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CARBON CAPTURE POTENTIAL IN WASTE MODIFIED SOILS: A REVIEW

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ABSTRACT: *Carbonation of lime modified soil could capture carbon dioxide (CO_2) alongside strength improvement for road pavement materials. Due to large amounts of CO_2 emissions and increasing cost of primary soil stabilizers such as lime and cement, the use of lime-based wastes have been encouraged. This paper reviews waste materials based on separate potential for CO_2 capture and strength improvement of soils. Such wastes include cement kiln dust (CKD), saw dust ash (SDA), steel slag, basic oxygen steel (BOS) slag, ground granulated blast furnace slag (GGBS), coal fly ash (CFA) and cattle bone powder (CBP). Based on separated considerations of CO_2 capture and strength improvement, CKD, SDA, BOS and GGBS have shown to have both high CO_2 capture and strength improvement potential for weak soil. Future laboratory studies on lime-based waste (such as CKD and SDA) treated soil for combined CO_2 capture and strength improvement need to be conducted.*

KEYWORDS: Carbon dioxide capture, Lime-based waste, Strength improvement, Weak soil.

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INTRODUCTION

The use of lime in combined carbonation and modification of clay for carbon capture alongside compressive strength improvement have been established (Iorliam *et al*., 2021; Iorliam, 2018). The improved soil could serve as combined carbon capture and road pavement function (Iorliam *et al*., 2021). However, the production of lime itself produces additional carbon dioxide (CO_2) emissions (Stork *et al.,* 2014). Mitigating the effects of increasing CO_2 and other greenhouse gases (GHGs) constitutes another concern to the geotechnical engineering. This is because the effects of these increases is causing the Earth to become warmer (Stocker *et al.,* 2014). Due to large amounts of CO_2 emissions and increasing cost of primary stabilizers such as cement and lime, the use of cheaper and very low CO_2 emissions materials such as waste products in soil improvement have been encouraged (Shillaber *et al.,* 2016).

Previous studies have shown that carbonation of waste materials can bind CO_2 and mitigate excess atmospheric CO_2 concentrations, and hence, mitigate global warming (Gunning *et al*., 2010). The report on CO_2 capture in waste materials is presented in Table 1. These waste materials include bauxite (BX), biomass ash (BA), cement kiln dust (CKD), cement bypass dust (CBD), clinical waste incinerator ash (CWIA), municipal solid waste incinerator bottom and fly ashes (MSWI-BA and MSWI-FA), six paper sludge incineration ashes from different producers (PSIA1–6), pulverised fuel ash (PFA), sewage sludge incinerator ash (SSA), steel wastewater sludge (SWS), and wood ash (WA). From stoichiometry in equation (1) by Steinour (1959), the theoretical carbon dioxide uptake ($ThCO_2$) of the waste materials was estimated.

$$ThCO_2 = 0.785(\text{CaO} – 0.56\text{Ca}CO_3 - 0.7SO_3) + 1.091\text{MgO} + 0.71Na_2\text{O} + 0.468(K_2\text{O} - 0.632\text{KCl}) \quad (1)$$

Also, the measured carbon dioxide uptake (MCO_2) was determined from laboratory experiment. The study reported that the highest $ThCO_2$ of 54% was found in PSIA2, and the corresponding MCO_2 was 12%, followed by $ThCO_2$ of 52% in CBD with corresponding MCO_2 of 26%, and then $ThCO_2$ of 49.5% in WA with the corresponding MCO_2 of 7.5%, etc. The study also determined $ThCO_2$ of 49.0% for ordinary Portland cement (OPC) and the corresponding MCO_2 of 29.5% for benchmark of CO_2 uptake.

