-flow rate of CO_2 gas under humidity control in a shorter time, compared with the weathering carbonization with only 0.04% CO_2 atmospheric concentration [56].

In fact, the construction waste materials are rich in different silicates which can be utilized in CO_2 sequestration [57]. Other industrial by-products can be used as alternative raw materials rather than the version silicates, e.g. steel slag, blast furnace slag, fly ash, red mud and fluidized bed reactors [58,59]. Steel slag is a by-product of steel-making that contains 34-55% CaO. In accordance with possible reaction of CaO with CO_2 to form $CaCO_3$, the CO_2 consolidation percentage can be up to 50 wt.% [60,61]. Blast furnace slag is a by-product of iron-making including dicalcium silicate, tricalcium silicate, calcium/magnesium-containing alkaline minerals, such as iron and calcium, magnesium and vitreous. The contents of CaO and MgO are ~28 and 8%, respectively. The CO_2 consolidation percentage reaches around 20% [62,63]. The fly ash is a huge amount solid waste in the thermal power plants, its consolidated CO_2 is about 10 wt.%. The municipal waste incineration residue contains 35-50% CaO and 3-4% MgO, and its CO_2 consolidation amount is near 15 wt.%. Another example is the solid waste-consuming cement/concrete; it is an alkali-activated blended cement/concrete that manufactured by mixing two components together. The first is the cementitious waste or aluminosilicate component, e.g. metakaolin, powdered-blast furnace slag, silica fume, zeolite, powdered-phosphorus slag, kaolinite and limestone. The second component is the alkali-activators component, e.g. alkaline salts and caustic alkalis [64,65].

3.2. Factors affecting CO2 capture

There are main factors that affect the capture and storage of CO_2 throughout the carbonization reaction, such as carbonization temperature, relative humidity, gas pressure, water/solid ratio, gas flow, particle size, and solid pretreatment conditions. All of these parameters can be adjusted with definite reaction time and temperature [66,67]. The

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carbonizationprocess, subsequently the content of CO_2 uptake, is very sensitive to CO_2 pressure and its flow rate. The carbonizationrate itself increases with the more gas flow rate and more pressure in shorter reaction time. Such conditions make deeper depths available for gas diffusion resulting in denser carbonizationwithinlonger depths [68-70]. The particle size of reactant directly governs the whole properties of carbonization. The smaller particle size, the larger surface area subjected to CO_2 gas. Hence, more carbonization is being occurred with more uptakes for CO_2 gas. Milling the cementitious material could broaden the reactive area subjected for curing; thus more carbonizationand consequently more CO_2 storage can be utilized [71,72]. Furthermore, water content "liquid/solid ratio" and relative humidity affect the carbonizationefficiency and gratified CO_2. Generally and depending on other factors; adjustment the humidity more than 60% leads to the fastest carbonizationreaction. A minimum liquid ratio ~10 wt% could to be in the reaction system to allow for carbonization, so there is no carbonizationoccurred without minimum water content. However, more water percentage may lead to CO_2 blocking against diffusion into the silicate microstructure, which results in lowering carbonizationand CO_2 uptake [73,74]. The conditions at which the maximum CO_2 uptake can be achieved are optimized by controlling the whole factors-affecting carbonizationreaction together depending on the nature of reactants [75]. Table 2 summarizes the mentioned carbonization factors on CO_2 uptake percentages that recorded in some relevant articles, using different silicate and waste materials.

Table 2: Carbonization factors and related CO_2 capture percentages in some silicate and waste materials.

