

A METHOD OF PRODUCING A SAND-LIKE MATERIAL

FIELD OF THE INVENTION

The present invention relates to a method of producing a sand-like material that has
5 geotechnical properties similar to sand. More particularly, the present invention relates to a
method of producing a sand-like material from clayey soil.

BACKGROUND

Sand is traditionally used as an infill material for land reclamation due to its ability to
10 compact, high strength and drainage properties. However, excessive extraction of sand from
rivers or seabed for land reclamation and other construction work poses environmental and
ecological concerns. Further, a global shortage of sand has driven the need for an alternative
infill material.

In recent years, clayey soil generated from excavation works, basement construction and
15 deep tunnelling works has become an alternative infill material in Singapore's land
reclamation works. However, as the excavated clayey soil possesses low permeability, low
shear strength, high compressibility and low load bearing capacity, further ground
improvement is needed to enhance stability of the newly reclaimed land. In practice, a few
meters thick of sand must be laid on top of the clayey infills to support the weight of ground
20 improvement machinery. Hence, there remains a heavy reliance on sand.

Several methods for producing sand or substitutes thereof have been proposed. For instance,
rocks have been crushed into particles around the size of sand grains. In another example,
cemented soil that is produced by mixing soil with cement as an additive to produce a weak
concrete is crushed into smaller sand-like particles. These methods have been unsatisfactory.
25 Particularly, in the former, rocks are also a scarce resource in a small country like Singapore,
and notwithstanding that the cement-soil mixture in the latter requires a long time (around
28 days) to cure, the use of cement also results in a high carbon footprint that undermines
efforts to decarbonise the construction sector.

It is therefore desirable for a method to produce a sand-like material that can relieve the problems of sand shortage.

SUMMARY OF INVENTION

- 5 The above and other problems in the art are solved and an advance in the art is made in accordance with this invention.

A first advantage of a method of producing a sand-like material in accordance with this invention is that the method converts clayey soil that is abundant to a sand-like material that has more desirable geotechnical properties.

- 10 A second advantage of a method of producing a sand-like material in accordance with this invention is that the method does not require additives such as cement, bloating agent or other chemicals.

- A third advantage of a method of producing a sand-like material in accordance with this invention is that the sand-like material thus produced does not pollute the environment since
15 no chemicals are used in the production process.

A fourth advantage of a method of producing a sand-like material in accordance with this invention is that the method is highly scalable and can be used in-situ at excavation sites to convert clayey soil to sand-like material.

- According to a first aspect of the invention, a method of producing a sand-like material is
20 provided. The method comprises obtaining clayey soil which includes a first mineral, granulating the clayey soil to form a plurality of granules, sintering the plurality of granules to convert the first mineral, completely or partially, into a second mineral, and cooling the sintered granules to obtain the sand-like material.

- In some embodiments, the first mineral is kaolinite that is converted to the second mineral,
25 metakaolinite during the sintering step.

Preferably, the clayey soil is granulated into a plurality of granules that approximates the size of sand grains. For instance, the clayey soil is granulated into a plurality of granules that is 3mm to 5mm in size.

In some embodiments, the method further comprises filtering the clayey soil to remove debris or coarse particles before granulating. Preferably, the clayey soil is mixed with water, for instance in a mixer, to obtain a homogenous slurry before filtering. The filtering is carried out using an aperture grille that is attached to a side of a mixer to screen out debris or coarse particles. After the slurry is passed through the grille, the slurry is allowed to settle under the effect of gravity. The heavier particles (e.g. sand and aggregate) in the slurry will sink faster while lighter particles (e.g. silt and clay) remain at the top portion of the slurry that is transferred for subsequent steps.

In some embodiments, the method further comprises dewatering the clayey soil or slurry preferably to a predetermined moisture content, such as 30% to 50% by mass before granulating.

In some embodiments, the granulating step is performed by extruding the clayey soil and cutting the extruded clayey soil into pellets with diameter preferably in the range of 3mm to 5mm.