Table 1: Theoretical and measured carbon dioxide uptake and degree of carbonation in waste materials (after Gunning *et al.*, 2010)

Waste	Percentage Composition (%) Oxide content (%)											
	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	P_2O_5	K_2O	Na_2O	SO_3	$ThCO_2$	MCO_2	DOC
BX	3.4	79.6	0.06	0	13.6	0.3	0.1	0.03	0.4	0	0	0
BA	5.1	0.3	24.2	8.8	0.7	35.9	21.1	0.3	3.3	37.5	0.4	1.07
CKD	16.4	4.6	45.2	1.5	2.9	0.1	3.9	0.5	22.3	28.0	9.0	32.14
CBD	17.8	4.4	66.3	1.1	2.7	0.1	1.7	0.3	4.6	52.0	26.0	50.00
MSWI-BA	5.2	14.5	33.1	2.8	7.9	1.9	1.1	2.2	27.9	26.5	4.0	15.09
MSWI-FA	32.4	15.8	32.1	3.4	3.4	2.9	0.8	1.8	3.6	26.0	7.0	26.92
PSIA1	20.8	9.3	54.9	1.6	4.7	0.2	0.7	0.1	6.4	40.0	10.5	26.25

PSIA2	19.7	8.3	65.8	1.3	0.8	0.2	0.3	2.1	0.5	54.0	12.0	22.22
PSIA3	25.0	19.0	45.0	5.3	1.1	0.4	1.0	1.2	0.8	37.5	16.5	44.00
PSIA4	23.8	5.5	60.0	1.4	1.7	0.7	0.2	0.3	5.1	49.0	25.0	51.02
PSIA5	10.0	6.8	69.6	1.7	1.0	2.0	0	0	7.0	44.0	24.5	55.68
PSIA6	15.5	8.8	67.4	2.1	0.9	1.9	0.04	0	2.0	52.0	26.5	50.96
PFA	55.6	23.0	1.3	1.0	13.8	0.5	2.7	0.5	0.1	4.0	0	0.00
SSA	39.9	11.2	14.8	2.9	5.6	21.2	2.3	0.7	0.3	15.0	0.5	3.33
SWS	0.8	2.0	7.9	2.6	71.7	0.7	0.1	0.3	8.0	5.0	0	0.00
WA	17.0	2.6	45.5	6.9	1.3	9.0	14.0	0.9	0.6	49.5	7.5	15.15
OPC	19.8	5.2	64.5	2.2	3.5	0	0.2	0.1	2.9	49	29.5	60.20

Note: $ThCO_2$ represents theoretical carbon dioxide uptake. MCO_2 = Experimentally measured carbon dioxide uptake.

DOC = Degree of carbonation

Other studies have shown that waste materials alone can be added to weak soils for improvement. Some of the waste used include, basic oxygen steel (BOS) slag, CKD, bamboo leaf ash (BLA), ground granulated blast furnace slag (GGBS), cattle bone powder (CBP) and saw dust ash (SDA) (Table 2). Generally, the use of these waste in weak soil treatment resulted in remarkable strength (UCS and CBR) and durability improvements. Some of the waste treated soils were adequate for use as capping materials (Iorliam *et al*., 2022) and others achieved soil modification (Poh *et al*., 2006; Iorliam *et al*., 2012a; Iorliam *et al*., 2012b; Iorliam *et al*., 2013; Sharma, & Sivapullaiah, 2016).

However, studies on combined carbon capture and soil improvement in waste treated soil is scarce; this prompted the current research on the review of carbon dioxide capture potential in waste modified soil. The objectives of the current study are to review the CO_2 capture potential of waste materials as well as the geotechnical improvement in waste treated soils based on combined factors of CO_2 uptake and strength improvement, and make recommendations for the waste materials that could achieve the combined properties.

Table 2: Previous soil improvement with waste materials only

Author	Topic	Waste and soil	Property improved
Iorliam *et al.* (2022)	Modification potential of saw dust ash (SDA) on Makurdi clay shale as capping material	SDA and Makurdi shale	Untreated Makurdi shale with UCS of 252 kN/m^2 when treated with 20% SDA, improved to UCS of 440 kN/m^2, 467 kN/$m^2$and 476 kN/m^2 at 7 days, 14 days and 28 days curing respectively. The CBR value of 2% for untreated Makurdi shale increased to a value of 18% at 20% SDA treated Makurdi shale.
Sharma and Sivapullaiah (2016)	Ground granulated furmace slag (GGBS) amended fly ash as an expansive soil stabilizer	Waste binder (70% fly ash + 30% GGBS). High swelling soil (80% BCS + 20% Na-bentonite clay)	GGBS treated expansive soil resulted in strength improvement. The UCS value of 300 kPa for the untreated expansive soil increased to 640 kPa, 710 kPa, and 875 kPa for 7 days, 14 days and 28 days curing at 20% GGBS treated expansive soil.

