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(54) Title: A METHOD TO ESTIMATE THE ADDITION OF LIME-BASED ACTIVATORS FOR SOIL STABILIZATION WITH GROUND GRANULATED BLAST FURNACE SLAG (GGBS) BASED ON INITIAL PH

(57) Abstract: Herein disclosed is a method for determining an amount of activator to be added to a GGBS-treated soil, the method comprising: determining a prefix amount of a binder based on a water content of a soil sample; determining prefix amounts of the activator based on a mass of a dried sample of soil which the soil sample is prepared from; determining, based on a mass of a wet soil sample, an amount of the binder corresponding to the prefix amount of the binder and amounts of the activator respectively corresponding to the prefix amounts of the activator; mixing each one of the amounts of the activator determined and the amount of binder determined with a soil sample which has a mass equal to the mass of the wet soil sample so as to form soil-activator-binder mixtures; obtaining pH values respectively from the soil-activator-binder mixtures; and establishing a relationship between the pH values and the amounts of the activator corresponding to the pH values so as to identify from the relationship the amount of activator to be added to the GGBS-treated soil.



A METHOD TO ESTIMATE THE ADDITION OF LIME-BASED ACTIVATORS
FOR SOIL STABILIZATION WITH GROUND GRANULATED BLAST
FURNACE SLAG (GGBS) BASED ON INITIAL pH

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Cross-Reference to Related Application

[0001] This application claims the benefit of priority of Singapore Patent Application No. 10202250514H, filed 19 July 2022, the content of it being hereby incorporated by reference in its entirety for all purposes.

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Technical Field

[0002] The present disclosure relates to a method for determining an amount of activator to be added to a soil.

Background

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[0003] Chemical stabilization may effectively mitigate an undesirable property of problematic soils, e.g., soft clay. In this regard, ground granulated blast furnace slag (GGBS) tends to be one of the sustainable chemical for soil stabilization. Ground granulated blast furnace slag may be an industrial by-product, which serves as a binder for stabilizing soil. Compared with traditional binders, such as cement, ground granulated blast furnace slag may achieve higher stabilization efficacy, and its production may emit less CO₂ and consume less energy than that of cement. However, the hydration rate of ground granulated blast furnace slag may be relatively slow.

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[0004] In soil stabilization, an activator may be used to help speed up the hydration rate of ground granulated blast furnace slag. Traditional activators may include by-products from various industries, for example, incineration bottom ash (IBA) and incineration fly ash (IFA). However, such by-products tend to end up being dumped in landfills, causing economic and environmental issues.

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[0005] Notwithstanding the above, the amount of activator to be added may have an effect on one or more properties (e.g., strength) of the soil that contains ground granulated blast furnace slag. For example, an insufficient amount of activator may lead to slow strength development rate or poor strength while excess activator addition may be a cause of (or associated with) long-term deterioration of one or more properties

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(e.g., strength) of GGBS-containing soil. What makes it more difficult is that the amount of activator to be added may vary with soil type and content of GGBS in soil. Traditionally, determination for the amount of activator to add may be conducted by casting a series of stabilized soil specimens, and then testing the unconfined compressive strength (UCS) of these specimens after 28 days of curing or even longer. Such procedure involves laborious experimental work and a considerably long waiting time.

[0006] There is thus a need to provide for a solution that addresses one or more of the limitations mentioned above. The solution should at least provide for a more rapid method to identify (e.g., estimate) the desirable amount of activator to be added to improve stability of GGBS-containing soils.

Summary

[0007] In a first aspect, there is provided a method for determining an amount of activator to be added to a GGBS-treated soil, the method comprising:

- determining a prefix amount of a binder based on a water content of a soil sample;

- determining prefix amounts of the activator based on a mass of a dried sample of soil which the soil sample was prepared from;

- determining, based on a mass of a wet soil sample, an amount of the binder corresponding to the prefix amount of the binder and amounts of the activator respectively corresponding to the prefix amounts of the activator;

- mixing each one of the amounts of the activator determined and the amount of binder determined with a soil sample which has a mass equal to the mass of the wet soil sample so as to form soil-activator-binder mixtures;

- obtaining pH values respectively from the soil-activator-binder mixtures; and

- establishing a relationship between the pH values and the amounts of the activator corresponding to the pH values so as to identify from the relationship the amount of activator to be added to the GGBS-treated soil.

Brief Description of the Drawings

[0008] The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the present disclosure. In the following description, various embodiments of the present disclosure are described with reference to the following drawings, in which:

[0009] FIG. 1A is a table indicating the chemical composition (weight%) of carbide sludge (CS), ground granulated blast furnace slag (GGBS), and marine clay. ND denotes not detected.

[0010] FIG. 1B is a plot of compressive strength ratio and the initial pH of treated slurry with 40 kg/m³ GGBS.

[0011] FIG. 1C is a plot of compressive strength ratio and the initial pH of treated slurry with 60 kg/m³ GGBS.

[0012] FIG. 1D is a table indicating the estimated desirable CS content according to the initial pH and its strength behavior.

[0013] FIG. 1E is a table listing the experimental workload and costs involved in different methods for determining the most desirable CS content.

[0014] FIG. 2A is a table summarizing material parameters of soil stabilization with lime- and CS-GGBS.

[0015] FIG. 2B is a table indicating the chemical composition (in weight % denoted as wt%) of CS, GGBS, ordinary Portland cement (OPC), marine clay, kaolin, and bentonite. ND denotes not detected.

[0016] FIG. 2C is a table indicating the testing programs for CS-GGBS-treated slurry.

[0017] FIG. 3A is a plot of pH of marine clay slurry with 40 kg/m³ GGBS.

[0018] FIG. 3B is a plot of pH of marine clay slurry with 60 kg/m³ GGBS.

[0019] FIG. 3C is a plot of pH of kaolin slurry with 40 kg/m³ GGBS.

[0020] FIG. 3D is a plot of pH of K9B1 slurry with 60 kg/m³ GGBS.

[0021] FIG. 4A is a plot of UCS of marine clay slurry with 40 kg/m³ GGBS.

[0022] FIG. 4B is a plot of UCS of marine clay slurry with 60 kg/m³ GGBS.

[0023] FIG. 4C is a plot of UCS of kaolin slurry with 40 kg/m³ GGBS.

[0024] FIG. 4D is a plot of UCS of K9B1 slurry with 60 kg/m³ GGBS.

[0025] FIG. 5A is a plot of compressive strength ratio and the initial pH of marine clay slurry with 40 kg/m³ GGBS.

[0026] FIG. 5B is a plot of compressive strength ratio and the initial pH of marine clay slurry with 60 kg/m³ GGBS.

[0027] FIG. 5C is a plot of compressive strength ratio and the initial pH of kaolin slurry with 40 kg/m³ GGBS.

5 [0028] FIG. 5D is a plot of compressive strength ratio and the initial pH of K9B1 slurry with 60 kg/m³ GGBS.

[0029] FIG. 6 is a table indicating the CS content estimated according to initial pH and the corresponding UCS ratios.

10 [0030] FIG. 7 is a plot of water content of CS-GGBS-treated marine clay slurry (GGBS content = 60 kg/m³).

[0031] FIG. 8 is a plot of water consumption ratio of CS-GGBS-treated marine clay slurry (GGBS content = 60 kg/m³).

[0032] FIG. 9 is a plot of the x-ray diffraction patterns of untreated marine clay and CS-GGBS-treated marine clay slurry (GGBS content = 60 kg/m³) at 56 days.

15 [0033] FIG. 10 is a plot of TG/DTG curves of untreated marine clay, and CS-GGBS-treated clay slurry (GGBS content=60 kg/m³) at 56 days.

[0034] FIG. 11 is a plot of relative weight loss of CS-GGBS-treated marine clay slurry (GGBS content=60 kg/m³) at 56 days.

20 Detailed Description

[0035] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the present disclosure may be practised.

25 [0036] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be
30 applicable to the same or similar feature in the other embodiments.

[0037] The present disclosure relates to a method for determining an amount of activator to be added to a soil (e.g., a binder-treated soil, such as GGBS-treated soil as

one non-limiting example). The activator can be a lime-based activator (or a magnesia-based activator) and the method is advantageous for determining a desirable amount of such lime-based activator (or magnesia-based activator) for addition into a soil so as to improve stability and strength of the soil. Said differently, the present method can be a method for estimating the addition of lime-based activators (magnesia-based activators) for soil stabilization based on initial pH of the soil. The addition of the lime-based or magnesia-based activators can involve ground granulated blast furnace slag (GGBS) in that the GGBS can already be present in the soil or introduced into the soil via the present method.

[0038] In the present method, lime such as (but not limited to) quicklime, hydrated lime, or other materials with lime as the main component, are activators compatible with GGBS for soil stabilization. Some industry by-products with a high content of lime (e.g., CaO or Ca(OH)₂) can also be used as an activator for GGBS-treated soil in the present method. Such by-products include, and not limited to, carbide sludge (CS), incineration bottom ash (IBA), and incineration fly ash (IFA). The present method is environmentally friendly from the use of such lime-based activators. Traditionally, such lime-based chemicals and by-products tend to be dumped in landfills, causing economic and environmental issues. Hence, the present method recycles waste for improving soil quality.

[0039] Advantageously, the present method is a faster method for determining the amount of activator, such as lime-based and magnesia-based activator, to be added for soil stabilization. Traditional methods tend to determine the content of activator (e.g., lime-based activator) based on the unconfined compressive strength (UCS) results at 28 days or even longer, which involves laborious experimental works and requires a long curing time. In contrast, the present method can estimate the content of an activator (e.g., lime-based or magnesia-based activator) within a few hours by measuring the pH (instead having to measure UCS) of an activator-GGBS-treated soil, which is important for soil stabilization with GGBS. Apparently, aforesaid traditional methods do not rely on the pH to estimate the amount of activator to be added. The traditional methods of relying on UCS also tend to involve laborious laboratory workload of sample casting as well as higher testing costs, which the present method circumvents.

[0040] The present method can be applied to determine the addition of other types of wastes in GGBS-treated soils. This promotes the stabilization efficacy of GGBS in soil treatment as well as the recycling of wastes, which can save the costs of raw materials and reduce the use of non-renewable resources.

5 [0041] Details of various embodiments of the present method, and advantages associated with the various embodiments are now described below. Where the embodiments and advantages are described in the examples section further hereinbelow, they shall not be iterated for brevity.

[0042] The present disclosure describes a method for determining an amount of
10 activator to be added to a soil (e.g., a binder-treated soil, such as a GGBS-treated soil as one non-limiting example). In various embodiments, the method comprises determining a prefix amount of a binder based on a water content of a soil sample. In various embodiments, the method comprises determining prefix amounts of the activator based on a mass of a dried sample of soil (understandably the dried sample of
15 the “soil” is from the soil which aforesaid soil sample is prepared from). In various embodiments, the method comprises determining, based on a mass of a wet soil sample, an amount of the binder corresponding to the prefix amount of the binder and amounts of the activator respectively corresponding to the prefix amounts of the activator. In various embodiments, the method comprises mixing each one of the amounts of the
20 activator determined and the amount of binder determined with a soil sample which has a mass equal to the mass of the wet soil sample so as to form soil-activator-binder mixtures. In various embodiments, the method comprises obtaining pH values respectively from the soil-activator-binder mixtures, and establishing a relationship between the pH values and the amounts of the activator corresponding to the pH values
25 so as to identify from the relationship the amount of activator to be added to the soil (e.g., a binder-treated soil, such as a GGBS-treated soil).

[0043] In the context of the present disclosure, the soil (e.g., a binder-treated soil, such as a GGBS-treated soil) may comprise a solid soil and water. The present method is applicable to a variety of soil having different amounts of water. The soil can be in its
30 slurry form. In other words, the term “soil” herein encompasses a slurry. A non-limiting example of the soil can be clay and its slurry form is a clay slurry.

[0044] In various embodiments, the activator may be a lime-based activator or a magnesia-based activator. The lime-based activator may comprise quicklime, hydrated lime, carbide sludge, or any mixture (e.g., a lime-based mixture) that produces Ca(OH)_2 when mixed with water. The main component of quicklime (i.e., CaO) is different from
5 hydrated lime (i.e., Ca(OH)_2), but quicklime can react with water in the pores of soil more quickly and ultimately generates Ca(OH)_2 , hence rendering the same effect as Ca(OH)_2 for soil stabilization. The magnesia-based activator may comprise magnesia, or any mixture (e.g., a magnesia-based mixture) that produces Mg(OH)_2 when mixed with water.

10 [0045] In various embodiments, the present method may further comprise determining the water content of the soil sample. Determining the water content of the wet soil may comprise obtaining an initial wet soil sample, weighing the initial wet soil sample, drying the initial wet soil sample to obtain the dried sample of the soil, weighing the dried sample of the soil, and calculating the water content by dividing the difference
15 between the initial wet soil sample and the dried soil sample with weight of the dried soil sample. The phrase “initial wet soil sample” is used to refer a wet soil sample extracted from a soil to be tested for determining the water content of the soil.

[0046] In various embodiments, determining the prefix amount of the binder based on the water content may comprise identifying a liquid limit of the dried soil sample, and
20 identifying the prefix amount of the binder by comparing the water content with the liquid limit to determine whether (i) the water content is less than the liquid limit or (ii) the water content is equal to or more than the liquid limit. Identifying the liquid limit of the dried soil sample may be carried out via Casagrande method or the cone penetration method, both of which (i.e., the Casagrande method and the cone
25 penetration method) are known methods in the field of geotechnical engineering.

[0047] In various embodiments, the prefix amount of the binder may be 10% to 30% by mass of the dried soil sample if the water content is less than the liquid limit, or 5% to 10% by mass of the dried soil sample if the water content is equal to or more than the liquid limit.

30 [0048] In various embodiments, determining the prefix amounts of the activator based on the mass of the dried soil sample may comprise identifying 5 to 10 (e.g., 7 or 8) prefix amounts of the activator based on the mass of the dried soil sample.

[0049] In various embodiments, the 5 to 10 prefix amounts may range from 1% to 5% by mass of the dried soil sample with each prefix amount differing from each other by 0.25% to 1% by mass of the dried soil sample.