In some embodiments, the sintering step comprises heating the plurality of granules at high temperatures to convert the first mineral to the second mineral. As an example, the plurality of granules is heated to at least 800°C, or at least 900°C. Preferably, the plurality of granules is heated in the range of 800-900°C for a predetermined duration to optimise energy efficiency while ensuring that the first mineral in the plurality of granules is completely converted to the second mineral to form a coherent sintered product.

In some embodiments, the plurality of granules is sintered in a static furnace at approximately 800°C to 900°C for approximately 1hr. Preferably, the plurality of granules is preheated by increasing the temperature at a ramp rate, such as 300°C/hr, until the sintering temperature is reached.

In some embodiments, the plurality of granules is sintered in a rotary kiln furnace at approximately 800°C to 900°C for approximately at least 10min to 15min. Preferably, the plurality of granules is pre-heated in a drying rotary kiln at a minimum temperature of 100°C for at least 5-10 mins before sintering in the rotary kiln furnace.

In a preferred embodiment, the cooling step is performed in a heat exchanger to harvest and recycle heat from the plurality of sintered granules.

According to a second aspect of the invention, there is provided a sand-like material that is produced in accordance with a method of the invention. The sand-like material possesses geotechnical properties similar to sand including but not limited to static compressive strength in the range of 10MPa to 20MPa, permeability of 1×10^{-3} to 1×10^{-4} m/s, friction angle of 30° to 39° and low dissolvability in water and acids.

According to a third aspect of the invention, there is provided a sand-like material for use as an infill material for land reclamation, and on-land soil works. In addition, the sand-like material can also be used as a substitute for an aggregate and/or sand in conventional concreting works. A lighter sand-like material can be used to make a lightweight concrete material.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a flowchart of a method of producing a sand-like material in accordance with an embodiment of the invention.

Fig. 2 shows a flowchart of a method of producing a sand-like material in accordance with a preferred embodiment of the invention.

Fig. 3 shows a system for large scale production of a sand-like material using a method in accordance with an embodiment of the invention.

Fig. 4 shows a plurality of granules that has been extruded and cut from clayey soil, in accordance with an embodiment of the invention.

Fig. 5 shows sintering schedules for Tests SL-1, SL-2, SL-3 and SL-4 of Example 1 (static furnace).

Fig. 6a, Fig. 6b and Fig. 6c show an intact granule that has been sintered, a cross section of a fully sintered granule, and a cross section of a partially sintered granule respectively.

Fig. 7 shows the sintered percentage of sintered products from SL-1, SL-2, SL-3 and SL-4 of Example 1 (static furnace) based on a visual inspection.

Fig. 8a and 8b show schematics of the compressive tests performed on the sintered products in the longitudinal direction and transverse direction respectively.

Fig. 9 shows the mean compressive strength of sintered products from SL-1, SL-2, SL-3 and SL-4 of Example 1 (static furnace).

Fig. 10 shows the friction angle measured for sintered products from Tests SL-1 and SL-2 of Example 1 (static furnace).

5 Fig. 11 shows a schematic of an exemplary setup used for measuring permeability of the sintered products.

Fig. 12 shows the density-moisture relationship of the sintered product obtained from Test SL-1 of Example 1 (static furnace).

10 Fig. 13 shows the X-ray Diffraction (XRD) peaks of clayey soil and sintered product from Test SL-1 of Example 1 (static furnace).

Fig. 14 is a scanning electron micrograph of the sintered product obtained from Test SL-1 of Example 1 (static furnace).

Fig. 15 shows the X-ray Diffraction (XRD) peaks of clayey soil, and sintered products obtained from Tests F1, F2, T2, T3 and M1 of Example 2 (rotary kiln).

15 Fig. 16 is a scanning electron micrograph of a sintered product obtained using a rotary kiln.

Fig. 17 shows the mean compressive strength of the sintered product from Test SL-1 of Example 1 (static furnace) and the sintered product from Test M1 of Example 2 (rotary kiln).

Fig. 18 shows the permeability of the sintered product from Test SL-1 of Example 1 (static furnace) and the sintered product from Test M1 of Example 2 (rotary kiln).