Iorliam *et al.* (2012a)	Effect of cement kiln dust (CKD) on some geotechnical properties of black cotton soil (BCS)	CKD and BCS	The UCS value of 182 kN/m^2 for untreated BCS increased to maximum values of 1464.6 kN/m^2, 1529.6 kN/m^2 and 2962.2 kN/m^2 for 7, 14 and 28 curing days respectively at 10% CKD treated BCS. The CBR of 2% for untreated BCS increased to 5% for 10% CKD treated BCS.
Iorliam *et al.* (2012b)	Improvement of black cotton soil (BCS) with cattle bone powder (CBP)	CBP and BCS	The UCS value of 182 kN/m^2 for untreated BCS increased to values of 367.12 kN/m^2 , 670.10 kN/m^2 and 1031.10 kN/m^2 for 7, 14 and 28 days curing respectively at 10% CBP treated BCS.
Iorliam *et al.* (2013)	Geotechnical properties of Makurdi shale treated with bamboo leaf ash (BLA)	BLA and Makurdi shale	The UCS value of untreated shale increased from 53.52 kN/m^2 to peak values of 154.6 kN/m^2, 172 kN/m^2 and 182 kN/m^2 at 7, 14 and 28 days, respectively at 20% BLA content. The soaked CBR of 6% for untreated shale increased to a peak value of 18% at 20% BLA treated shale.
Poh *et al.* (2006)	Soil stabilization using basic oxygen steel (BOS) slag fines	BOS slag, English China clay (ECC), mercia mudstone (MM)	The UCS value of 0.7 MPa for untreated ECC increased to the highest value of 1.39 MPa and 1.5 MPa for 7 days and 28 days curing respectively at 20% BOS treated ECC.

Carbonation Processes

Previous studies have been conducted on carbonation processes in lime alone (De Silva *et al.*, 2006), lime treated soils (Iorliam *et al.*, 2021; Cizer *et al.*, 2010; Al-Mukhtar *et al.*, 2010) and cement treated soils (Nakarai & Yoshida, 2015). The summary of the carbonation processes is presented in Table 3. The report shows that carbonation of lime decreases with increasing compacted density. Also, the degree of carbonation (DOC) of lime is usually less than 100% (De Silva *et al.*, 2006; Iorliam *et al.*, 2021). The DOC refers to the experimentally determined carbonates of cation-rich materials compared to the amount of carbonates that would be formed if a complete carbonation of available cations was achieved (Matsushita *et al.*, 2000).

Combined optimum carbonation and strength improvement in lime treated soil is achieved at controlled air voids (Iorliam *et al.*, 2021). In lime-pozzolana mortars, there exists a competition for lime between hydration and carbonation reactions. If curing is under moist conditions, hydration reactions are firstly enhanced, followed by carbonation leading to strength gain. But if curing is under dry conditions, carbonation is enhanced while hydration reactions are slowed down leading to overall reduction in strength (Cizer *et al.*, 2010).

In carbonation of lime treated soil, the amount of calcium carbonate ($CaCO_3$) increases with the amount of $Ca(OH)_2$ addition and curing time (Al-Mukhtar *et al.*, 2010). The concentration of CO_2 influences the rate of carbonation. High CO_2 concentration could achieve a particular carbonation and hence $CaCO_3$ formation in a shorter time compared to low concentration (Nakarai & Yoshida, 2015).