Factors in methods	CO_2 capture (%)	Data source
Accelerated carbonizationfor building blocks made of concrete waste aggregates at 0.5 MPa CO_2 pressure at room temperature for 2 hr.	16 %	Shao et al. [76]
Mineral carbonizationfor cement kiln dust using 45 mL/min CO_2 rate, 98% relative humidity at ambient temperature and pressure for 12 days.	34.6 %	Huntzinger et al. [77]
Carbonizationfor alkaline waste soil. The optimized curing factors were 10 L/min. CO_2 flow rate at 40 °C, 65% humidity and 0.4% water/solid ratio for 16 hr.	18 %	Sehgala et al. [78]
Carbonizationreaction for ~50 μm waste cement at temperature 49.9 °C, 3.0 MPa CO_2 pressure and 0.29% water/solid ratio.	25 %	Iizuka et al. [79]
Curing reaction for 80 μm stainless steel slag at 50 °C, 0.3 MPa gas pressure and 0.3 water/solid ratio for 8 hr.	13 %	Baciocchi et al. [80]
Accelerated carbonizationfor precast concrete pipes at 0.15 MPa gas pressure, 60% relative humidity at room temperature for 2 hr.	8 %	Rostami et al. [81]
Curing of electric arc furnace black slag at 40 °C and gas pressure of 4.95 MPa for 10 days.	4 %	Gurtubay et al. [82]
Carbonizationcuring of wollastonite at 60 °C, 0.35 % water/solid ratio, 4 MPa CO_2 pressure and 94% relative humidity for 24 hr.	18 %	Ashraf et al. [83]
Carbonizationreaction for slag/cement blends at 0.15 MPa and 87% relative humidity for 2 hr.	9.8 %	Monkman and Shao [84]
Preparation and carbonizationcuring of C_2S and C_3S using 15% CO_2, 94 % relative humidity at 55 °C for 48 hr.	20 %	Ashraf and Olek [85]

In general, all of the carbonization parameters can be adjusted with a definite reaction time and

temperature to develop CO_2 uptake% and the properties of the final useful product. Like driving your car, which requires controlling speed with distance from the front vehicle, eyes and ear focus, mirrors, and brakes matching with each other, it is required to drive and control the carbonization reaction with all factors together. Actually, this optimization depends on the required properties and the amount of sequestered CO_2 gas.

4. Application in construction materials and related curing

Some examples of the application of the accelerated carbonization process in the manufacturing of building blocks and construction materials are given here, in addition to presenting an overall curing mechanism. According to the rapid increase and large amounts of CO_2 gas, most current studies focus on achieving the capture target by sequestering CO_2 gas in silicate slag slurry through determining the rate of carbonization reaction, studying the mineralogical characteristics of the hardened product, and determining the reaction pathway.

4.1. Waste-based construction units

In existing literature, there are many types of building bricks manufactured through carbonization of different slags and construction waste. Weida and Quanbing [86] have prepared and hardened some construction blocks from steel slag/slaked lime admixture through the carbonization reaction with pure CO_2 gas, the obtained bricks were characterized by the denser carbonate crystals with improved mechanical and physical properties. Baciocchi et al. [87] have hardened the slurries of electric arc furnace/basic oxygen furnace slag mixes through the thin-film route using aqueous accelerated carbonization reaction at elevated temperature and 10 bar gas pressure. They got 403 g of CO_2/kg slag; in addition, Ca, Mg, Fe and Mn-based carbonates were precipitated successfully. Said et al. [88] have extracted and precipitated a carbonate type from steel-making slag using different ammonium salts. Using a mixture of OPC and aggregate, Zhan et al. [89] prepared units of construction aggregates/Portland cement concrete blocks. The accelerated carbonization reaction was carried out under 0.1 bar CO_2 at room temperature, leading to enhanced compressive strength and drying shrinkage