20 Fig. 19 shows the thermogravimetric analysis of the sintering step in Test C from Example 3 (inclination of rotary kiln).

Fig. 20 shows the X-ray Diffraction (XRD) peaks of the sintered products from Tests S1 to S4 of Example 3 (inclination of rotary kiln).

25 Fig. 21 shows compressive strength of a sand-like material obtained from sintering in a static furnace and a mid-sized rotary kiln.

DETAILED DESCRIPTION

In a first aspect, the present invention relates to a method of producing a sand-like material. The sand-like material possesses geotechnical properties similar to sand and may be used as an infill material for land reclamation, or for on-land soil and concreting works.

- 5 Unless otherwise stated, any range that is disclosed herein is inclusive of the end points. For instance, a range of X to Y will include X and Y.

Fig. 1 shows an outline of a method in accordance with an embodiment of the invention. The method (100) comprises obtaining clayey soil (102), granulating the clayey soil to form a plurality of granules (104), sintering the plurality of granules (106) and cooling the plurality
10 of sintered granules to obtain the sand-like material (108).

Clayey soil belongs to the category of fine-grained soil, which has plasticity and comprises mainly clay minerals like kaolinite. Kaolinite mineral is formed by the breakdown of feldspar by the action of water and carbon dioxide. Feldspars are a group of rock-forming minerals. Clay minerals particles are in “plate-like” form.

- 15 Clayey soil is characterised by low permeability and a high potential for shrinkage and swelling due to changes in moisture content. High moisture content led to low shear strength, low load-bearing capacity and high compressibility.

In Singapore, about 40% of the ground contains clayey soil. The clayey soil often has platy texture and must be excavated at constructions sites for disposal due to its low shear strength,
20 low permeability, high compressibility, and low load bearing capacity which makes the clayey soil unsuitable for use in construction. Hence, there is an abundance of clayey soil and the present method is advantageous in providing a mean for converting clayey soil that is of low economical value to a useful sand-like material.

For producing the sand-like material, the clayey soil that may be excavated from construction
25 sites is granulated into a plurality of granules that preferably approximates the size of sand grains. As an example, the clayey soil may be granulated into granules that are 3mm to 5mm in size. The clayey soil may be granulated by various means known in the art, including but not limited to an extrusion process followed by cutting, or by rolling the clayey soil into small balls.

The plurality of granules then undergoes a sintering process, whereby the plurality of granules is treated at high temperatures (sintering temperature), during which a mineral or chemical content of the plurality of granules is altered. As an example, the clayey soil may comprise a first mineral that is converted completely or partially during the sintering step into a second mineral. Preferably, the first mineral is kaolinite and the second mineral is metakaolinite. Dependent upon the sintering temperature, the metakaolinite can be further transformed into high strength mullite and amorphous silica at higher temperatures (i.e. $\geq 1000^{\circ}\text{C}$).

Lastly, the plurality of sintered granules is cooled.

The sintered product is preferably a solid coherent product and exhibits geotechnical properties similar to sand, i.e. a sand-like material.

Fig. 2 shows a preferred embodiment of the method (200) in accordance with the present invention. The clayey soil, that is obtained (202), is mixed with water (rainwater or recycled water may be used) to form a homogenous slurry (204) to facilitate filtering (206), whereby debris such as plant material (e.g. roots), coarse particles and sand are filtered out. As an example, since based on British Standard, a size of 0.6 mm to 2.0 mm is considered as coarse sand, the soil slurry may be filtered using an aperture grille that is attached to a side of a mixer to screen out the debris or coarse particles that are more than 0.6 mm in size. After the slurry is passed through the grille, the slurry is allowed to settle under the effect of gravity. The heavier particles (e.g. sand and aggregate) in the slurry will sink faster while lighter particles (e.g. silt and clay) remain at the top portion of the slurry that is transferred for subsequent steps.