Table 3: Previous carbonation processes in lime or cement

Author	Topic	Materials	Findings
De Silva *et al*. (2006)	Carbonate binders: reaction kinetics, strength and microstructure	Compacted lime	Carbonation of lime is decreased when the density of compacted lime is increased.
Eades *et al*. (1962)	Formation of new minerals with lime stabilization as proven by field experiments in Virginia	Subgrade soils and lime.	Not all lime applied in soil treatment produces calcium silicate. Part of the lime produces $CaCO_3$. For all the soil sections treated with 5% $Ca(OH)_2$, approximately 2.5% $CaCO_3$ was obtained.
Cizer *et al*. (2010)	Competition between hydration and carbonation in hydraulic lime and lime-pozzolana mortars	Hydraulic lime, lime-pozzolana mortars, sand	A combined reaction of hydration and carbonation takes place in hydraulic lime or lime-pozzolana mortars. There exists a competition for lime between hydration and carbonation. Moisture content strongly influences the degree and the order of these reactions. In lime-pozzolana mortars, if curing is under moist conditions, hydration reactions are enhanced, while carbonation is delayed. But if curing is under dry conditions, carbonation is enhanced, while hydration reactions are slowed down leading to overall reduction in strength.
Al-Mukhtar *et al*. (2010)	Behaviour and mineralogy changes in lime-treated expansive soil at 20 ºC	Bentonite (impersol) clay, lime (0–20% content)	They noted that the reflections of XRD patterns for $CaCO_3$ increased with the amount of $Ca(OH)_2$ added and curing time, which was likely due to carbonation of the $Ca(OH)_2$ by CO_2
Nakarai and Yoshida (2015)	Effect of carbonation on strength development of cement treated Toyoura silica sand	Toyoura silica sand, 8% Cement	The concentration of CO_2 influences the rate of carbonation. 8% cement treated Toyoura silica sand cured under accelerated (≈ 5% CO_2) conditions took 91 days to achieve approximately 40% $CaCO_3$ content, while equivalent treated soil cured under sealed natural atmospheric (≈ 0.03% CO_2) condition took 365 days to achieve approximately similar $CaCO_3$ content.
Iorliam *et al*. (2021)	Carbon capture potential in lime modified kaolin clay	Kaolin and lime	Carbonation of lime treated kaolin can produce $CaCO_3$. Carbonation of 8% Ca$(OH)_2$ treated kaolin produced up to 10±0.15% $CaCO_3$ content based on TGA. A control of air voids content could produce desired carbonation and strength improvement. For lime treated kaolin, a compaction to 10% air voids content achieved the combined desired carbonation (10±0.15% $CaCO_3$ content) and strength improvement (280 kPa). This strength is equivalent to CBR value of 29% and was recommended for stabilized capping layer.

MATERIALS AND METHODS

Materials

The description of waste materials previously used in soil improvement is presented below. The waste materials with their corresponding theoretical CO_2 uptake is presented in Table 4.

Table 4: Chemical composition of some wastes with their corresponding theoretical carbon dioxide uptake

Oxide content (%)	Percentage Composition (%)							
	SDA (Iorliam et al., 2022)	BOS (Poh *et al.*, 2006)	CKD (Iorliam *et al.*, 2012a)	CBP (Iorliam *et al.*, 2012b)	GGBS (Sharma & Sivapul-laiah, 2016)	Steel slag (Wu *et al.*, 2019)	CFA Brooks *et al.*, 2011)	Lime (Joel & Agbede, 2008)
SiO_2	16.5	10.78	11.5	3.5	29.2	31.4	55	1.54
Al_2O_3	2.3	1.34	3.1	0.5	13.8	0–4.8	20.3	0.5
CaO	34.1	52.19	67.72	49.15	44.9	52.65	12	67.08
MgO	6.7	5.04			6.2	1	3.5	1.26
TiO_2	0.12		0.35	0.01	2.1		-	0.32
MnO	0.41	2.45	0.12	0.12	-		-	0.05
Fe_2O_3	3.41	10.14	3.55	0.11	5.5	10.2–14.2	6.3	0.03
FeO	-	17.16	-	-	-	-	-	
P_2O_5	2.67	1.28	-	37			-	
K_2O	26.45	0.07	1.14	1.14	1			0.05
Na_2O	1.57	0.07			0.3			0.02
SO_3	0.7		0.78				1.5	
ZnO	0.07		-	0.02			-	
Others						0–5.7	1	
LOI	5.1		8.7	10.61			0.2	26.85
Free lime (%)	-	10.19	-	-	-	-	-	-
CaO/ SiO_2(%)	2.07	4.84	5.89	14.04	1.54	1.68	0.22	43.56
$CaCO_3$	-	-	-	-	-	-	-	-
ThCO_2	47.18	46.55	53.26	39.12	42.69	42.42	12.41	54.07