[0050] In various embodiments, determining, based on the mass of the wet soil sample, the amount of the binder corresponding to the prefix amount of the binder and the amounts of the activator respectively corresponding to the prefix amounts of the activator may comprise calculating the amount of the binder based on the formula: $M_G = M_S / (1 + W) * C_G$, wherein M_G is the mass of the binder corresponding to the prefix amount of the binder, M_S is the mass of the wet soil sample, W is the water content, and C_G is the prefix amount of the binder, and calculating each of the amounts of the activator based on the formula: $M_A = M_S / (1 + W) * C_A$ wherein M_A represents one of the masses of the activator corresponding to one of the prefix amounts of the activator, M_S is the mass of the wet soil sample, W is the water content, and C_A represents one of the prefix amounts of the activator.

[0051] In various embodiments, the mass of the wet soil sample may be 100 g to 300 g (e.g., 100 g to 200g, 200 g to 300 g). This mass allows for extraction of sufficient filtrate in a subsequent step of the present method, which is a step involved in obtaining the pH values from the soil-activator-binder mixtures.

[0052] In various embodiments, mixing each one of the amounts of the activator determined and the amount of binder determined with a soil sample which has a mass equal to the mass of the wet soil sample so as to form soil-activator-binder mixtures may comprise mixing each one of the amounts of the activator determined with the amount of binder determined to form activator-binder mixtures, and mixing each one of the activator-binder mixtures with the soil sample to form the soil-activator-binder mixtures. In certain non-limiting embodiments, mixing each one of the amounts of the activator determined and the amount of binder determined with a soil sample which has a mass equal to the mass of the wet soil sample so as to form soil-activator-binder mixtures may comprise mixing directly each one of the amounts of the activator determined and the amount of binder determined with the soil sample to form soil-activator-binder mixtures. Said differently, the activator and the binder can be first mixed prior to mixing with the soil sample or the activator and the binder can be mixed directly into the soil sample.

[0053] In various embodiments, the present method may further comprise preparing a plurality of the wet soil samples, which is a wet sample, for mixing with each of the activator-binder mixtures to form the soil-activator-binder mixtures.

5 [0054] In various embodiments, mixing each one of the activator-binder mixtures with the soil sample to form the soil-activator-binder mixtures may comprise placing the soil-activator-binder mixtures in separate containers, and mixing each of the soil-activator-binder mixtures for several times within a duration of 1 hour to 24 hours. This helps promote the dissolution of the activator and the binder, as well as any reaction between the activator and the binder.

10 [0055] In various embodiments, obtaining pH values respectively from the soil-activator-binder mixtures may comprise (i) extracting a portion of one of the soil-activator-binder mixtures, (ii) centrifuging the portion to obtain a filtrate and a residue, (iii) measuring the pH of the filtrate, and (iv) repeating steps (i) to (iii) to obtain the pH value of the other soil-activator-binder mixtures.

15 [0056] In various embodiments, establishing a relationship between the pH values and the amounts of the activator corresponding to the pH values so as to identify from the relationship the amount of activator to be added to the soil (e.g., a binder-treated soil, such as a GGBS-treated soil) may comprise plotting each of the pH values against one of the amounts of the activator used in forming one of the soil-activator-binder mixtures
20 which the pH value is correspondingly derived from to form a pH-activator content plot, and identifying from the pH-activator content plot the amount of activator to be added to the soil (e.g., a binder-treated soil, such as a GGBS-treated soil). Most soils may vary in pH from 4 to 10. The pH of a saturated $\text{Ca}(\text{OH})_2$ solution lies in the range of 12.3 to 12.6, while that of a saturated $\text{Mg}(\text{OH})_2$ solution lies in the range of 10.6 to
25 11, depending on clay types. With the increase of activator content, the pH of the soil-activator-binder mixtures increased first and then remained constant owing to the saturation of $\text{Ca}(\text{OH})_2$ or $\text{Mg}(\text{OH})_2$. Based on the pH-activator content plot, the minimum activator content required to obtain a saturated $\text{Ca}(\text{OH})_2$ or $\text{Mg}(\text{OH})_2$ solution is the desired amount of activator to be added to a GGBS-treated soil.

30 [0057] In any case to understand the present method better, various non-limiting examples of the steps of the present method are described in the examples section hereinbelow.

[0058] The word “substantially” does not exclude “completely” e.g. a composition which is “substantially free” from Y may be completely free from Y. Where necessary, the word “substantially” may be omitted from the definition of the present disclosure.

5 [0059] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0060] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

10 [0061] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0062] Unless specified otherwise, the terms “comprising” and “comprise”, and grammatical variants thereof, are intended to represent “open” or “inclusive” language such that they include recited elements but also permit inclusion of additional, unrecited elements.

15

Examples

[0063] The present disclosure relates to a method for determining (e.g., estimating) a desirable amount of lime-based activator in a short period of time (e.g., in a few hours) by measuring the pH of the soil that is treated with such lime-based activator.

20 [0064] The present method advantageously addresses the rapid estimation of the desired content of lime-based activator for activator-GGBS-treated soil. The present method can be applied to GGBS-treated soils (one example of a binder-treated soil) using lime-based activators to significantly reduce the laboratory workload, materials consumption, curing time, and testing costs for determining the most desirable activator content. In soil stabilization projects, the present method can considerably shorten the construction period, which further decreases the construction cost and avoid the risk of project delays. In the context of the present disclosure, the most desirable activator content (the desired amount of activator) refers to the amount of activator to be added based on the initial pH curve, wherein the lowest activator content after which two
25 successive activator addition presented a negligible increase in pH is selected as the
30 desired content. This activator content can also be regarded as the minimum activator

content required to obtain a saturated activator solution for treated soil. The desired activator content can also lead to an increase in UCS.

[0065] In addition, the present method promotes the recycling of carbide sludge (CS) and other types of wastes, which can mitigate the landfilling demand for wastes to save the costs and taxes for landfills and waste treatments. The utilization of wastes in construction reduces the activator costs, and mitigates the environmental issues related to cement production. In various examples of the present disclosure, such as the various examples below, the expression “wt%” denotes for weight percent.

[0066] The present method is described in further details, by way of non-limiting examples, as set forth below.

[0067] Example 1A: General Description of a Non-Limiting Example of the Present Method

[0068] The present method can include the following steps:

[0069] Step 1. A representative sample of the soil was prepared, and the water content (W) of soil evaluated using the following procedure. First, the mass of a container (M_c) was weighed and a certain mass of soil (i.e., “wet soil”) was placed into the container. Then, the mass of the container with wet soil (M_{c_ws}) was weighed. The container and soil were placed into an oven to dry it until the mass of the container and soil remained constant. Finally, the mass of the container with the dry soil (M_{c_ds}) was weighed. The water content (W) of the soil was calculated using:

$$W = (M_{c_ws} - M_{c_ds}) / (M_{c_ds} - M_c) \quad (1)$$

[0070] It is to be noted that step (1) is optional. For example, if the water content of the soil is already known, then this step may not be needed.

[0071] Step 2. Based on the water content of soil and the target strength of GGBS-treated soil, the GGBS content (CG) to be used in soil stabilization was determined. For natural soft clay with a water content lower than or close to its liquid limit (e.g., 30 wt%-50 wt%), the GGBS content of 10-30 wt% of dry soil is used to increase the UCS to magnitudes of 100 kPa to 1000 kPa for foundation and excavation applications. While for the stabilization of high water content clay slurry (i.e., water content greater than its liquid limit), the GGBS content of 5 wt%-10 wt% of dry soil is considered to convert slurries to solid form with the target UCS of 10 kPa to 100 kPa as fill for land reclamation. The term “liquid limit” in the present disclosure refers to the water content

at which the soil changes from the liquid state to a “plastic state”. In other words, “liquid limit” can be considered the minimum water content at which soil flows upon application of a very small shear force.

[0072] Step 3. Various activator contents (CA) from 1 wt% to 5 wt% of the dry soil (in
 5 stepwise increment of 0.25 wt%-1 wt%) were prepared. The activator in various
 examples of the present disclosure are lime-based activator of GGBS (e.g., quicklime
 or carbide sludge). Generally, the number of activator contents (N) used can be 5 to 10.
 The range of activator content can be adjusted based on soil properties and GGBS
 content. The activator addition should be able to increase the pH of GGBS-treated soil
 10 up to 12.4 or higher.

[0073] Step 4. The mass of wet soil samples (Ms) considered for testing in various
 examples were to be 100 g to 300 g, depending on the water content of soil. Generally,
 the lower the water content, the higher the mass of soil is required. Thereafter, the
 corresponding GGBS mass (MG) was calculated as follows:

$$15 \quad MG = Ms/(1+W)*CG \quad (2)$$

[0074] where Ms is the mass of soil samples, W is the water content of wet soil, and CG
 is the prefixed GGBS content.

[0075] Similarly, the corresponding activator mass (MA) can be calculated:

$$MA = Ms/(1+W)*CA \quad (3)$$

20 [0076] where CA is the prefixed activator content.

[0077] Step 5. Based on the number of activator contents (N) determined in step 3, N
 batches of wet soil samples were prepared. Thereafter, N batches of GGBS and activator
 were prepared, respectively. One of the N batches of activator samples was added to
 one of the GGBS samples. The activator content on the container was labeled, and the
 25 activator and GGBS were homogenously mixed using a clean plastic rod. Afterward,
 this procedure was repeated for the remaining ($N-1$) activator and GGBS samples.

[0078] Step 6. The N batches of wet soil with the N batches of activator-GGBS mixtures
 were mixed in respective plastic bottle with a clean plastic rod for 30 to 60 seconds
 until a homogenous mixture was obtained. Afterward, the bottle was sealed and the
 30 soil-activator-GGBS mixtures were mixed for 30 seconds every 10 minutes for one
 hour.

[0079] Step 7. After the one-hour mixing, around 100 mL of the mixtures was taken and split into two 50 ml centrifuge tubes. Then, the tubes were placed in a centrifuge for 5 mins at 5,000 revolutions to separate “pore water” and any solid at 25°C. Then, the centrifuged “pore water” was collected and the pH value of the centrifuged “pore water” was measured using a pH meter with an accuracy of 0.01 pH units, and the pH with the corresponding activator content was recorded. This pH value is defined as the initial pH of activator-GGBS-treated soil. The term “pore water” in the present disclosure refers to water contained in pores of soil.

[0080] Step 8. The activator content and the corresponding pH of treated soil together was plotted. With the increase of activator content, the pH value of activator-GGBS-treated soil increased initially, and then remained nearly constant. Based on the initial pH curve, the lowest activator content after which two successive activator addition presented a negligible increase in pH is selected as the most desirable activator content. This content was regarded as the minimum activator content required to obtain a saturated lime-based activator (e.g., $\text{Ca}(\text{OH})_2$) solution for the treated soil.

[0081] To demonstrate the above steps, a non-limiting example is discussed below in example 1B.

[0082] **Example 1B: Non-Limiting for Demonstrating Example 1A**

[0083] The present example demonstrates the feasibility of the present method for determining (e.g., estimating) a desirable lime-based activator (CS) content of GGBS-treated clay slurry (e.g., CS-GGBS-treated clay slurry).

[0084] Singapore marine clay slurry was prepared and treated by CS-GGBS, wherein carbide sludge (CS) was used as the activator. The GGBS was purchased from a local supplier. The CS was collected from a local gas company. After collection, CS was pre-treated by oven-drying at 105°C, and the dry CS was then manually ground and sieved (300- μm) before use. As shown in FIG. 1A, the chemical composition of these raw materials was obtained through X-ray fluorescence (XRF).

[0085] In this example, two GGBS contents (40 and 60 kg/m^3), i.e., 5.6 wt% and 8.4 wt% of dry soil, were used for slurry treatment. In addition, seven CS contents (5 to 17 kg/m^3 - 2 kg/m^3 stepwise increment from 5 to 17 kg/m^3), i.e., 0.7 wt% to 2.4 wt% of dry soil were used.

[0086] Following step 1 of example 1A, the clay slurry with a water content of 100 wt% was used.

[0087] Following step 2 of example 1A, two GGBS content, i.e., 40 and 60 kg/m³ (5.6 wt% and 8.4 wt% of dry soil), were used.

5 [0088] Following step 3 of example 1A, seven CS contents from 5 to 17 kg/m³ (0.7 wt% to 2.4 wt% of dry soil) with 2 kg/m³ stepwise increment from 5 to 17 kg/m³ were used.

[0089] Following step 4 of example 1A, the mass of wet soil was determined to be 100 g. Corresponding GGBS content are 2.8 g (5.6 wt% of dry soil) and 4.2 g (8.4 wt% of dry soil); the seven CS contents used are 0.35, 0.49, 0.63, 0.77, 0.91, 1.05, and 1.19 g.

10 [0090] Following step 5 of example 1A, fourteen samples of clay slurry equal to 100 g were prepared. Seven samples of 2.8 g GGBS, and seven samples of 4.2 g GGBS were prepared separately. Afterward, seven CS samples of 0.35, 0.49, 0.63, 0.77, 0.91, 1.05, and 1.19 g were mixed with the seven samples of 2.8 g GGBS, respectively. Seven CS samples of 0.35, 0.49, 0.63, 0.77, 0.91, 1.05, and 1.19 g were mixed with the seven samples of 4.2 g GGBS, respectively.

[0091] Following step 6 of example 1A, the seven CS-GGBS mixtures (GGBS = 2.8g) were mixed with the seven samples of clay slurry, respectively. The seven CS-GGBS mixtures (GGBS = 4.2g) were mixed with the seven samples of clay slurry, respectively.

20 [0092] Following steps 7 and 8 of example 1A, the pH of these fourteen samples were evaluated. The desired CS content was determined as 15 kg/m³ for the treated slurry with 40 kg/m³ (5.6 wt%) GGBS, and 17 kg/m³ for the treated slurry with 60 kg/m³ (8.4 wt%) GGBS.