The filtered soil slurry is then dewatered (208) to reduce a moisture content of the clayey soil before granulating (210). Preferably, the moisture content is reduced to a predetermined moisture level that facilitates the subsequent granulation step. Most preferably, the filtered soil slurry is dewatered to 30% to 50%, preferably 30% to 35% moisture content that is close to the plastic limit of the clayey soil. Various apparatus that are known to the skilled person may be used for dewatering including but not limited to a heat oven, vacuum suction chamber and the like. In a preferred embodiment, water that is removed from the slurry during dewatering is recycled for mixing with clayey soil (204).

The dewatered clayey slurry may form a soil paste that is subsequently granulated (210) using various means as previously described to form a plurality of granules.

Before sintering (214), the plurality of granules preferably undergoes a preheating step (212) to further reduce the moisture content of the plurality of granules. In some embodiments, the moisture content may be further reduced to close to zero. Preheating may be carried out as part of the sintering process or separate from the sintering process. Dependent on the apparatus used for preheating, it may be preferable to preheat the plurality of granules by increasing the temperature gradually.

Preferably, the sintering step (214) comprises heating the plurality of granules at high temperatures to convert the first mineral to the second mineral. As an example, the plurality of granules is heated to at least 800°C, or at least 900°C as the required mineralogy change may not occur at lower temperatures.

Most preferably, the plurality of granules is heated in the range of 800-900°C for a predetermined duration to optimise energy efficiency while ensuring that the first mineral in the plurality of granules is completely converted to the second mineral to form a coherent sintered product.

The sintering step may be performed in a static furnace, a rotary furnace or other heating apparatus commonly known by one skilled in the art. Most preferably, the sintering step is performed in a rotary furnace which allows for a more efficient heat transfer and hence leads to shorter sintering time and lower energy consumption. For instance, the plurality of granules is sintered by heating in a rotary furnace at a temperature in the range of 800°C to 900°C for 5 to 10 mins.

The sintered granules are then cooled (216) to obtain the sintered products that may be a sand-like material (218). The cooling step may be part of the sintering step or a separate step. Preferably, the cooling takes place separately in a heat exchanger so that heat from the sintered granules can be harvested and recycled for use in preheating (212) and sintering (214).

As would be understood by the skilled person, the methods described in the preceding paragraphs provide a facile method of converting clayey soil into a useful sand-like material. The methods do not require any additives and the sand-like material is produced from

naturally found clayey soil. Hence, the sand-like material is environmentally friendly and does not leech harmful chemicals.

Furthermore, the methods of the present invention are easily upscaled to increase production capacity and for on-site applications. As an example, Fig. 3 shows a schematic diagram of a system for producing a sand-like material using a method of the present invention. The system (300) comprises a slurry mixer (302) for mixing water with clayey soil to form a slurry, a pump (304) for pumping the filtered slurry that has passed through a filtering screen (306), a ceramic vacuum filter (308) for dewatering the filtered slurry to form a paste, a conveyor belt (310) for conveying the paste to a pelletising extruder (312) for granulating the paste to form a plurality of granules, a drying rotary kiln (314) for preheating the granules, a sintering rotary kiln (316) for sintering the granules and a heat exchanger (318) for cooling the sintered granules. The system may be set up at construction sites to perform in-situ conversion of the excavated clayey soil.

In a second aspect, the present invention provides a sand-like material that is produced by any of the methods described in the preceding paragraphs. The sand-like material possesses geotechnical properties similar to sand including but not limited to static compressive strength in the range of 10MPa to 20MPa, permeability of 1×10^{-3} to 1×10^{-4} m/s, friction angle of 30° to 39° and low dissolvability in water and acids. Preferably, the sand-like material comprises a solid coherent sintered product comprising metakaolinite that is produced by a process that is optimised for energy efficiency. The sand-like material may comprise mullite and/or silica, dependent on the sintering process.

In a third aspect, the present invention provides a sand-like material for use as an infill material for land reclamation, and on-land soil works. In addition, the sand-like material can also be used as substitute for aggregate and/or sand in conventional concreting works. A lighter sand-like material can also be used to make lightweight concrete material. The sand-like material has the favourable characteristics of high compressive strength, high friction angle and low dissolvability.