Saw Dust Ash

Saw dust ash is produced by incineration of saw dust. The SDA used in soil improvement study by Iorliam *et al.* (2022) was obtained as follows. Saw dust was collected from a saw mill yard in Makurdi, Nigeria and was incinerated into ash at the temperature of 1000°C in an oven. SDA passing through sieve no. 200 with a 0.075 mm aperture was used for soil improvement in accordance with BS 3892 (BSI, 1997). The oxide composition and theoretical CO_2 uptake of SDA is contained in Table 4. The major oxides components of the SDA are CaO (34.1%), K_2O

(26.45%), SiO_2 (16.5%) and MgO (6.7%).

The presence of high CaO (34%) which is greater than 20% in SDA is an indication of a material with high reactivity and cementitious properties (Menendez *et al*., 2021). SDA shows high theoretical CO_2 uptake value of 47.18% (Table 4). SDA or wood ash is globally produced in large quantities annually. In Nigeria alone, approximately 8.6 million cubic tonnes of sawdust is generated yearly (Akhator *et al*., 2017).

Basic Oxygen Steel Slag

Basic oxygen steel slag is a by-product of steel production industry particularly from basic oxygen furnace (BOF) method. The steelmaking slag from electric arc furnace (EAF) method is called the EAF slag. The BOS slag used in soil improvement by Poh *et al*. (2006) was supplied by the Tarmac Group, United Kingdom. The main components of the BOS slag are CaO (52.19%), FeO (17.16%), SiO_2 (10.78%), Fe_2O_3 (10.14%) and MgO (5.04%). The high content of CaO (52.19%) which is greater than 20% in BOS slag is an indication of a material with high reactivity and cementitious properties (Menendez *et al*., 2021).

From Table 4, the theoretical CO_2 uptake capacity by BOS is 46.55%. Large quantities of steel slag is generated annually. In 2020, the estimated steel slag production was between 180 million and 270 million tons (USGS 2021). In Nigeria alone, approximately 96 to 145 million metric tons of steel slag is produced yearly (Olonade *et al*., 2015).

Cement Kiln Dust

Cement kiln dust is a by-product of the cement manufacturing industry which is generated during the calcining process in the kiln (Alabadan *et al*., 2005). The dust is a mixture of partially calcined and unreacted raw feed particulate, clinker dust and ash (Wayne & Donald, 2008). The CKD used in soil improvement by Iorliam *et al.* (2012a) was obtained from Benue cement factory, Gboko Benue State, Nigeria. The oxide composition of the CKD shows that the major oxide contents are CaO (67.72%), SiO_2 (11.5%), Fe_2O_3 (3.55%) and Al_2O_3 (3.10%). The composition of CKD shows high CaO content of 67.72% which is greater than 20%, thus indicating that CKD has high reactivity and cementitious properties (Menendez *et al.*, 2021).

The theoretical CO_2 uptake by CKD is 53.26%. CKD waste is abundantly available globally. The amount of CKD generated is equivalent to 17.5% of the amount of cement produced (Van Oss *et al.*, 2003). In 2020, based on the global cement production of 4.4 million tonnes, 770,000 tonnes of CKD were generated globally (USGS, 2022). In Nigeria alone, 58.9 million metric tonnes (MMT) of CKD waste are generated annually (Etim *et al*., 2021).