25 [0093] A traditional method was also conducted to determine the desirable CS content based on the UCS of CS-GGBS-treated slurries at 28 and 56 days. The UCS of these samples were evaluated in triplicate. For the fourteen CS-GGBS mixtures used in this example, six cylindrical specimens (50 mm diameter and 100 mm height) of each mixture were cast (84 specimens in total) and tested at the prefixed curing ages. Then, the most desirable CS content based on the UCS could be obtained For each mixture, the initial pH and UCS ratio (the UCS of treated slurry divided by the maximum UCS at the same curing age) are plotted against the CS content in FIG. 1B and FIG. 1C.

30 [0094] The profiles of the initial pH and UCS ratio are quite similar. As shown in FIG. 1D, the estimated desirable CS content based on pH, as well as the corresponding UCS

ratio of specimens are listed. The specimens with the estimated CS contents could achieve a high level of UCS (at least 91% of the maximum UCS) at 28 and 56 days.

[0095] The experimental work and costs involved in the two methods are listed in FIG. 1E. Compared with the traditional method, the present method shows considerable advantages. Therefore, instead of casting lots of CS-GGBS-treated specimens and measuring their UCS after 28 or 56 days of curing, the most desirable CS content can be quickly estimated by mixing the binders and soft clay, and measuring the initial pH one hour later.

[0096] **Example 2A: General Discussion of a Non-Limiting Example on Addition of Carbide Sludge as Activator for Enhancing Strength Development of Ground Granulated Blast Furnace Slag-Treated Slurry based on Initial pH (Present Method)**

[0097] The use of carbide sludge (CS)-ground granulated blastfurnace slag (GGBS) for clay slurry treatment has shown superior strength performance compared with ordinary Portland cement (OPC). There exists a desirable CS content to achieve the maximum unconfined compressive strength (UCS) of CS-GGBS-treated slurry, but this content may vary with soil type and GGBS content. The desired CS content is traditionally determined by evaluating the UCS at 28 or 56 days. However, in the present example, the present method is demonstrated as a rapid method that can determine (e.g., estimate) a desirable CS content in one hour by measuring the pH, instead of UCS, of CS-GGBS-treated slurry. Results show that the 28-day and 56-day UCS versus CS content curves of CS-GGBS-treated slurries were quite similar to their one-hour pH profiles. Hence, the pH versus CS content profile could be used to estimate the CS content, i.e., the minimum CS content required to obtain a saturated activator (e.g., $\text{Ca}(\text{OH})_2$) solution was estimated as the desired CS content. The CS-GGBS-treated slurry with the estimated CS content based on initial pH achieved a high strength level ($\geq 91\%$ of the maximum UCS) after curing for 28 and 56 days. Additionally, the thermal gravimetric analysis (TGA) results further indicated that excess CS addition beyond aforesaid desired CS content led to the generation of more hydrotalcite phases, but less calcium silicate hydrate (CSH), which contributed to the strength difference.

[0098] By way of background, port maintenance and coastal development may generate billions tonnes of dredged clay slurry every year. These dredged materials may have an

ultra-high water content and hence present poor engineering properties, including negligible shear strength and great compressibility. Chemical stabilization can effectively mitigate these undesirable properties of dredged clay slurry to prepare it as fill material for engineering applications. The application of this technique to land reclamation has been widely reported, in which binders were mixed with dredged clay slurry to improve the unconfined compressive strength (UCS) to 10-100 kPa. For this type of application, a relatively low binder content, usually no more than 90 kg/m³, was used. Ordinary Portland cement (OPC) was commonly utilized in ground improvement projects over the past decades. However, OPC presents relatively low efficacy in the treatment of clay slurry when a relatively low binder dosage is used. Moreover, OPC manufacture induced high energy consumption (3,300 MJ per tonne) and CO₂ emission (0.7-0.8 tonnes per tonne). Therefore, many attempts have been carried out to reduce OPC usage by blending it with other materials (e.g., cement-fly ash, cement-slag), or using sustainable alternatives.

[0099] The application of ground granulated blastfurnace slag (GGBS) as in the present method, in clay stabilization has gained great interest. GGBS is an industrial by-product containing high content of aluminosilicates and calcium compounds. The sole use of pure GGBS in soil stabilization tends to yield very slow strength development, and quicklime or hydrated lime are employed to enhance the strength development of GGBS-treated soils. Reactions between GGBS and alkaline can facilitate geopolymer synthesis. The generation of aluminosilicates, calcium silicate hydrate (CSH), ettringite, and hydrotalcite phases in GGBS specimens, can significantly improve the mechanical properties of the treated soil. To reduce the carbon footprint associated with lime production, carbide sludge (CS), another by-product manufactured in the acetylene industry, is used to substitute lime in GGBS-treated soil. CS mainly consists of Ca(OH)₂ (>80 wt%) and CaCO₃ (~10 wt%), and a large number of CS is generated worldwide, e.g., about 28 million tonnes in China per year. Currently, CS has been used for CO₂/SO₂ capture and contaminated soil treatment but the total utilization rate of CS is smaller than 20%. Hence, the use of CS-GGBS in soil improvement as demonstrated in the method of the present disclosure has the potential to recycle CS and reduce the environmental issues caused by lime manufacture.

[00100] The lime/CS content affects the strength of GGBS-treated soil. Insufficient lime/CS content retards polymerization process and thus affect strength improvements, while excess lime/CS addition is often associated with deteriorated long-term strength performance. FIG. 2A summarizes the material parameters of soil stabilization with lime- and CS-GGBS. These results show that there is a desirable CS or lime dosage to achieve the highest UCS of CS-GGBS-treated soils, and the lime/CS-to-GGBS ratio may change with soil type, GGBS content, water content, and curing age. As shown in FIG. 2A, the lime/CS-to-GGBS ratio for treated soils happens to lie in a range of 10 wt%-33 wt%, and is around 5 wt%-10 wt% for lime- and CS-GGBS pastes (i.e., binder-water mixture without soil). The large variation of the lime/CS-to-GGBS ratio makes the configuration for one soil considerably difficult to predict for other soils, including dredged clay slurry with a low GGBS content and ultra-high water content. Traditionally, the determination of optimum lime/CS content requires the cast of many specimens, and a waiting period of 28 days or longer to obtain the UCS results. Such traditional procedure involves laborious experimental work and long curing periods. Therefore, a rapid method to estimate the CS content for CS-GGBS-stabilization is of great interest for engineering applications, which the present method affords.

[00101] **Example 2B: Materials and Methods – Materials**

[00102] Three types of clay slurries made from marine clay, kaolin, and kaolin-bentonite mixture (90 wt% kaolin and 10 wt% bentonite, K9B1 in short) were stabilized by CS-GGBS.

[00103] The marine clay was collected in Singapore. Kaolin and bentonite purchased in Singapore were used to prepare slurry. The GGBS was obtained from EnGro Corporation Limited, and OPC (grade 42.5) provided by Buildmate Pte Ltd, Singapore, was used as control. The CS collected from WKS Industrial Gas Pte Ltd, Singapore, was oven-dried at 105°C, and then manually ground and sieved (300-μm) before use. As shown in FIG. 2B, the chemical composition of these raw materials was obtained through X-ray fluorescence (XRF). The liquid limits of marine clay, kaolin, K9B1 were 60 wt%, 58 wt%, and 74 wt% respectively, and the plastic limits of these clays were 24 wt%, 23 wt%, and 30 wt% respectively. The dredged marine clay slurry usually had a water content 2-5 times its liquid limit, depending on the dredging techniques and dredging locations. Afterwards, the dredged materials are dumped at the reclamation

site for sedimentation under self-weight before chemical stabilization. To obtain the practical water content of clay slurries upon stabilization, sedimentation tests were conducted. The initial water content of these clay slurries was adjusted to 4 times its liquid limit. Afterwards, the slurries settled under self-weight in a 1000 mL cylindrical column, and the settlement (the decline in the interface between soil slurry and bleed water) was recorded. After one month, the settlement was steady, and the sedimented Singapore marine clay, kaolin, and K9B1 slurry had a water content of 101 wt%, 79 wt%, and 146 wt% respectively. Therefore, the initial water contents of 100 wt%, 80 wt%, and 150 wt% were selected for these types of clay slurries.

10 **[00104] Example 2C: Materials and Methods – Mixing Proportions**

[00105] For examples 2A to 2J, binder content was taken as the mass of binder added to one cubic meter of clay slurry. For marine clay slurry, two GGBS contents, 40 and 60 kg/m³, were used, while for kaolin and K9B1 slurry, 40 kg/m³ and 60 kg/m³ GGBS were used, respectively. CS contents from 5 kg/m³ to 17 kg/m³ (with a stepwise increment of 2 kg/m³) were used to determine the CS content for these stabilized slurries. The selection of these CS contents was based on preliminary tests. In the examples, OPC was used as a control, and the OPC contents were the same as the GGBS contents. The mix proportions and testing program of CS-GGBS-treated slurry are shown in FIG. 2C. The selection of these binder contents took into consideration preliminary testing results.

20 **[00106] Example 2D: Materials and Methods – Testing Procedure**

[00107] For sample preparation, the binder and clay slurry were blended in a mixer for 10 minutes. Afterwards, the fresh mixture was then cast into cylindrical molds (50 mm diameter and 100 mm height), and careful manual vibration was performed to remove air bubbles. The top of molds was then covered with polythene sheet, and specimens were stored in zipper bags. Specimens in zipper bags were stored in a moist room at 26±2°C with 98±2% humidity.

[00108] The pH of CS-GGBS-treated slurry was tested at 1, 2, and 3 hours after mixing (FIG. 2C), aiming to investigate the short-term pH change. For comparison, the pH of the CS-clay mixture with the CS content increased from 5 to 17 kg/m³ (with a stepwise increment of 2 kg/m³) was also tested. Two methods were used for pH measurements depending on the curing periods. In the first few hours after the mixing, the stabilized

clay slurry was still in a slurry form. Thus, the centrifugal extraction method was used to extract pore water from the clay slurry for pH measurement. In this technique, around 40 mL sample was put into a 50 ml centrifuge tube and the mixture was shaken as per ASTM D6276 (ASTM 2006). The specimens were then placed in a centrifuge for 5 mins at 5,000 revolutions to separate pore water and solid. The extracted pore solution was then used for pH measurement using the Laqua-1100 pH meter. While at 7, 28, and 56 days, the stabilized clay gained considerable strength, and the centrifugal extraction method was no longer applicable. Following the procedure indicated by ASTM D4972 (ASTM 2019), 10 g of the dry sample was crushed and sieved through a 75- μ m sieve, and was then mixed with 10 g of distilled water to conduct pH measurement after waiting for one hour. The pH value obtained by this method was reported to be close to the pH obtained from extracted pore water.

[00109] The UCS of specimens at each curing period was measured in triplicate per ASTM-D2166 (ASTM 2013). After UCS tests, crushed samples of stabilized marine clay slurry at 7 and 56 days were dried by using freeze-drying method for water content measurement and other analyses. Dry samples were then finely ground to pass through 75- μ m sieves to conduct XRD testing with Bruker D8 X-ray diffractometer. PerkinElmer TGA 4000 was used to perform TGA tests from 30°C to 900°C (10 °C/min) in a nitrogen atmosphere.

20 [00110] **Example 2E: Results and Analysis – pH**

[00111] The pH values of these three types of clay slurries with the addition of CS and/or GGBS are plotted in FIG. 3A to 3D. The marine clay, kaolin, and K9B1 slurry had a pH of 7.22, 4.39, and 6.83, respectively. When only CS was added, there was a remarkable increase in the pH of these clay slurries. The pH of kaolin slurry with 5 kg/m³ CS was relatively lower than that of other types of clay slurry, which was because kaolin had the lowest pH (~4.4). For all types of clay slurry, its pH increased with increasing CS content until Ca(OH)₂ was saturated, and a CS content of 7-13 kg/m³ was required to achieve saturated aqueous Ca(OH)₂. The pH of CS-slurry remained constant at 1, 2, and 3 hours after the homogeneous mixing of raw materials, and hence only the data at 1 hour after mixing was plotted. The addition of pure GGBS to clay slurries also lead to the increase of pH up to a range of 9-11, depending on soil type and GGBS

content. This is because the dissolution of GGBS absorbs H^+ in the pore solution, leading to an increase in pH.

[00112] When CS and GGBS were added together, the pH of these specimens was slightly higher than that of CS-slurry. Additionally, the pH of clay slurry with CS-GGBS addition remained nearly unchanged in the first three hours as shown in FIG. 3A to 3D. Hence, the initial pH was defined as the pH of CS-GGBS-treated slurry measured at 1 hour after mixing. The initial pH of CS-GGBS-treated slurry was very close to that of the CS-slurry, indicating that the initial pH of CS-GGBS-treated slurry was mainly controlled by CS content, and the influence of GGBS hydration on pH was insignificant in this short period.

[00113] While at 7, 28, and 56 days, the difference among the pH of treated specimens with varying CS content was relatively small. As shown in FIG. 3A to 3D, a more flattened pH profile was shown at 56 days, and the pH of these CS-GGBS-treated slurries was in the range of 11-12, consistent with the typical pH regime of GGBS hydration products such as CSH. Reported works also indicate approximating pH level of 11-12.2 for GGBS-treated soil. This is because, at longer curing ages, the $Ca(OH)_2$ induced by CS was consumed in the reactions with GGBS and clay minerals to generate hydration products, resulting in the enhancement of soil strength. Therefore, the pH values of specimens at long curing ages were mainly controlled by hydration products. Nonetheless, the kaolin slurry stabilized by pure GGBS, which still had a remarkably lower pH than the CS-GGBS-treated kaolin after 56-day curing. This is because the kaolin slurry has a low pH value (4.39), which delayed GGBS hydration, and thus the increment in pH caused by GGBS hydration was minimal.

[00114] **Example 2F: Results and Analysis – UCS**

[00115] The UCS of CS-GGBS-treated slurries at 7, 28, and 56 days is shown in FIG. 4A to 4D. At 7 days, all pure GGBS-treated slurries were unable to be demolded, and the CS-GGBS treated kaolin and K9B1 with 5 kg/m^3 CS also presented no strength. Hence, GGBS could not stabilize these slurries without sufficient CS addition (CS content $\geq 5 \text{ kg/m}^3$) at an early age. The specimens that yielded minimal strength at 7 days had a lower initial pH than the other specimens (FIG. 3A to 3D). Moreover, the pure GGBS-treated kaolin slurry, with an initial pH of ~ 9 , even presented negligible

strength after curing for 56 days. This confirmed that the initial pH was critical for the strength development of CS-GGBS-treated slurry.