For instance, for on-land soil works, the sand-like material can be used as a general fill for embankment construction. The sand-like material can also be used for backfilling excavated areas and for improving ground stability by removing soft soil and filling with the sand-like material.

The sand-like material can also be used in concreting works as a substitute for coarse sand or fine aggregate in a concrete mixture. Since the average density of the sand-like material is lighter than the aggregate, the substitution of the aggregate for the sand-like material in the concrete mixture would yield a lightweight concrete material.

- 5 The invention is further described in the examples below. It should be noted that the examples are provided to exemplify the invention and should not be seen in any way to be limiting the scope of invention.

Example 1

Characterisation of Clayey Soil

- 10 Soft clayey soil was excavated and characterised. The clayey soil is grey in colour and contains a small amount of gravel and sand. The water content of the excavated soft clayey soil is in the range of 70 – 80 %; its liquid limit is about 75 – 80 %, and its plastic limit is around 33 – 38 %. The particle size distribution of a few random soil samples is shown in Table 1. Based on the unified soil classification system (USCS), the soil type is classified as
- 15 inorganic clays of high plasticity, fat clays (CH).

Gravel Percentage (%)	Sand Percentage (%)	Silt Percentage (%)	Clay Percentage (%)
1 to 3	2 to 18	31 to 43	36 to 56

Table 1: Particle size distribution of the excavated soil clayey soil.

Filtering and Dewatering

- The excavated soft clayey soil was first filtered to remove gravel and sand which are inert in the sintering process, debris and other coarse particles. Removal of the inert gravel and sand
- 20 aids in reducing energy consumption during the sintering step.

The filtered soft clayey soil was transferred into a 105°C oven for dewatering to reduce the moisture content. Reducing the moisture content of the soft clayey soil before proceeding to

the next stage of the granulating process is preferred, as soft clayey soil with a high moisture content has high adhesion.

The high adhesion will hinder the mechanical operation of the granulating process. Based on experience, high moisture content soft soil repeatedly stuck to the metal parts of the granulation machine. The higher adhesion value between the clay and metal surface will lead to a higher force needed to separate the soil away from the metal surface.

Without wishing to be bound by theory, the adhesion between the clayey soil and other surfaces may be partially attributed to the surface tension of water in the soil's void, which is related to the moisture content of the soils. This adhesion could be expressed as a "friction force" acting on the interface and is dependent on the soil moisture content.

The soil-metal friction force (i.e., adhesion) increased with increasing moisture content for sandy and clayey soil to a certain moisture content value. Beyond some "optimum" moisture content value, the adhesion would significantly decrease when the soil's moisture content increased. This phenomenon can be classified into three phases: friction, adhesion, and lubrication.

The friction phase occurs when the soil has little moisture; the adhesion coefficient is the smallest in this phase. In the adhesion phase, the increment in moisture causes the moisture layer between the soil and metal to expand and increases the adhesive forces. In the lubrication phase, the increase in moisture is so high that it reduces the adhesive force at the interface. The soil's moisture layer expanded so much that free water is present on the soil metal surface at this final stage.

Based on the conditions described in the three phases above, the inventors postulate that the moisture content of the soft clayey soil considered "ideal" for the granulation process should fall within the later stage of the friction phase and the early stage of the adhesion phase. Therefore, determining the range of ideal moisture content for the granulation process is important.

In general, the peak adhesion would lie between the liquid limit and the plastic limit of the clay. The inventors conclude that the ideal moisture content of soft clayey soil for the granulation process is near (or slightly lower than) the plastic limit.

In this example, the clayey soil was placed into an oven for 30 minutes at 105 °C to evaporate the moisture in the soil. After this step, the clayey soil forms a soil paste with moisture content in the range from 30% to 35 %, which is close to the range of the plastic limit. This soil paste is then ready for the granulating process.

5 Granulating

The dewatered soil paste was granulated by an extrusion and cutting process.

A manual extruder with 3 mm diameter holes at the outlet was used. After a few 3 mm soil threads were extruded, the soil threads were manually cut into 3mm to 5mm lengths of cylindrical shape unfired 'green' granules, see Fig. 4.