Cattle Bone Powder

Cattle bone powder is obtained by grinding the incinerated cattle bones to fine powder. The CBP used in soil improvement by Iorliam (2012b) was obtained as follows. Cattle bones were collected from an abattoir in North-Bank market, Makurdi, Nigeria. They were cleaned and sun-dried to reduce their oil content. The bones were incinerated in a furnace at a temperature of 900ºC. Afterwards, the bones were allowed to cool and were later ground in a hammer mill to fine powder. The chemical composition of the CBP shows that the major contents are CaO (49.15%), P_2O_5 (37.0%) and SiO_2 (3.5%) (Table 4). The high CaO content of 49.15% is greater than 20%, which is an indication that CBP has high reactivity and cementitious properties

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(Menendez *et al.*, 2021). It is shown that the theoretical CO_2 uptake capacity of CBP is 39.12% (Table 4). Cattle bones are readily available globally in large quantities at abattoir sites due to a large number of cows that are being slaughtered daily for meat production. In Nigeria, cow bones which are wastes usually litter some cities and villages, thereby constituting environmental pollution.

Ground Granulated Blast Furnace Slag

Ground granulated blast furnace slag is obtained after granulated blast furnace slag is ground into powder. Blast furnace slag is a by-product of pig iron production. GGBS alone has slow cementitious properties (Bijen, 1996). Some GGBS such as is most available in the UK is classified as a latent hydraulic GGBS cement with compositions broadly intermediate between pozzolanic materials and Portland cements (Taylor, 1990). The GGBS used for soil improvement by Sharma and Sivapullaiah (2016) was obtained from Larsen and Toubro ready mix concrete plant, Bangalore, India. The oxide composition of the GGBS shows the major contents as CaO (44.9%), SiO_2 (29.2%), Al_2O_3 (13.8%) and MgO (6.2%) (Table 4). The theoretical CO_2 uptake of GGBS was estimated as 42.69% (Table 4). Large quantities of iron slag is generated annually. In 2020, the global iron slag production was estimated between 310 million and 380 million tons (USGS, 2021).

Steel Slag

Steel slag is a waste from metallurgical industry which is produced during the manufacturing process of steel (Meng & Liu, 2009). The steel slag used for soil improvement by Wu *et al.* (2019) was obtained from a steel processing factory at Jiaxing City, China. The oxide composition of the steel slag is also contained in Table 4. The major oxide compositions are CaO (average 52.65%), SiO_2 (31.4%) and Fe_2O_3 (average 12.2%). The high CaO content of 52.65% is greater than 20% and suggests that the steel slag has high reactivity and cementation properties (Menendez *et al.*, 2021). The steel slag exhibited high theoretical CO_2 uptake value of 42.42% (Table 4). Large quantities of steel slag are generated annually. In 2020, the estimated global steel slag production was between 180 million and 270 million tons (USGS 2021). In Nigeria alone, approximately 96 to 145 million metric tons of steel slag are produced yearly (Olonade *et al.*, 2015).

Coal Fly Ash

Coal fly ash (CFA) is a by-product of coal combustion. Coal combustion is one of the major sources of energy generation such as electricity. The by-product of coal combustion include CFA, bottom ash, slag and flue gas desulphurization (Kutchko & Kim, 2006). The CFA used in soil improvement by Brooks *et al.* (2011) was obtained from Montour plant of PPL Corporation in Washingtonville, Pennsylvania, USA. The oxide composition of the CFA is mainly SiO_2 (55%), Al_2O_3 (20.3%), CaO (12.0%), Fe_2O_3 (6.3%), and MgO (3.5%) (Table 4). The CaO content of 12% which is less than 20% content shows that, the CFA has low reactive and weak cementation characteristics (Menendez *et al.*, 2021). The CFA has the sum of SiO_2, Al_2O_3 and Fe_2O_3 greater than 70%, such can be classified as a pozzolanic material. The theoretical CO_2 uptake of CFA is 12.41% (Table 4).