[00116] Compared with the pure GGBS-treated slurry, CS-GGBS-treated slurry yielded considerably higher strength at all curing periods, which should be attributed to the facilitated geopolymerization process. Besides, however, when the CS content was higher than a certain value, further increment in CS content presented negligible enhancement in terms of UCS, especially at 28 and 56 days. Taking CS-GGBS-treated marine clay slurry with 60 kg/m³ GGBS as an example, the 56-day UCS increased from ~100 kPa to ~400 kPa when the CS content increased from 0 kg/m³ to 13 kg/m³, but further CS addition, e.g., from 13 kg/m³ to 17 kg/m³, led to UCS reduction from ~400 kPa to 369 kPa. It is concluded that the proper CS content would remarkably enhance the stabilization efficiency of GGBS, while excess CS content might even pose a detrimental effect on the UCS. Besides, for these three types of clay slurry, CS-GGBS presented considerably higher stabilization efficacy than OPC at all the curing ages. At 28 days, the CS-GGBS-treated slurry with the desired CS content can achieve a UCS up to 3.5~10 times that of corresponding OPC-treated slurries. The high stabilization efficacy of GGBS-based binders was also indicated in the treatment of other types of soil.

[00117] The initial pH and UCS ratio (the UCS of treated slurry divided by the maximum UCS at the same curing age) of the treated slurry are plotted against CS content in FIG. 5A to 5D. It is notable that the profiles of the initial pH and UCS ratio are quite similar, especially at 28 and 56 days. For each type of clay slurry, there is a sharp increment in both the UCS ratio and initial pH with the increase of CS content from 0 to a certain value, and then both UCS ratio and initial pH reach their peaks at an approximating CS content. This indicates that the initial pH might be able to estimate the desired CS content of CS-GGBS-treated slurry.

[00118] Based on the initial pH curve, the lowest CS content after which two successive CS addition presented a negligible increase in pH is selected as the desired content. This CS content can also be regarded as the minimum CS content required to obtain a saturated activator (e.g., Ca(OH)₂) solution for treated slurry. As shown in FIG. 6, the estimated CS content based on pH and the corresponding UCS ratio of specimens are listed. It was clearly shown that specimens with the estimated CS contents could

achieve a high level of UCS (at least 91% of the maximum UCS) at 28 and 56 days. In fact, the CS content yielded the highest 56-day UCS is quite close to the estimated CS content, i.e., the difference is smaller than 2 kg/m^3 , which further confirms the effectiveness of the method of the present disclosure. Therefore, instead of casting lots of CS-GGBS-treated specimens and measuring UCS after 28 or 56 days as in traditional methods, the CS content to achieve the discussed effects can be quickly estimated by mixing the binders and clay slurry, and then measure the initial pH one hour later as demonstrated in the method of the present disclosure.

[00119] Example 2G: Results and Analysis – Water Content

[00120] The water content, i.e., the mass of water over the dry mass of solid, of CS-GGBS treated marine clay with 60 kg/m^3 GGBS at 7 and 56 days are plotted in FIG. 7. The calculated initial water content at 0 day (i.e., before hydration) is also provided for reference. The water content of treated slurry presents a similar trend versus CS content at these two curing ages. The water content initially decreased with increasing CS content and then remained nearly constant when the CS content was higher than a certain value (15 kg/m^3 at 7 days and 9 kg/m^3 at 56 days). Since all the stabilized samples were covered with polythene (i.e., polyethylene) sheets in locked bags, the reduction in water content should be attributed to hydration reactions. Considering both FIG. 3B and FIG. 7, it can be concluded that GGBS hydrated slowly under a relatively low initial pH level, and the hydration rate increased with the initial pH until a saturated $\text{Ca}(\text{OH})_2$ solution was obtained.

[00121] For CS-GGBS-treated slurry, GGBS reacted with water to produce solid hydration products. Thus, the change in water content was caused by both the consumption of water and the increase of solid mass. In this process, the transfer of water in stabilized clay slurry can be expressed as:

$$m_{w0} - \Delta m_w = w(m_s + m_{\text{GGBS}} + m_{\text{CS}} + \Delta w) \quad (\text{i})$$

[00122] in which m_{w0} is the initial mass of water; m_s , m_{GGBS} , and m_{CS} are the mass of soil, GGBS, and CS, respectively; w is the water content of cured specimen and Δm_w represents the mass of water consumed in hydration reactions.

[00123] To better describe the amount of water involved in GGBS hydration, the water consumption ratio (W_{con}), defined as the mass of consumed water over the GGBS mass,

was considered. This parameter reflects the hydration degree of GGBS, and W_{con} is expressed as:

$$W_{con} = \frac{\Delta m_w}{m_{GGBS}} = \frac{m_{w0} - w(m_s + m_{GGBS} + m_{CS})}{(1 + w)m_{GGBS}} \quad (ii)$$

[00124] As shown in FIG. 8, the water consumption ratio increased from 7 to 56 days, indicating the continuous hydration of GGBS. At 7 and 56 days, the water consumption ratio increased with increasing CS content from 0 to 9 kg/m³, and then remained almost constant or even decreased with higher CS addition. Since the consumption of water was caused by GGBS hydration, this result further confirmed that the hydration rate of GGBS was limited because of the relatively low initial pH. Besides, the specimen with a CS content of 5 kg/m³ had a water consumption ratio close to that of the pure-GGBS treated at 7 days, indicating that the added CS was mainly consumed to neutralize clay slurry. Moreover, excess CS addition could even result in the reduction of water consumption ratio at 56 days. This indicates that excess CS addition cannot further improve the hydration rate of GGBS to produce more hydration products at longer curing ages.

[00125] Example 2H: Results and Analysis – XRD analysis

[00126] The XRD patterns of raw marine clay and CS-GGBS-treated marine clay slurry (60 kg/m³ GGBS) with CS contents of 5, 13, and 17 kg/m³ are presented in FIG. 9. These three CS contents represent the treated slurry with insufficient CS content, the desirable CS content, and excess CS content, respectively. The peaks of quartz, kaolinite, montmorillonite, calcite, and clinocllore were recognized in the unstabilized marine clay. Some XRD patterns (e.g., montmorillonite at $2\theta=35.9^\circ$) of untreated marine clay weakened after stabilization, indicating that clay minerals were involved in pozzolanic reactions.

[00127] For all stabilized specimens, the presence of geopolymer was identified. The broad diffraction pattern appeared at $2\theta=20-40^\circ$ indicates the aluminosilicate matrix with amorphous to semi-crystalline nature. Besides, crystalline hydration products such as calcium silicate hydrate (CSH), calcium aluminate hydrates (CAH), hydrotalcite (HT), and ettringite (AFt) were identified. These types of hydration products were also indicated in other studies. With the increase of CS content from 5 kg/m³ to 13 kg/m³

and 17 kg/m³, the intensity of some reflections of CSH (e.g., $2\theta=34.1^\circ$) became more prominent, implying the growth of more crystalline CSH in these samples. In addition, the XRD patterns of CAH (e.g., $2\theta=12.4^\circ$ and 37.6°) were also identified in treated slurry. The increment in the reflection intensity of heulandite ($2\theta=11.1^\circ$) and hydrotalcite (HT, $2\theta=11.3^\circ$) was also observed in the samples with high CS addition. Heulandite is a Ca-containing zeolite phase, and HT, a kind of carboaluminates, has also been reported in GGBS-treated soil. HT and HT-like phases can fill the voids among clay particles and provide precipitation sites for the growth of hydration products, which could enhance strength development. However, excess formation of HT and HT-like phases might cause cracks, which might cause the reduction of strength. Besides, calcium hydroxide (CH) was not identified in any specimen, and the consumption of CH should be attributed to the geopolymerization reactions. This was consistent with the pH results, as the pH of CS-GGBS-treated slurry at 56 days was in a range of 11.5-11.7, which was less than the pH of a saturated CH solution (~ 12.4).

15 **[00128] Example 2I: Results and Analysis – TGA**

[00129] Thermogravimetry analysis (TGA) and derivative of thermogravimetry analysis (DTG) results for the unstabilized marine clay, and CS-GGBS-treated slurry are shown in FIG. 10. with the minerals labeled. The residual weight of untreated clay continually decreased along with the elevated temperature, and the two peaks at 400-600°C and 650-750°C in the DTG plot of untreated marine clay were related to the decomposition of kaolin and montmorillonite, respectively.

[00130] Apart from the decomposition of clay minerals, the mass loss of treated slurry in 30-200°C was mainly assigned to the removal of bond water and physically adsorbed water within geopolymer frameworks, as well as the decomposition of ettringite (AFt), and AFm phases (monosulfate, and hemi- or monocarboaluminate). More precisely, the intensified peaks at 50°C-110°C are caused by the release of interlayer water in CSH and CAH, while AFt decomposes at around 80°C-130°C. Two DTG peaks observed around 140°C and 170°C indicated the presence of AFm phases, and the DTG peaks of AFm phases became stronger with higher CS addition. The treated slurry with 13 kg/m³ CS presented a sharper DTG peak around 70°C, while the peaks located at 140°C and 170°C were more prominent in the specimen with 17 kg/m³ CS. This indicated that the latter specimen contained more AFm phases, but had less amount of CSH and CAH.

The broader peaks in DTG curves from 200°C to 400°C could be assigned to HT and HT-like phases due to the removal of water and carbon dioxide. The weight loss in 400-600°C can be attributed to the decomposition of calcium hydroxides and kaolin, while the DTG peak at 700°C indicates the decarbonization of montmorillonite and calcite.

5 For CS-GGBS-treated clay, the sample with 5 kg/m³ of CS had the smallest weight loss in TGA testing, while the sample with 13 kg/m³ CS presented a similar higher weight loss than that of the sample with 17 kg/m³ CS. This indicated that excess CS content cannot promote the production of more hydration products when GGBS content was fixed.

10 **[00131]** The relative weight loss, defined as the weight loss of stabilized clay slurry minus the weight loss of unstabilized clay, was used to evaluate the quantities of hydration products. The relative weight loss of these samples in 30-400°C was divided into two main stages. As shown in FIG. 11, the CS-GGBS-treated marine clay slurry with 13 kg/m³ (the desired CS content) and 17 kg/m³ produced similar amounts of CSH,
15 AFt, and AFm, although the proportion of these materials would be different. FIG. 11 also showed that the treated slurry with 17 kg/m³ CS produced the highest amounts of HT and HT-like phases. Based on XRD and TG-DTG results, it was indicated that CS addition not only facilitates the GGBS hydration, but also influences the types of hydration products.

20 **[00132] Example 2J: Discussion of Examples 2A to 2I**

[00133] The reaction mechanism of lime/CS-GGBS in paste was studied. Their results indicate that Lime/CS not only provides a relatively high alkaline environment to facilitate GGBS hydration, but also participates in GGBS hydration to produce hydration products. In the present study, the desirable initial pH value was in a range
25 of 12.31-12.52 for clay slurry treatment.

[00134] The initial pH of CS-GGBS-treated slurry was mainly controlled by CS content, and presented a similar profile as that of UCS, especially at 28 and 56 days. In examples 2A to 2I, the minimum CS content required to achieve a saturated Ca(OH)₂ solution was identified (e.g., estimated) to be the desired CS content. The effects of
30 initial pH on strength development are described as follows. The initial pH of GGBS-treated slurry was low without CS addition. Thus, the dissolution of geopolymer precursor, i.e., GGBS, was relatively slow due to the lack of hydroxyl, and the

formation of geopolymer was delayed, especially at an early age. This explains the negligible strength of pure GGBS treated slurry. CS addition could raise the pH value, which facilitates the dissolution of GGBS as well as the precipitation of aluminosilicate, enhancing the strength development. Hence, CS-GGBS-treated slurry with the highest
5 CS addition usually showed the highest UCS at 7 days (FIG. 4A to 4D). However, at longer curing ages (e.g., 56 days), excess CS addition cannot promote the formation of more hydration products because the GGBS content was fixed. This was supported by the water content results, as the water consumption ratio of GGBS remained constant or even decreased when the CS content was higher than a certain value (FIG. 7).
10 Therefore, the initial pH of CS-GGBS-treated slurry could be used to estimate its strength behavior.

[00135] In examples 2A to 2I, similar types of hydration products, mainly CSH, CAH, AFt, gehlenite, and HT phases, were identified in specimens with different CS content at 56 days. TG-DTG results (FIG. 10) further showed that the CS-GGBS-treated slurry
15 with the desired CS content (13 kg/m^3) and excess CS content (17 kg/m^3) showed approximating total weight loss, which was significantly higher than that of the specimen with 5 kg/m^3 CS. This finding agrees with the water content results, and confirms that CS addition beyond the desired CS content cannot further promote the formation of more hydration products. In addition, intensified DTG peaks related to
20 CSH were found in the specimen with the highest UCS (13 kg/m^3). This contributes to its superior strength performance. Moreover, TG-DTG results also showed that excess CS addition leads to the generation of more HT and HT-like phases. Although the voluminous HT and HT-like phases can fill the voids, the excessive generation of these materials tend to cause cracks in the soil matrix, posing detrimental effects on strength.
25 In addition, previous studies also indicated that the presence of excessive calcium compound affects the structure of geopolymer network and alter the Si/Al ratio of aluminosilicate, which contribute to the strength disparity between specimens with the optimum and excessive CS addition.

[00136] The efficacy of using initial pH to estimate the optimum CS content has been
30 verified based on the UCS results of three types of CS-GGBS-treated slurries. The specimen with the estimated CS content based on initial pH achieved a high strength level ($\geq 91\%$ of the maximum UCS), at 28 and 56 days as shown in FIG. 6. The method

of the present disclosure method can provide a reference at the design stage of CS-GGBS stabilization, and contributes to fully realize the stabilization efficacy of GGBS. Hence, the laborious laboratory workload and time cost required for determining a desirable CS content can be significantly reduced.