- 10 The 'green' granules were air-dried for a day before proceeding to the sintering step.

Sintering and Cooling

The 'green' granules underwent a high-temperature sintering step and a subsequent cooling step.

- 15 The main components of the 'green' granules are clay minerals that have the phyllosilicates' structure, particularly the mineral kaolinite, $\text{Al}_4[\text{Si}_4\text{O}_{10}](\text{OH})_8$. Other than kaolinite, clay also contains other minerals like quartz (SiO_2) and feldspar. After the high-temperature sintering process, the kaolinite-quartz-feldspar mixes may transform into a solid and coherent product.

- Without wishing to be bound by theory, it is proposed that kaolinite in the clay undergoes dehydroxylation (loses structural water) and turns into metakaolinite at about 500°C to 20 600°C. A highly viscous Silica and Alumina (Al_2O_3) rich liquid may appear in between the clay particles at 800°C; this liquid created capillary forces that densify the particles and increase the cohesion of the particles at elevated temperature. This formation of liquid phase sintering is also called vitrification, where this process shrinks the particles and increases the strength. At a higher temperature (i.e. $\geq 1000^\circ\text{C}$), metakaolinite can transform into high 25 strength crystalline mullite and amorphous silica.

In this example, the 'green' granules were placed into a laboratory Lenton Chamber Furnace to sinter at four firing schedules. Table 2 and Fig. 5 show the firing schedules with three operation parameters: the temperature ramping rate, the target sintering temperature, and the dwelling duration.

Tests	Target Sintering Temperature (°C)	Dwelling Duration (hr)
SL-1	900	1
SL-2	900	0.5
SL-3	500	1
SL-4	500	2

Table 2: Firing schedules of the sand-like materials.

The temperature ramping rate was fixed at 300°C/hr for all the tests. This slow temperature ramping rate is needed to prevent a drastic change in temperature experienced by the granules because a drastic change in temperature within a very short time resulted in an explosion effect to the granules during the sintering process. The explosion is due to the moisture within the granule turning into steam and trying to escape from it.

Tests SL-1 and SL-2 adopted the same target sintering temperature of 900°C. Vitrification is expected to occur at this firing schedule, but mullite might not be formed in the end product. A stronger end product with the formation of mullite requires a higher sintering temperature (i.e. $\geq 1000^\circ\text{C}$), but at the same time, more energy will be consumed for the higher sintering temperature. Therefore, to have a cost-effective operation, 900°C sintering temperature was used. Test SL-1 had a dwelling duration of one (1) hour, while the dwelling duration for Test SL-2 was half an hour. The comparison between Test SL-1 and Test SL-2 shows the effect of dwelling duration on the sintered product's characteristics.

A lower target sintering temperature of 500°C and a longer dwelling duration of one (1) hour and two (2) hours were employed in Test SL-3 and Test SL-4, respectively. Metakaolinite would appear at the sintering temperature of 500°C; hence, the result of Test SL-3 and SL-4 provide further insights into the properties of the end product that possesses metakaolinite (not going through vitrification process) and with dissimilar dwelling duration. After the

sintering process, the end sintered products were cooled down to room temperature for at least a day.

Characterisation of Sintered Product

5 The sintered products underwent visual inspection and other physical and engineering properties tests, such as the static compression test, consolidated drained triaxial shear test and constant head permeability test, to determine the ultimate compressive strength, friction angle and permeability, respectively.

Sintered Percentage

10 Ten samples from each test were randomly chosen to be cut open. Observations have been made on the sintered area of the core of the sintered product, judging based on the colour composition within, where the orange-coloured areas are those sintered and the dark, grey-coloured areas are those of non-sintered (original colour of the soft soil is dark grey due to presence of iron oxide). The final appearance of the iron oxide-rich soil after thermal treatment is dark orange. Fig. 6(a) to 6(c) show examples of an intact sintered product before
15 cutting open, cross section of a fully sintered and coherent product and cross section of a partially sintered product respectively.