properties, compared with the steam-cured specimens. Zhan et al. [90] performed hardening process for recycled concrete aggregates at 10 kPa CO_2 pressure and room temperature till 70% humidity percentage for four h. El-Hassan and Shao [51] studied the effect of pre-curing on the hardening process for slag aggregates/cement slurry with 0.4% liquid/solid ratio, to get concrete block units with 127x76x38 mm^3. Setting for four h at 50% relative humidity and room temperature has increased the CO_2 sequestration form 8.5% to 24%, which reached 35% with full hardening after four days. Xuan et al. [91] have prepared building cylinder blocks with 33.5x50 mm^2 using construction waste containing concrete slurry and fine recycled concrete aggregates less than 5 mm that pressured at 30 MPa for 30 sec. A pre-curing at room temperature at 50% relative humidity for six h was performed, followed by the accelerated carbonization using 0.1 bar CO_2 for 1, 3, 24, 48, 96 and 144 h; 75% CO_2 uptake was reached after 3 h of carbonization. More hardening extent and enhanced physico-mechanical properties have been recorded with more setting time due to increase of calcite, and altering of porosity and density.
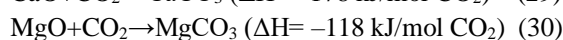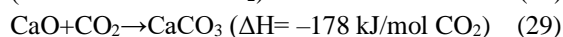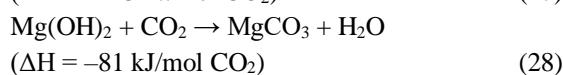
4.2. CO$_2$ diffusion and curing

During hardening, CO_2 is diffused into the reactant silicate to form hard carbonate by reaction with leached calcium ions. This depends on diffusion mechanism of CO^{3-} and Ca^{2+} from/to substrate, boundary layer, precipitation in bulk solution and particle size. Huntzinger et al. [92] have set up the model of hardening reaction and found that it is governed by the carbonization rate depending upon some aspects, such as diffusion rate of CO_3^{2-} to reaction interface, leaching rate of Ca^{2+} and the precipitation rate of final product. There is no precipitated product in case of hindering the role of ions migration on the surface; based on carbonization reaction, the cementing capacity of various calcium and magnesium waste residue is studied. Huijgen et al. [93] have illustrated a diffusion model for the hardening process performed to the steel slag and wollastonite blocks. Santos et al. [94] performed a geochemical modelling of aqueous carbonization equilibria after mineral hardening for argon-oxygen decarburization and continuous casting slags using un-pressurized thin-film and pressurized slurry carbonization methodologies, the parameters including hardening time, temperature, loading

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percentages and gas pressure were optimized. Mattila et al. [95] prepared calcium carbonate blocks by reaction of steel-making slag with ammonium salt solution and then with carbon dioxide at 20-70 °C and atmospheric pressure. The ammonia ratio was essential factor for carbonate precipitation; the chemical kinetic modeling was constructed and confirmed the experimental data. Calcium extraction rate was found to be dependent on slag particle size and structure. Van Zomeren et al. [96] performed the geochemical modelling, leaching experiments and microscopic/mineralogical analysis to control the slag pH and leaching of vanadium after the effective hardening for steel slag at 0.2 bar $CO_2$with water-saturated conditions at 50-90 °C with reducing of pH value and leaching of vanadium. Chang et al. [97] have correlated the experimental data of kinetics of hardening reaction with a surface coverage model. The hardening has got highest carbonization potential (89.4%) for basic oxygen furnace slag slurry containing cold-rolling wastewater after 120 min at room temperature.

Other properties have been listed, such as environmental impact, due to the ability for solid carbon fixation getting useful eco-friendly materials. Minimizing the hardening time that requires lower usage of energy with lower cost, weathering stability and reducing of alkalinity degree of the cured cement are some of other advantages [98,99]. In addition, the related articles have focused on hardening-influencing factors, such as waste type, admixture ingredients, dimensions and pressure of molds, relative humidity, hardening temperature and timing, and particle size. Also for building blocks, the finer size and humidity possess more CO_2 uptake, so more silica/calcite content can be formed in short time. It is necessary to contain a minimum water amount for the capillary porosities. The gas pressure also affects the hardening extent where more pressure lets more gas to be adsorbed getting more calcite, compared with atmospheric pressure at the same hardening conditions [100].