5 **[00137] Example 3: Summary**

[00138] The present disclosure provides for a method for rapid determination (including estimation) of a desirable CS content for CS-GGBS-treated slurry. From the above examples, the following conclusions can be drawn:

[00139] 1. The initial pH of CS-GGBS-treated slurry depended on the CS content; while at longer curing ages, the pH of these specimens was mainly controlled by the hydration products.

[00140] 2. The profile of initial pH against CS content was quite similar to the UCS curve of treated slurry at 28 and 56 days. The UCS of treated slurry initially increased with CS content up to a certain value, afterwards, further CS addition presented negligible enhancement in terms of UCS and might even pose deleterious effects on strength.

[00141] 3. The desired CS content can be estimated by measuring the initial pH of CS-GGBS treated slurry one hour after mixing. The lowest CS content required to obtain a saturated $\text{Ca}(\text{OH})_2$ solution is one consideration as the desirable CS content. At 28 and 56 days, CS-GGBS-treated slurry with this estimated CS content obtained a high strength level. This method can be used at the design stage of CS-GGBS stabilization, which can significantly reduce the laborious laboratory workload and time cost required for determining the CS content.

[00142] 4. The XRD and TG-DTG results indicated the formation of aluminosilicate, CSH, CAH, AFt, AFm, and HT phases. The proportions of hydration products changed with different CS addition.

[00143] While the present disclosure has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the present disclosure as defined by the appended claims. The scope of the present disclosure is thus indicated by the appended claims and all changes

which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A method for determining an amount of activator to be added to a GGBS-treated soil, the method comprising:
 - 5 determining a prefix amount of a binder based on a water content of a soil sample;
 - determining prefix amounts of the activator based on a mass of a dried sample of soil which the soil sample was prepared from;
 - determining, based on a mass of a wet soil sample, an amount of the binder
 - 10 corresponding to the prefix amount of the binder and amounts of the activator respectively corresponding to the prefix amounts of the activator;
 - mixing each one of the amounts of the activator determined and the amount of binder determined with a soil sample which has a mass equal to the mass of the wet soil sample so as to form soil-activator-binder mixtures;
 - 15 obtaining pH values respectively from the soil-activator-binder mixtures; and
 - establishing a relationship between the pH values and the amounts of the activator corresponding to the pH values so as to identify from the relationship the amount of activator to be added to the GGBS-treated soil.
- 20 2. The method of claim 1, wherein the activator is a lime-based activator or a magnesia-based activator.
3. The method of claim 2, wherein the lime-based activator comprises quicklime, hydrated lime, carbide sludge, or any mixture which produces Ca(OH)_2 when mixed
- 25 with water.
4. The method of claim 2, wherein the magnesia-based activator comprises magnesia, or any mixture which produces Mg(OH)_2 when mixed with water.
- 30 5. The method of any one of claims 1 to 4, wherein the GGBS-treated soil comprises solids and water.

6. The method of any one of claims 1 to 5, further comprising determining the water content of the soil sample, wherein determining the water content of the wet soil comprises:

- obtaining an initial wet soil sample;
- 5 weighing the initial wet soil sample;
- drying the initial wet soil sample to obtain the dried sample of the soil;
- weighing the dried sample of the soil; and
- calculating the water content by dividing the difference between the initial wet soil sample and the dried soil sample with weight of the dried soil sample.

10

7. The method of any one of claims 1 to 6, wherein determining the prefix amount of the binder based on the water content comprises:

- identifying a liquid limit of the dried soil sample; and
- identifying the prefix amount of the binder by comparing the water content with
- 15 the liquid limit to determine whether (i) the water content is less than the liquid limit or (ii) the water content is equal to or more than the liquid limit.

8. The method of claim 7, wherein the prefix amount of the binder is:

- 10% to 30% by mass of the dried soil sample if the water content is less than
- 20 the liquid limit; or
- 5% to 10% by mass of the dried soil sample if the water content is equal to or more than the liquid limit.

9. The method of any one of claims 1 to 8, wherein determining the prefix amounts

25 of the activator based on the mass of the dried soil sample comprises identifying 5 to 10 prefix amounts of the activator based on the mass of the dried soil sample.

10. The method of claim 9, wherein the 5 to 10 prefix amounts range from 1% to 5% by mass of the dried soil sample with each prefix amount differing from each other

30 by 0.25% to 1% by mass of the dried soil sample.

11. The method of any one of claims 1 to 10, wherein determining, based on the mass of the wet soil sample, the amount of the binder corresponding to the prefix amount of the binder and the amounts of the activator respectively corresponding to the prefix amounts of the activator comprises:

5 calculating the amount of the binder based on the formula:

$$M_G = M_S / (1 + W) * C_G$$

wherein M_G is the mass of the binder corresponding to the prefix amount of the binder, M_S is the mass of the wet soil sample, W is the water content, and C_G is the prefix amount of the binder;

10 and

calculating each of the amounts of the activator based on the formula:

$$M_A = M_S / (1 + W) * C_A$$

15 wherein M_A represents one of the masses of the activator corresponding to one of the prefix amounts of the activator, M_S is the mass of the wet soil sample, W is the water content, and C_A represents one of the prefix amounts of the activator.

12. The method of any one of claims 1 to 11, wherein the mass of the wet soil sample is 100 g to 300 g.

20

13. The method of any one of claims 1 to 12, wherein mixing each one of the amounts of the activator determined and the amount of binder determined with a soil sample which has a mass equal to the mass of the wet soil sample so as to form soil-activator-binder mixtures comprises:

25 (i) mixing each one of the amounts of the activator determined with the amount of binder determined to form activator-binder mixtures, and mixing each one of the activator-binder mixtures with the soil sample to form the soil-activator-binder mixtures;

or

30 (ii) mixing directly each one of the amounts of the activator determined and the amount of binder determined with the soil sample to form soil-activator-binder mixtures.

14. The method of 13, further comprising:
preparing a plurality of the soil sample, which is a wet sample, for mixing with
each of the activator-binder mixtures to form the soil-activator-binder mixtures.

5

15. The method of claim 13 or 14, wherein mixing each one of the activator-binder
mixtures with the soil sample to form the soil-activator-binder mixtures comprises:

placing the soil-activator-binder mixtures in separate containers, and mixing
each of the soil-activator-binder mixtures for several times within a duration of 1 hour
to 24 hours.

10

16. The method of any one of claims 1 to 15, wherein obtaining pH values
respectively from the soil-activator-binder mixtures comprises:

(i) extracting a portion of one of the soil-activator-binder mixtures;

15

(ii) centrifuging the portion to obtain a filtrate and a residue;

(iii) measuring the pH of the filtrate; and

(iv) repeating steps (i) to (iii) to obtain the pH value of the other soil-activator-
binder mixtures.

20

17. The method of any one of claims 1 to 16, wherein establishing a relationship
between the pH values and the amounts of the activator corresponding to the pH values
so as to identify from the relationship the amount of activator to be added to the GGBS-
treated soil comprises:

plotting each of the pH values against one of the amounts of the activator used
in forming one of the soil-activator-binder mixtures which the pH value is
correspondingly derived from to form a pH-activator content plot; and

25

identifying from the pH-activator content plot the amount of activator to be
added to the GGBS-treated soil.

30

FIG. 1A

Material	CaO	SiO ₂	MgO	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	TiO	Na ₂ O	Others	Loss on ignition
CS	62.82	3.27	0.93	1.53	ND	0.51	0.03	ND	0.24	30.67
GGBS	43.04	28.28	7.02	13.78	0.49	4.23	1.39	0.35	0.94	0.48
Marine clay	1.67	59.85	1.36	18.89	5.34	0.74	1.08	0.78	2.91	7.37

FIG. 1B

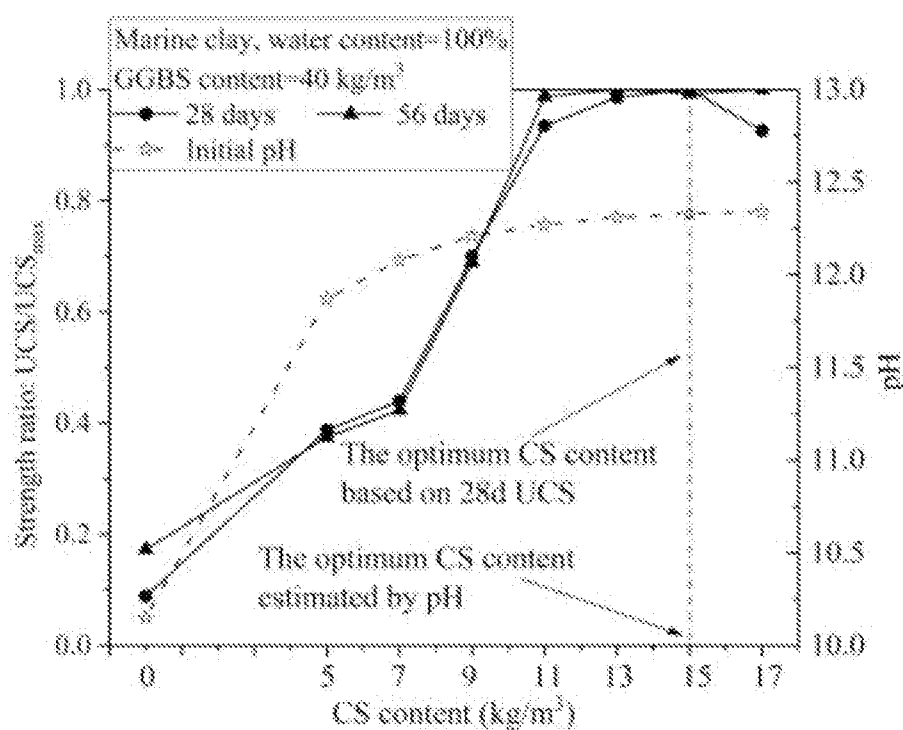


FIG. 1C

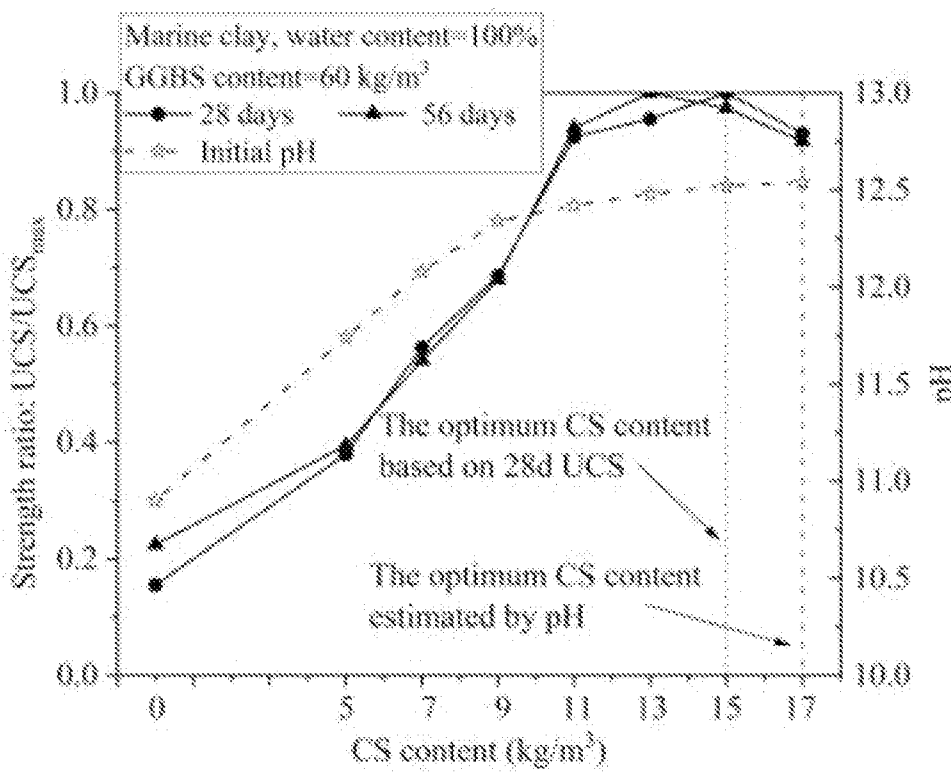


FIG. 1D

Clay type	GGBS content (kg/m ³)	Estimated desirable CS content according to initial pH (kg/m ³)	Corresponding UCS ratio	
			28 days	56 days
Clay slurry	40	15	1	1
	60	17	0.930	0.917

FIG. 1E

Laboratory workload and costs	The present method	Traditional method
Laboratory workload	Four hours, including, mixing, centrifuge extraction, and pH testing.	Ten hours for sample casting; and six hours for sample demolding and UCS testing
Curing periods	None	Up to 56 days
Material consumption	1.4kg clay slurry, 48.8g GGBS, and 10.8g CS	25.2kg clay slurry, 878.6g GGBS, and 194.4g CS
Testing fees	None	Equipment charging of S\$ 120.0 for the UCS test in the lab

FIG. 2A

Soil	Water content	Alkaline Type	Content	GGBS content	Lime/CS-to-GGBS ratio
Engelay Lower Oxford clay	130%	Hydrated lime	5-10%	5-25%	20% at 28 days
Silty sand soil	40%	Quicklime	4-14%	6-16%	25% at 28 days
Clayey silt	20%	Hydrated lime	1, 3, and 5%	5-15%	33% at 7 days; and 20% at 28 days
Marine clay	40%	Hydrated lime	1-8%	10-15%	11% at 28 days
	60%	Quicklime and hydrated lime	0.625%-5%	12.5%	20% at 7 and 28 days; and 10% at 90 days
Marine clay	60%	CS	1-12%	20-30%	25% at 7 and 28 days; and 20% at 90 days for GGBS content of 20% 20% at 7 days; 15% at 28 days; and 90 days for GGBS content of 30% 25% for quicklime-GGBS; and 33% for CS-GGBS at 28 days
Dredged sludge	70%	Quicklime and CS	1-6%	7-27%	

FIG. 2B

Material	CaO	SiO ₂	MgO	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	TiO	Na ₂ O	Others	Loss on ignition
CS	62.82	3.27	0.93	1.53	ND	0.51	0.03	ND	0.24	30.67
GGBS	43.04	28.28	7.02	13.78	0.49	4.23	1.39	0.35	0.94	0.48
OPC	62.13	20.77	4.11	3.66	2.93	1.76	0.69	0.37	0.58	3.00
Marine clay	1.67	59.85	1.36	18.89	5.34	0.74	1.08	0.78	2.91	7.37
Kaolin	0.06	64.70	0.80	30.17	ND	0.05	0.50	0.04	3.68	0
Bentonite	8.60	40.99	11.54	5.79	3.28	0.22	0.41	0.34	1.13	13.95

FIG. 2C

Clay type	Water content (%)	CS content (kg/m ³)	GGBS content (kg/m ³)	Curing period (days)	Tests
Marine clay	100		40 and 60		The pH and strength at all curing ages.
Kaolin	80	0, 5, 7, 9, 11, 13, 15, 17	40	7, 28, and 56	Water content of treated marine clay slurry at 7 and 56 days.
K9B1	150		60		XRD and TGA of treated marine clay slurry at 56 days.