CFA is abundantly available globally; in the USA alone, nearly 50 million tons of CFA is generated annually (Brooks *et al.*, 2011). Nigeria has large coal reserves of at least 2 billion metric tons of sub-bituminous to bituminous coals and unquantifiable lignite deposits with 650 million tonnes spread over 15 states (EIA, 2008). After Nigerian's independence in 1960, there was a shift from the use of coal to diesel fuel for rail transportation, and later gas for electricity generation. This led to a decrease in coal exploration from almost 1 million metric tons in 1959 to less than 10 thousand tons in 2005 (Nwaobi *et al.*, 2005). Thus, the report on the current amount of CFA production in Nigeria is scarce.

Lime

Lime is a primary stabilizer; however, it is included in this study as a control stabilizer. The lime used for soil as reported by Joel and Agbede (2008) was obtained in Makurdi, Benue State, Nigeria. The oxide composition of the lime shows its major contents as CaO (67.08%), SiO_2 (1.54%) and MgO (1.26%) (Table 4). The high CaO content of 67.08% is greater than 20%, which is an indication of a material with high reactivity and cementitious properties (Menendez *et al.*, 2021). The theoretical CO_2 uptake capacity of lime is 54.07%. Lime is abundantly available, with global production of 430,000 tons annually as at 2021 (USGS, 2022).

Techniques for Confirmation and Quantification of Carbonates

In geotechnical experiment, to confirm the formation of carbonates and to determine their quantity in soil samples, literature has shown different techniques. A summary of these techniques and what information is obtained in each case is presented in Table 5.

One of the techniques that has proven to be effective for this purpose is calcimeter. Basically, $CaCO_3$ content is determined by measuring the gas volume of CO_2 which results from the reaction process of hydrochloric acid with soil lime. Recently, most studies used the Eijkelkamp calcimeter (volumetric calcimeter) to determine the content of carbonate formed in soil (Washbourne *et al.*, 2015; Iorliam *et al.*, 2021). Another important instrument for the measurement of carbonates formed in clay is thermogravimetric analysis (TGA). TGA is usually referred to as a material characterization tool. However, this tool works in a different way compared to the calcimeter. The amount of carbonate formed is determined by subjecting the carbonated soil to heat and the weight loss as a function of temperature is measured. TGA is able to measure discrete quantities of carbonate and other heat-sensitive soil components (Manning *et al.*, 2005). TGA has been successfully applied in studies by Iorliam *et al.* (2021) and Washbourne *et al.* (2015).

Other techniques used for confirmation and quantification of minerals in soils include scanning electron microscopy (SEM) and X-ray diffraction (XRD). Researchers have successfully used SEM to confirm the presence of $CaCO_3$ content based on surface morphology as well as chemical composition (Iorliam *et al.*, 2021; De Silva *et al.*, 2006). XRD has also been used for the confirmation of $CaCO_3$ mineral composition (Al-Mukhtar *et al.*, 2010). The spatial distribution and internal structure of carbonate formation in treated soil could be determined using X-ray computed tomography (XRCT) (Iorliam, 2018).

Table 5: Techniques for confirmation and quantification of carbonates

Property	Calcimeter	TGA	XRD	SEM	XRCT
Calcium carbonate content	✓	✓			
Mineralogical composition		✓	✓		
Chemical composition				✓	
Surface appearance				✓	
Internal structure					✓

RESULTS AND DISCUSSION

Effect of Degree of Carbonation on Carbon Capture Potential

The results presented in Table 1 show that some wastes have high theoretical CO_2 uptake as well as the experimentally measured CO_2 uptake. The ratio between experimentally measured CO_2 uptake and theoretical CO_2 uptake is expressed as DOC. The DOC is a common means to quantify experimentally measured CO_2 uptake of cation-rich material relatively to the theoretical CO_2 uptake (Matsushita *et al.*, 2000). Theoretical CO_2 uptake of waste materials is based on stoichiometry, in this case using Steinour formula as shown in Equation 1 (Steinour, 1959).