As a whole; the curing mechanism includes precipitation of calcium cations as calcite/silica intermixes in the pores of silicates getting the stable, hard and denser network structures. Such precipitation improves the mechanical and physical properties; the carbonate materials generally promote the major characteristics of different products

[101,102]. Equations 22-24 conclude the overall hardening reactions of different silicates [103]. An extra hardening occurs when CSH is precipitated via hydration/carbonization curing followed by further carbonation, as shown in Equations 25-26 [104,105]. Additionally, equations 27-30 illustrate some information on the thermodynamics of carbonization [106].

$$CaO.SiO_2 + CO_2 \rightarrow \ CaCO_3 + SiO_2 \qquad (22)$$
$$2CaO.SiO_2 + 2CO_2 \rightarrow \ 2CaCO_3 + SiO_2 \qquad (23)$$
$$3CaO.2SiO_2 + 3CO_2 \rightarrow \ 3CaCO_3 + 2SiO_2 \qquad (24)$$
$$3CaO.SiO_2 + yH_2O + (3\text{-}x)CO_2 \rightarrow$$
$$xCaO.SiO_2.yH_2O + (3\text{-}x)CaCO_3 \ (\qquad 25)$$
$$xCaO.SiO_2.yH_2O + (3\text{-}x)CaCO_3 + zCO_2 \rightarrow$$
$$(x\text{-}z)CaO.SiO_2.yH_2O + zCaCO_3 \qquad (26)$$
$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$
$$(\Delta H = -113 \text{ kJ/mol } CO_2) \qquad (27)$$
$$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$$
$$(\Delta H = -81 \text{ kJ/mol } CO_2) \qquad (28)$$
$$CaO + CO_2 \rightarrow CaCO_3 \ (\Delta H = -178 \text{ kJ/mol } CO_2) \quad (29)$$
$$MgO + CO_2 \rightarrow MgCO_3 \ (\Delta H = -118 \text{ kJ/mol } CO_2) \ (30)$$
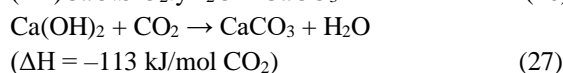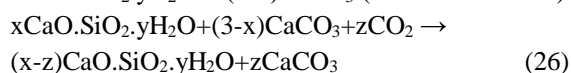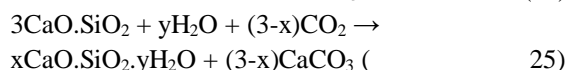
Actually, there is a deficiency in the current related work. Existing research mainly focuses on the chemical reaction of the carbonization process for waste residue and how to capture CO_2 effectively. However, CO_2 capture and storage is the required to complete the chain. This chain is a sustainable and practical technology where only carbonization residue can be used. A promising application is to harden the silicates into useful building block materials while capturing CO_2. The overall consideration provides the best environmental way for utilizing CO_2 waste gas with solid waste like concrete slurry and others to get "eco-friendly" hardened building blocks.

5. Conclusions and future perspectives

Exploitation of solid waste and low-carbon calcium silicate is recommended for producing sustainable construction materials. The carbonization process is proposed for curing via a chemical reaction between CO_2 gas and silicate; the gas is stored in the form of carbonate isomers. This mechanism results in the direct capture of CO_2 gas in stable forms. The main reason for the enhanced mechanical and physical properties of carbonized products and composites is the stable calcium carbonate precipitated during carbonization, and the carbonate/silica gel interface. Calcium and magnesium silicates can be carbonized

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into useful block materials, which can simultaneously solve the problems of solid waste and gas utilization. The main factors affecting carbonization reaction are temperature, gas pressure, silicates' particle size, and humidity. CO_2 pressure should be highly valued, because of the low gas solubility at atmospheric pressure which greatly affects the carbonization rate and gas storage. Environmentally, the accelerated carbonization reaction is aimed for crosslinking low-carbon silicate and industrial solid waste to decrease greenhouse gas emissions. Some questions remain to be studied as future perspectives: How has the structure of silicate evolved in-situ during carbonization? What are the carbonization conditions that give silica gel? What is the diffusion dynamic equation of carbon dioxide in the product? Finally, it can be stated that performing the recommended carbonization reaction by the waste of carbon dioxide gas to solid waste could be a novel future perspective for the possible disposal of the two most harmful waste materials.

6. Conflicts of interest
There are no conflicts to declare.

7. Acknowledgments

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