FIG. 3A

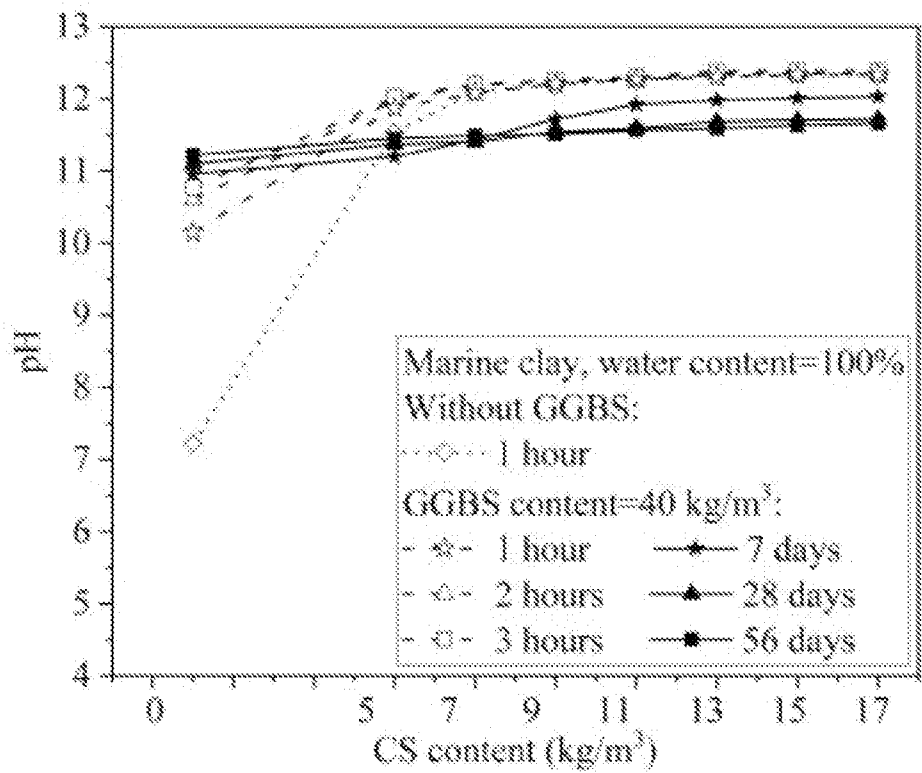


FIG. 3B

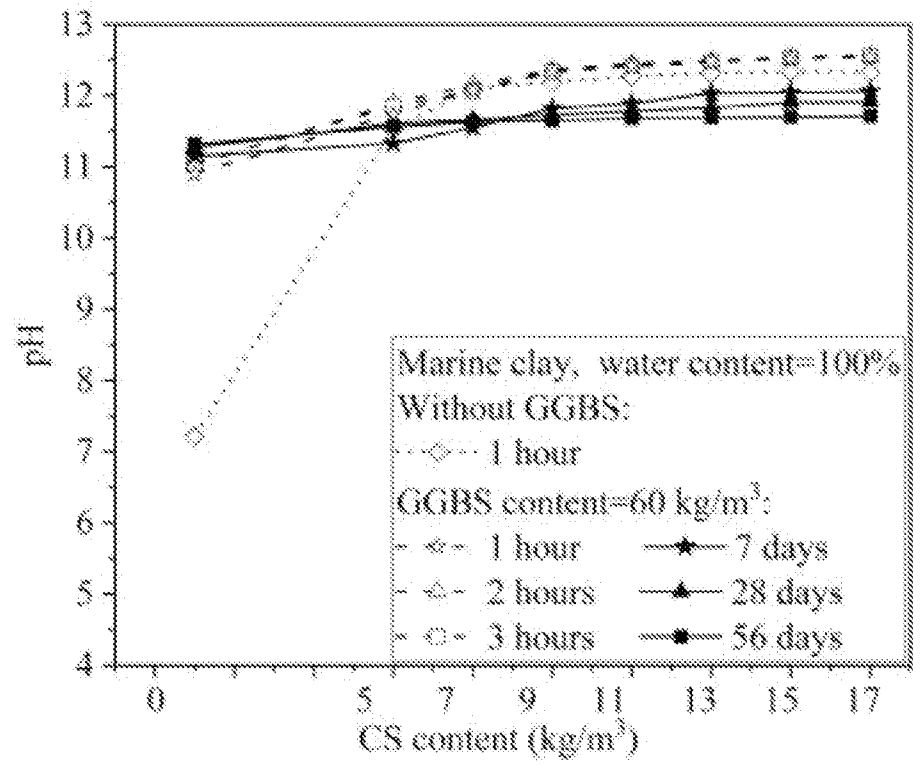


FIG. 3C

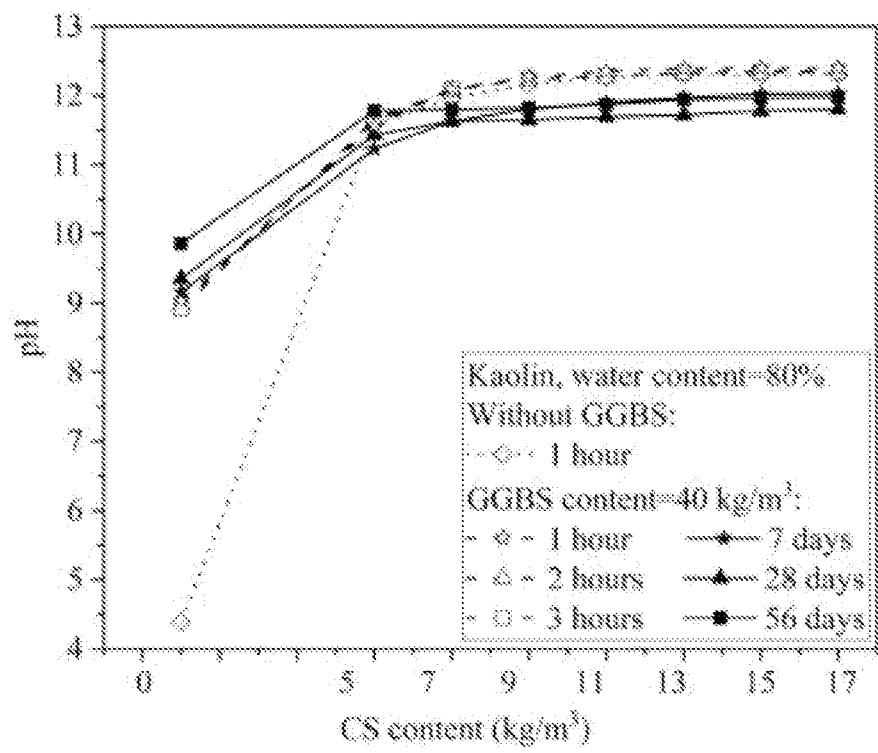


FIG. 3D

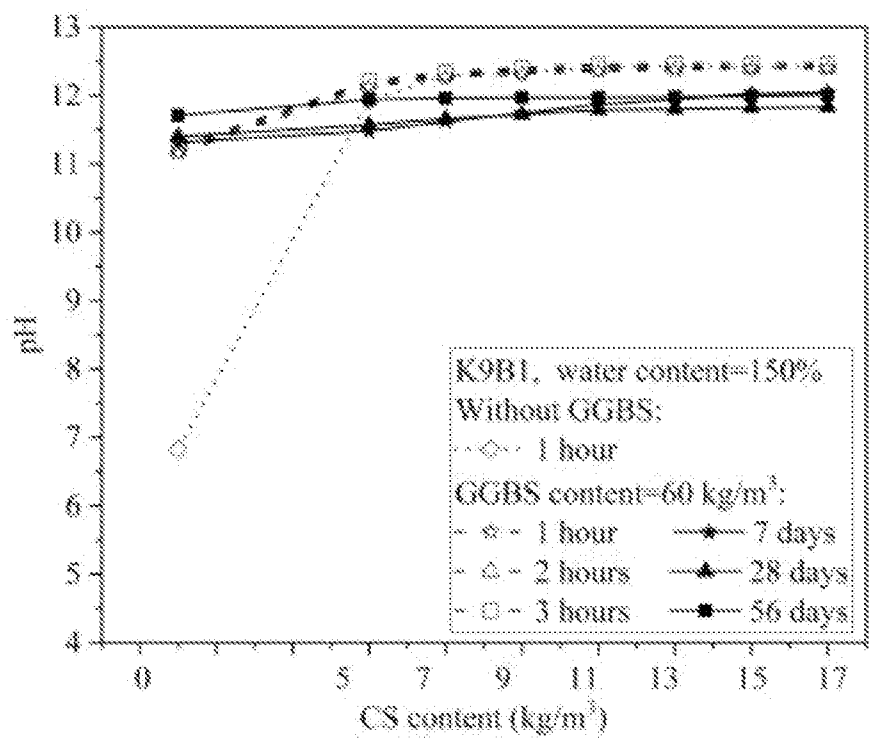


FIG. 4A

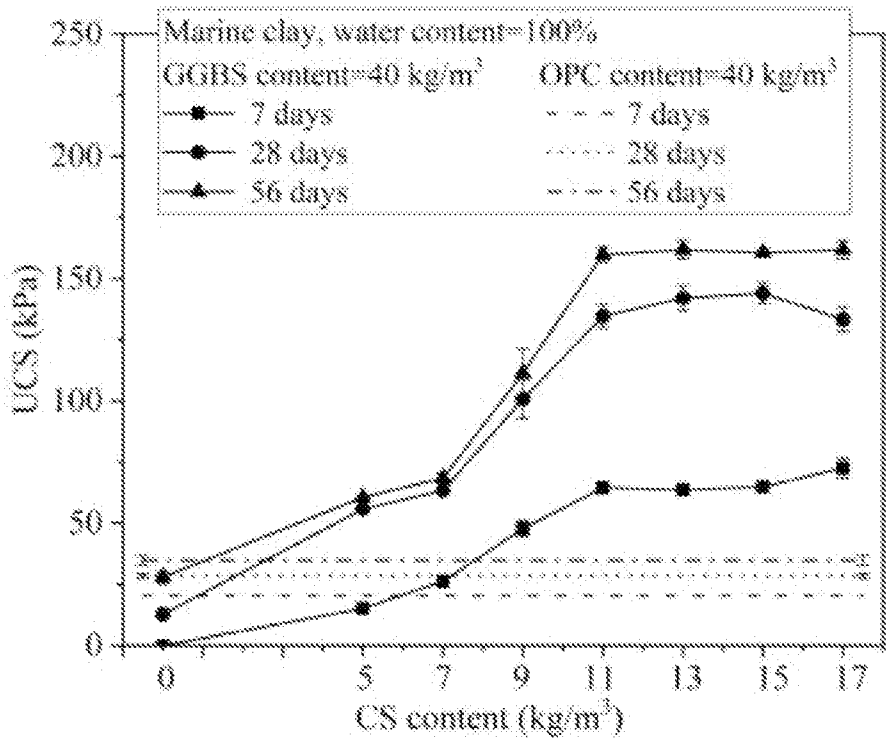


FIG. 4B

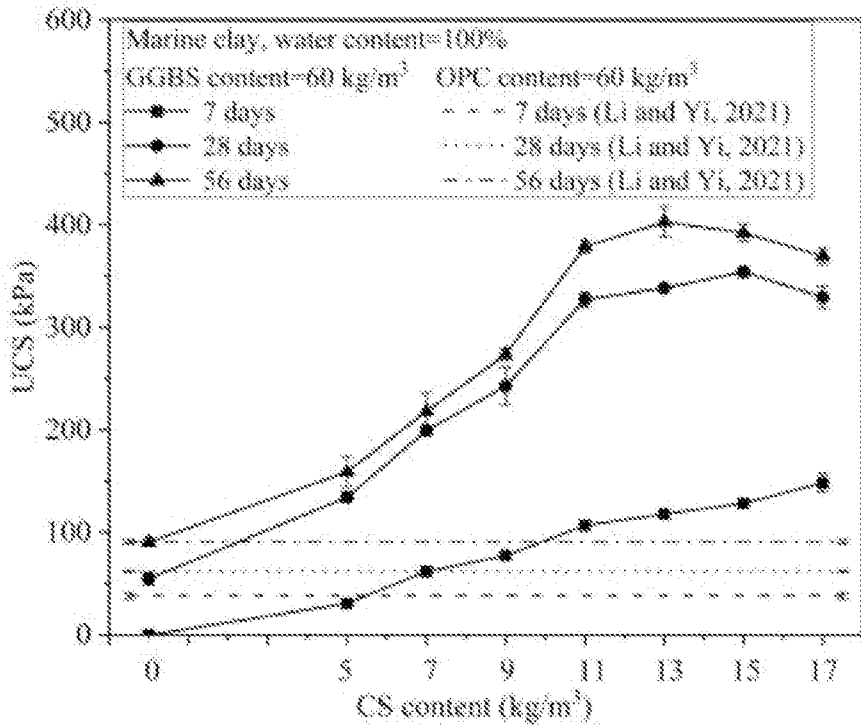


FIG. 4C

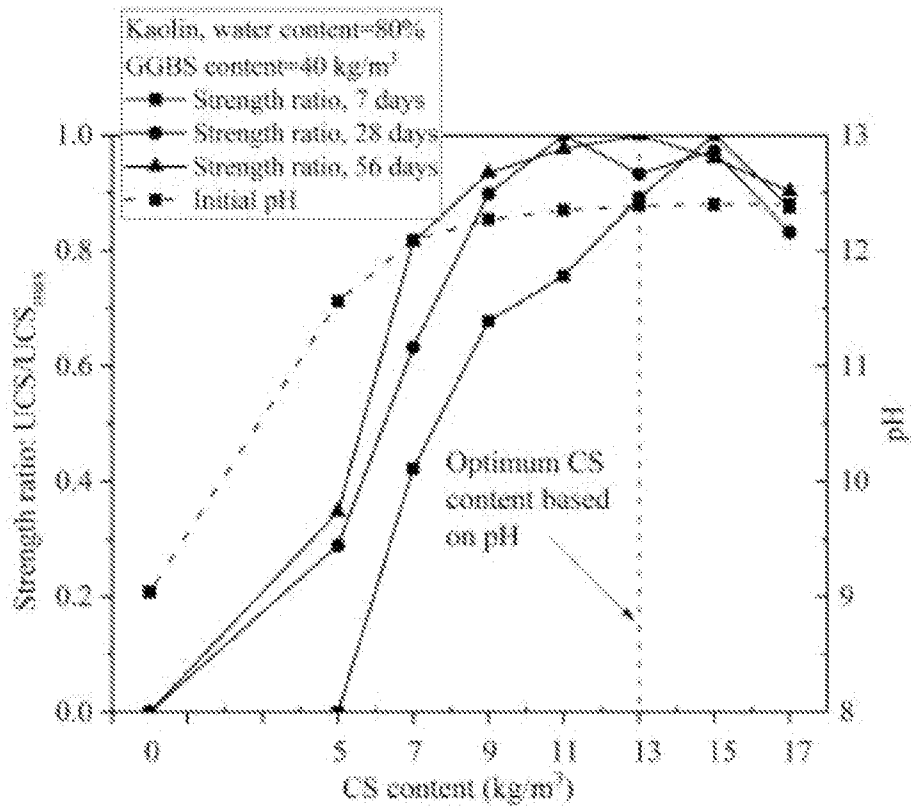


FIG. 4D

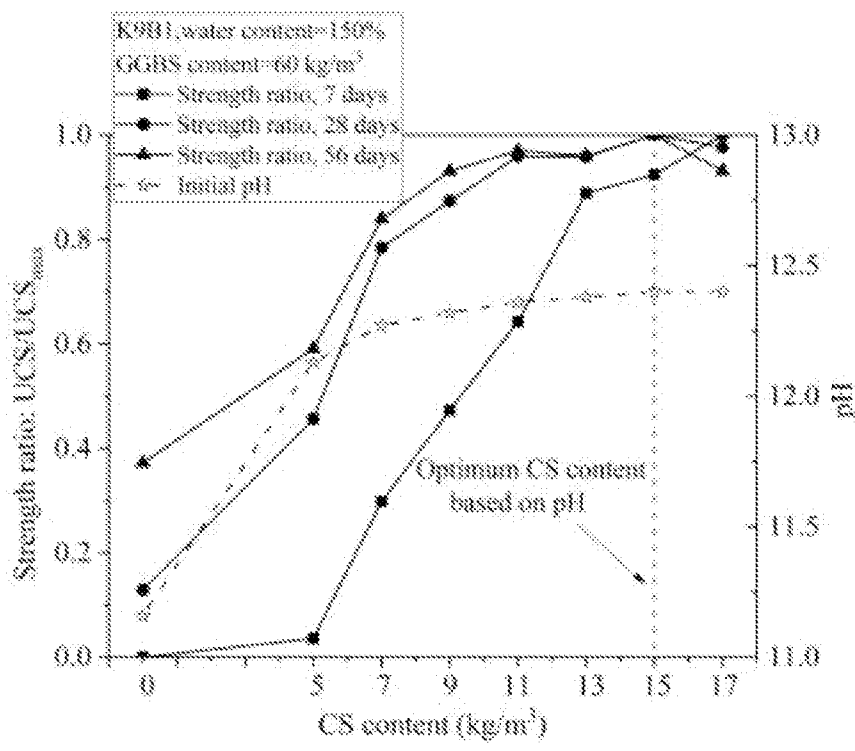


FIG. 5A