From Table 1, the wastes with high DOC include PSIA1-6 (from 26.25%–55.68%), CBD (50%), CKD (32.14%), MSWI-FA (26.92%), WA (15.15%) and MSWI-BA (15.09%). The DOC of these wastes compare favourably with the benchmark DOC of 60.20% from OPC. The theoretical CO_2 uptake of lime-based waste materials is usually less than the experimentally measured CO_2 uptake. Wastes with high free lime are highly reactive and could have high measured CO_2 uptake proportional to the high theoretical CO_2 uptake, and subsequent high DOC (Gunning *et al.*, 2010; Huntzinger *et al.*, 2009). The results in Table 4 show that the following waste materials have high theoretical CO_2 uptake. These include CKD (53.26%), SDA (47.18%), BOS (46.55%), GGBS (42.69%), steel slag (42.42%) and CBP (39.12%). The high theoretical CO_2 uptake of CKD and SDA determined in the current study is consistent with high theoretical and experimental measured CO_2 uptake in the previous study by Gunning *et al.* (2010). SDA is used throughout the current study to also refer to WA, since their originating material is similar.

Effect of Lime-Based Waste Additions to Strength Improvement of Soil

Table 2 shows that the addition of some waste materials to weak soils could remarkably improve the strength (CBR and UCS) properties of the soil.

The addition of lime-based waste to weak soils for strength improvement is well established. In the current study (Table 2), it is shown that the addition of waste materials such as CKD, SDA, BOS, GGBS, CBP and BLA to weak soils resulted in remarkable strength (UCS and CBR) improvement. The improvement of some waste treated soils were adequate for

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application in stabilized capping layer (Iorliam *et al.*, 2022) while others achieved modification of the soil (Poh *et al.*, 2006; Sharma & Sivapullaiah, 2016).

Combined Strength Improvement and Carbon Dioxide Capture Potential in Lime-Based Waste Treated Soil

It is known that CO_2 capture alongside strength improvement can be achieved in lime treated soil (Table 3). From Table 3, it was shown that the control of air voids in carbonated lime treated soil could achieve carbon capture alongside remarkable strength improvement adequate for use as capping layer materials in road pavement (Iorliam *et al.*, 2021). Also, an optimal condition exists in cement treated mortar for successful combined carbonation and hydration reactions (Cizer *et al.*, 2010). The possibility of combined carbonation and modification/hydration processes in waste treated soils would be an indication of successful combined carbon capture and strength improvements. In the current review, some wastes have shown in separate studies that they could be added to weak soils for strength improvement resulting from either modification or hydration reactions. Also the same waste could bind CO_2 resulting from carbonation reaction and hence achieve CO_2 capture. Based on separate considerations of strength improvement and CO_2 uptake, it suggests that CKD and SDA addition to soils have high combined CO_2 capture and strength improvement potential.

CONCLUSION

The current study reviewed waste materials based on separate potentials for CO_2 capture and strength improvement of soils. The following conclusions can be drawn from the study:

- Based on CaO content (Menendez *et al.*, 2021), CKD, steel slag, BOS, CBP, GGBS and SDA can be classified as materials with high reactivity and cementitious properties. CFA can be grouped as materials with low reactivity and low cementitious properties.
- Paper sludge incinerated ashes (PSIA1- 6), CKD, CBD and SDA have exhibited high theoretical CO_2 uptake proportional to high experimental measured CO_2 uptake (Gunning *et al.*, 2010).
- In the current study, the following waste materials have shown high theoretical CO_2 uptake. These include CKD (53.26%), SDA (47.18%), BOS (46.55%), GGBS (42.69%), steel slag (42.42%) and CBP (39.12%). CKD and SDA have shown consistent reports of having high theoretical CO_2 uptake.
- The following waste additions to weak soils have exhibited remarkable strength (UCS and CBR) improvement. These are CKD, SDA, BOS, GGBS CBP and BLA.
- Based on distinct considerations of CO_2 capture and strength improvement, CKD and SDA additions to soils have shown high potentials for combined CO_2 capture and strength improvement.

Further laboratory studies on lime-based waste (such as CKD and SDA) treated soil for combined CO_2 capture and strength improvement need to be conducted.

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