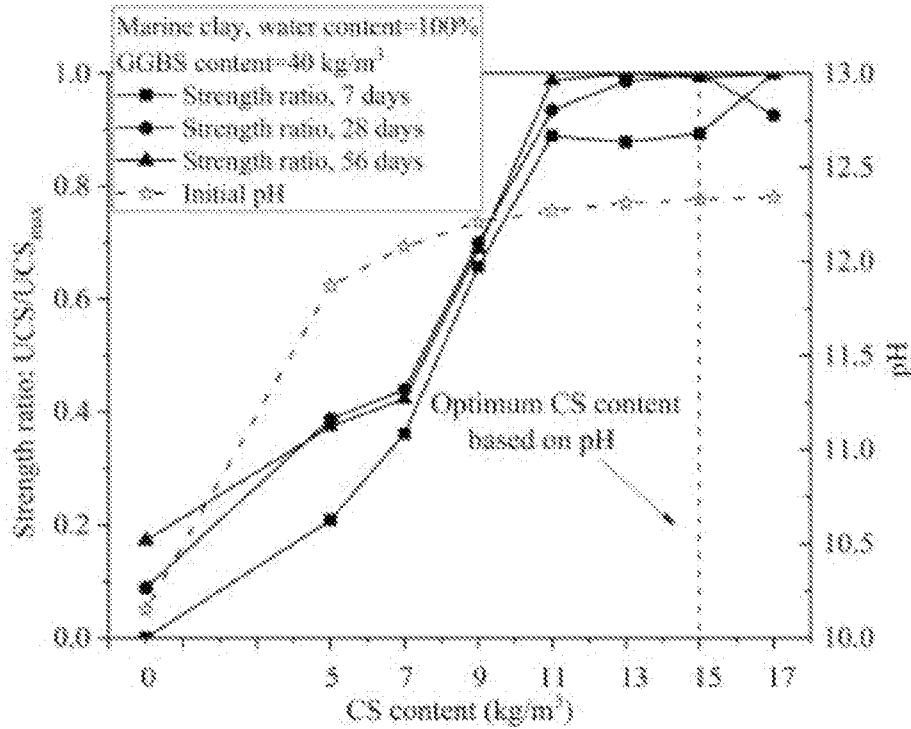


FIG. 5B

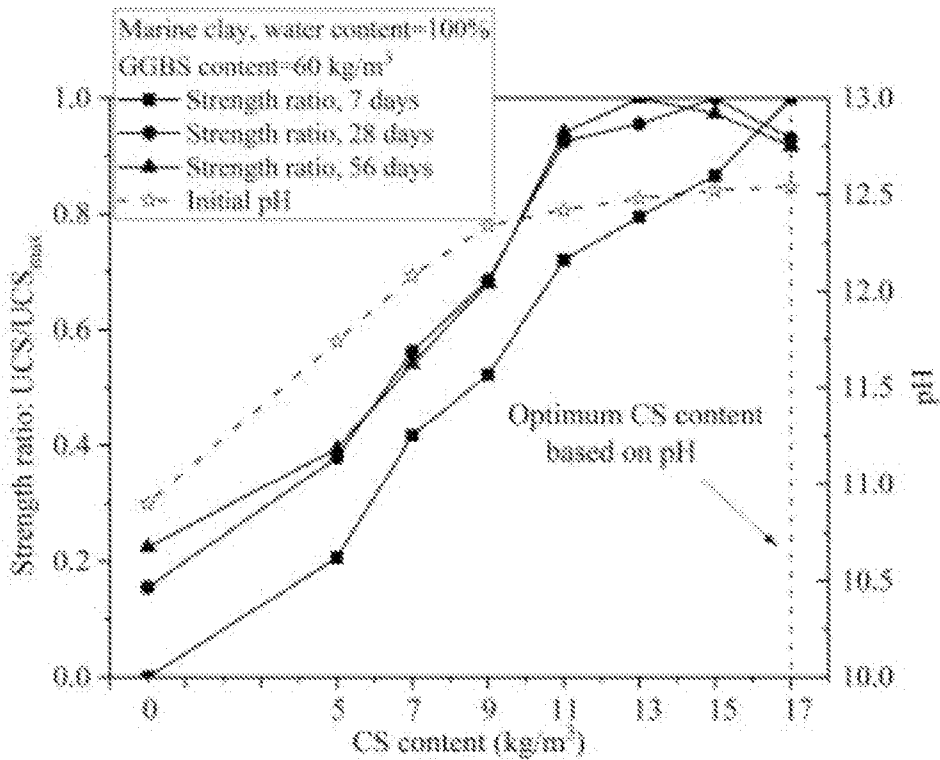


FIG. 5C

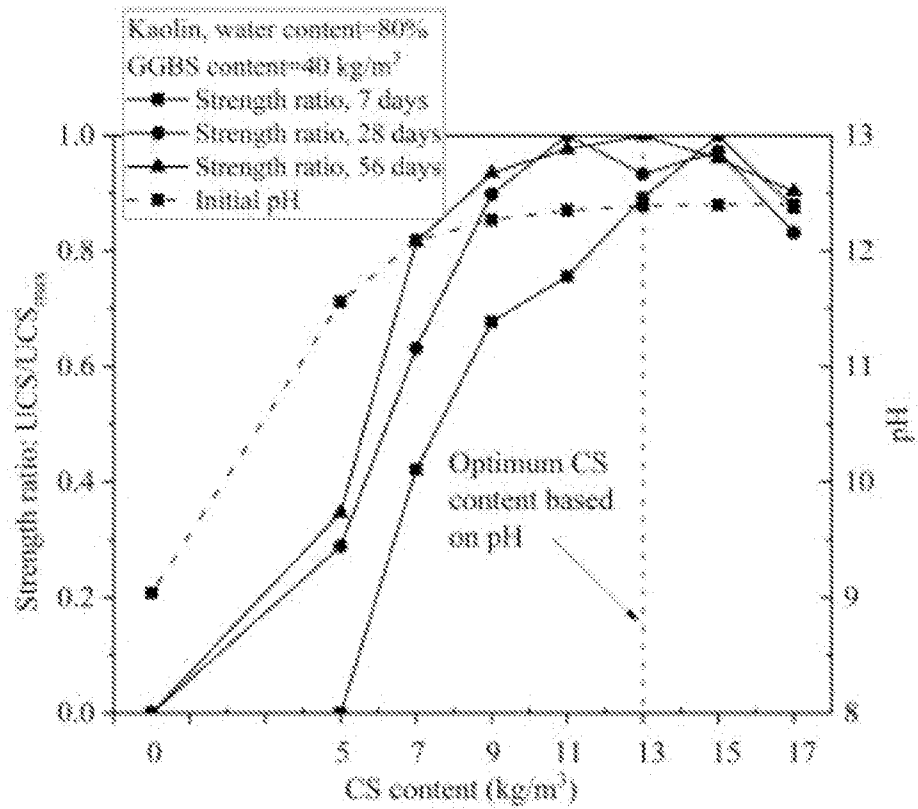


FIG. 5D

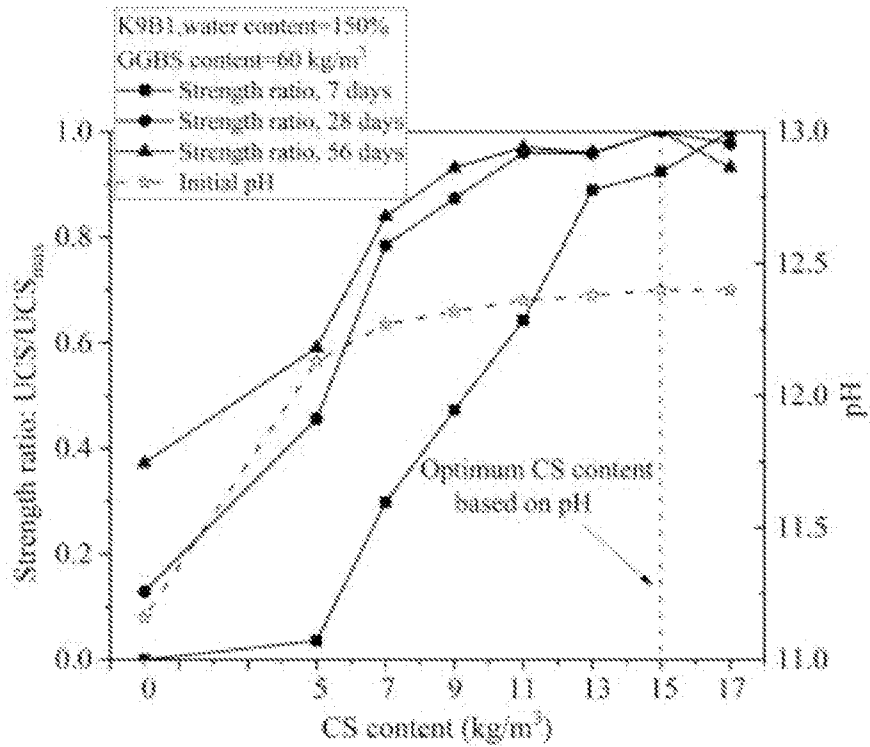


FIG. 6

Clay type	GGBS content (kg/m ³)	Estimated CS content according to initial pH (kg/m ³)	Corresponding UCS ratio	
			28-day	56-day
Marine clay	40	15	1	1
Marine clay	60	17	0.930	0.917
Kaolin	40	13	0.937	1
K9B1	60	15	1	1

FIG. 7

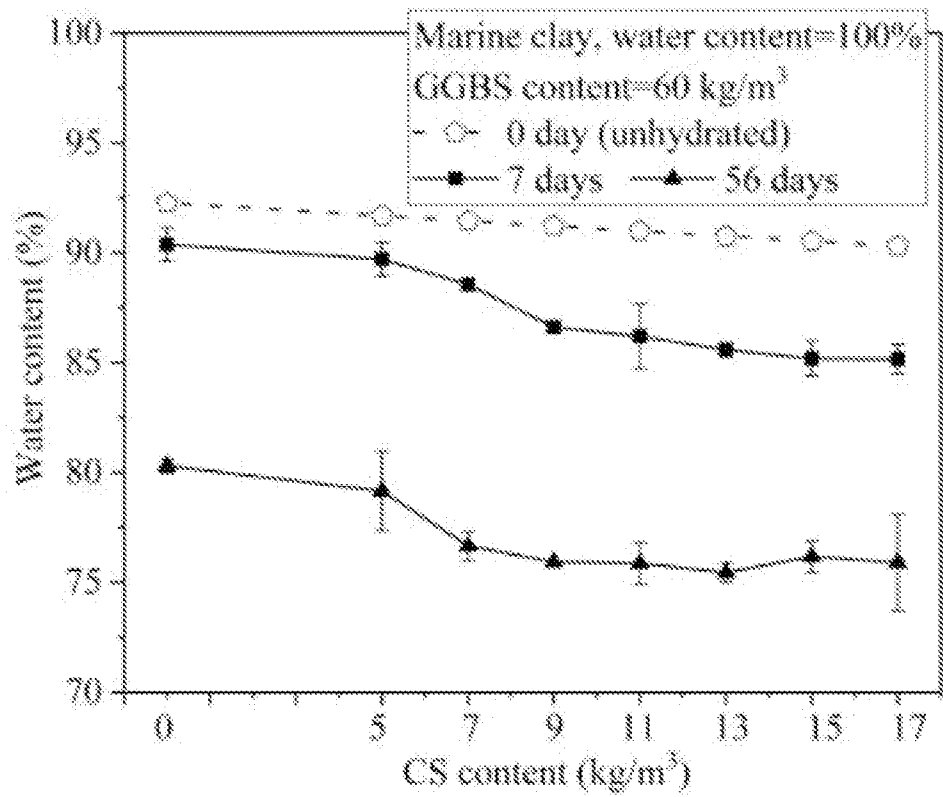


FIG. 8

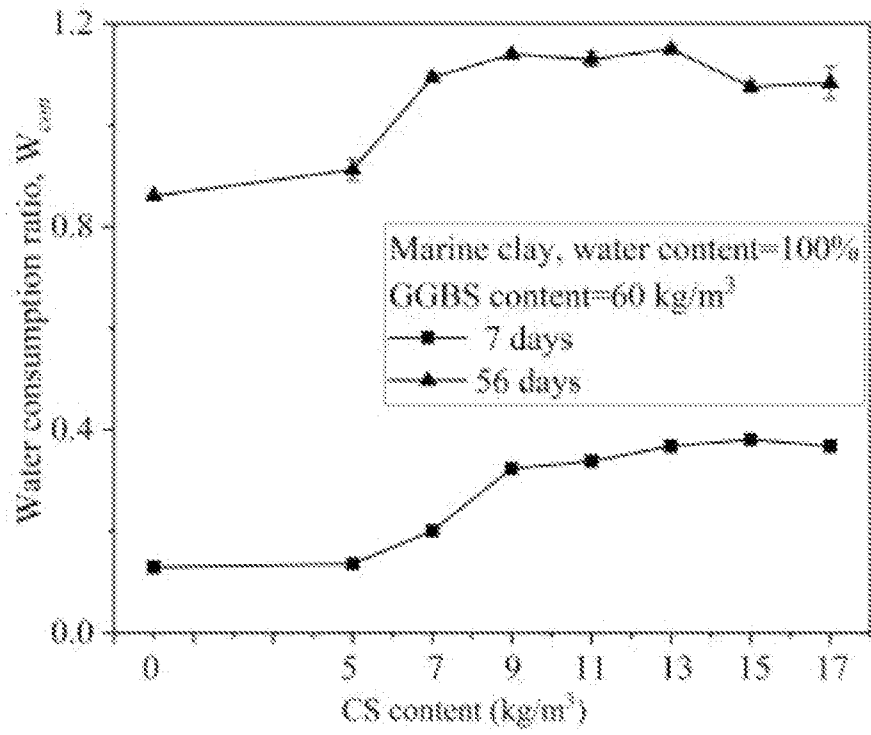


FIG. 9

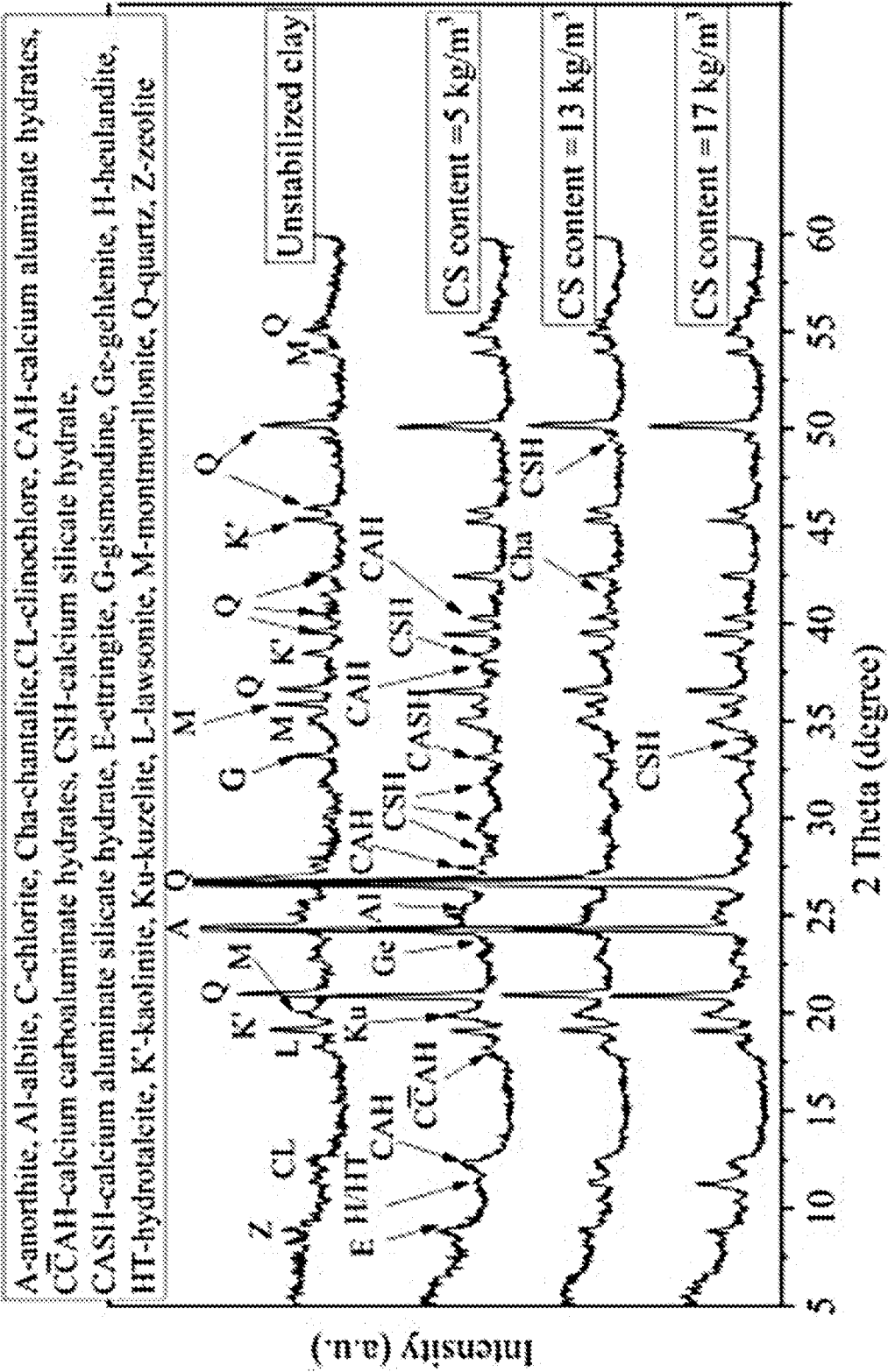


FIG. 10

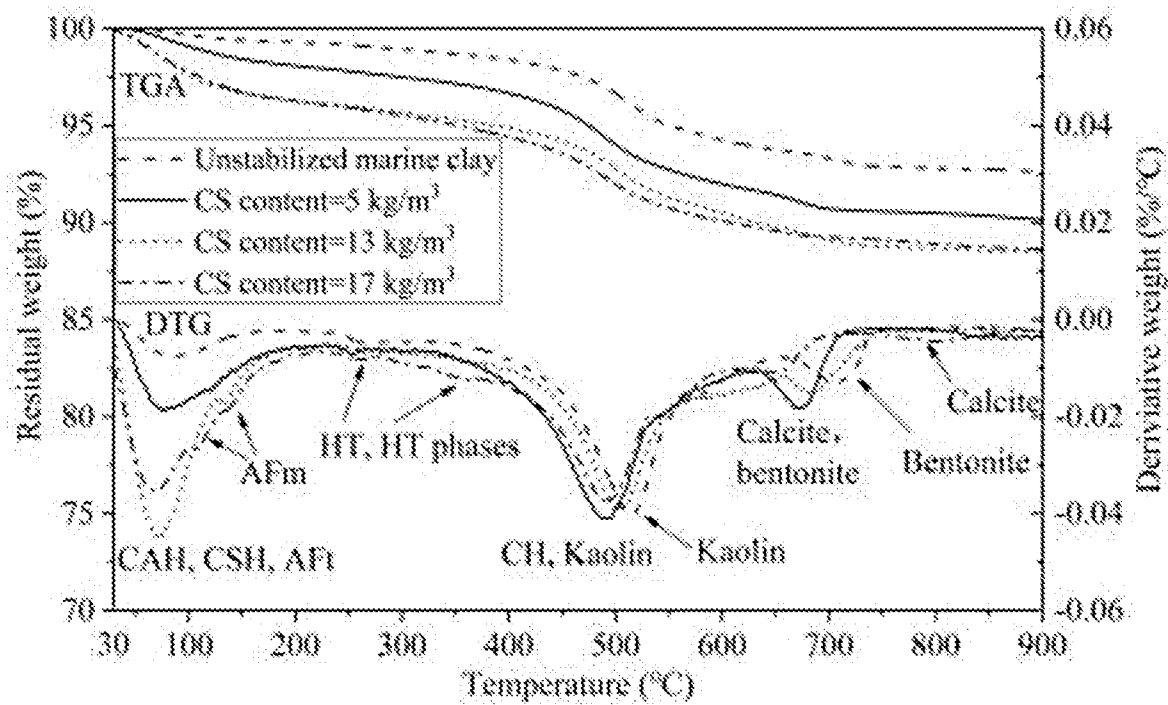
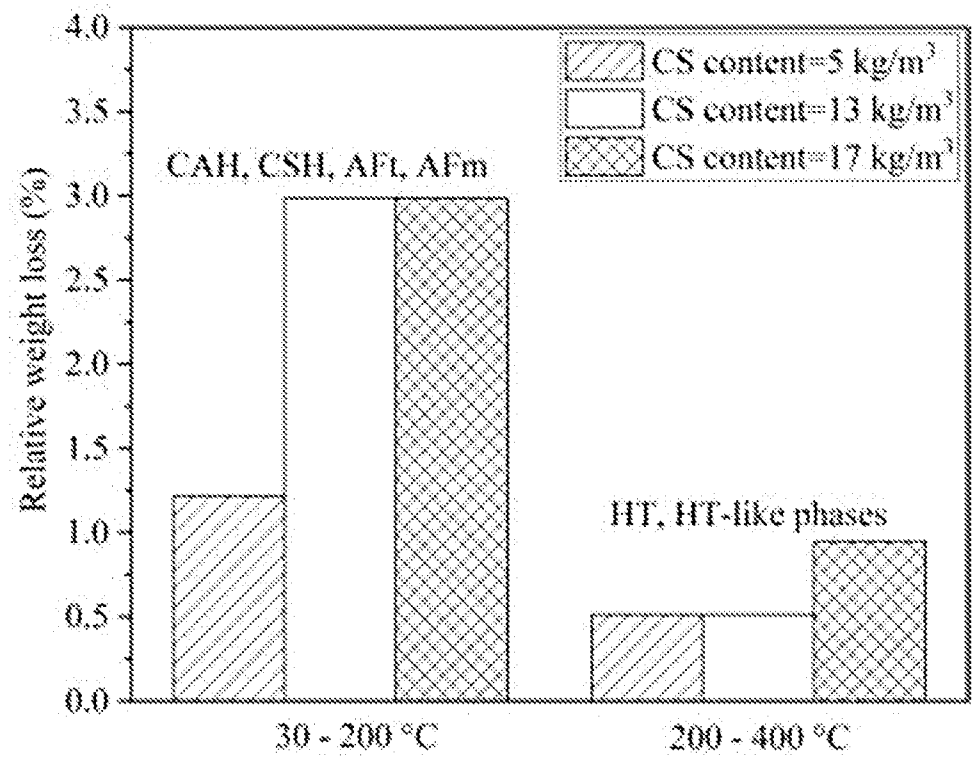


FIG. 11



INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2023/050508

A. CLASSIFICATION OF SUBJECT MATTER**C09K 17/00 (2006.01) C04B 7/14 (2006.01) C04B 40/00 (2006.01)**

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Database: FAMPAT

Keywords: ground granulated blast furnace slag, GGBS, GGBFS, soil, earth, marine clay, slug, binder, activator, activating agent, lime, magnesia, carbide slug, calcium oxide, calcium hydroxide, pH and related terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GB 1575075 A (VIZGAZDALKODASI TUDOMANYOS KU) 17 September 1980 see whole document	1-17
A	JP 2015-074914 A (NIPPON STEEL & SUMITOMO METAL CORP) 20 April 2015 see whole document of the machine translation	
A	JP 2007-314661 A (UBE INDUSTRIES ET AL.) 6 December 2007 see whole document of the machine translation	

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.***Special categories of cited documents:**

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"E" earlier application or patent but published on or after the international filing date

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

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Date of the actual completion of the international search

20/10/2023

(day/month/year)

Date of mailing of the international search report

24/10/2023

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2023/050508

Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
GB 1575075 A	17/09/1980	NONE	
JP 2015-074914 A	20/04/2015	NONE	
JP 2007-314661 A	06/12/2007	NONE	