The approximated percentage of the sintered area of a specimen can be calculated based on the sintered area at the centre of the product over the total area at the centre of the product. Fig. 7 illustrates the approximate sintered percentage of the tests. The calculated sintered
20 percentage of SL-1, SL-2, SL-3 and SL-4 is close to 100%, 70%, 16% and 45% respectively.

It is found that the sintered product that underwent sintering at 900°C has a larger sintered area than that sintered at 500°C. This result suggests that 500°C is far below the required temperature to transform the 'green' granule into a coherent product.

25 The comparison between the sintered products that underwent sintering at different dwelling durations but the same temperature (i.e., between Test SL-1 versus Test SL-2, and Test SL-3 versus Test SL-4) shows that the tests that had a longer dwelling duration achieved a larger sintered area than those with a shorter dwelling duration.

A conclusion that can be drawn is that a longer dwelling duration allows more heat to travel into the granule, hence allowing more complete sintering. Among the tests, only SL-1 was fully sintered and formed a coherent product.

Compressive Strength

- 5 A Zwick Roell Z100 universal testing machine with a maximum testing load of 100 kN was used to obtain the ultimate unconfined compressive strength of the sintered products. Forty-two (42) randomly chosen samples from each of the four (4) test series were subjected to the compression test with a strain rate of 1 mm/min, where twenty-one (21) specimens were tested on the longitudinal axis and the other half of specimens tested on the transverse axis.
- 10 In the longitudinal axis, the specimen was standing ‘vertically’ up, with the flat surfaces of the cylindrical sample in contact with the top and bottom platen of the compression machine. While for the transverse face, the flat surfaces were perpendicular to the top and bottom platen. Fig. 8a and Fig. 8b illustrate the specimen position when subjected to the compression test in the longitudinal and transverse directions respectively until failure occurs.
- 15 The compressive strength value in the longitudinal direction can be derived by dividing the yield force with the cross-section area of the specimen. In comparison, the derivation of the strength value at the transverse direction would require the Hertzian contact stress theory. As would be understood by the skilled person in the art, the Hertzian contact stress theory is a theory that can be used to compute the stresses and forces acting during the contact of two
- 20 elastic bodies, particularly in this case, where the contact point of one of the bodies is curved.

The mean compressive strength of the sintered products in the longitudinal and transverse direction can be found. As shown in Fig. 9, the strength of the sintered products when tested along the longitudinal direction is higher than that along the transverse direction.

- In addition, most of the sintered products that underwent sintering at a higher and a longer dwelling duration possessed higher compressive strength, except that the transverse direction compressive strength of Test SL-1 and SL-2 was almost the same.
- 25

Friction Angle

The friction angle of the sintered products was determined using a consolidated drained triaxial test. The consolidated drained triaxial test determines strength and stress-strain

relationships of a cylindrical specimen of either intact or reconstituted soil, where the specimens are consolidated at a desired ‘consolidation pressure’ and then sheared at a constant rate of axial deformation in compression with open drainage. Only the materials produced in Test SL-1 and SL-2 were sent for the triaxial test because of the large amount of incomplete sintered clay produced observed in Test SL-3 and SL-4.

Fig. 10 shows the value of the friction angle for Test SL-1 and Test SL-2. It can be concluded that the sintered product with a higher percentage of sintered area and strength, Test SL-1, would possess a higher friction angle than that of Test SL-2.

The friction angle values obtained were compared with the typical sands available. Typical loose sands’ friction angle is between 27° to 32°; medium dense sands’ is between 32° to 37°; while higher than 37° is those dense sands and very dense sands. It can be seen that the friction angle of SL-1 (34.7°) falls in the category of medium dense sands. In contrast, SL-2 can be categorised as loose sands based on the friction angle of 29.4°. This result is promising as this indicates that this sintered product is granular in nature and has high friction angle.

Therefore, the sintered product is sand-like and can effectively interlock to form a stable ground if used as an infilling material in a land reclamation project.

Permeability

A series of constant head permeability tests, see Fig. 11, were conducted for the sintered product from Test SL-1. The permeability value is essential in the land reclamation project, as the infill material requires a high drainage characteristic to consolidate in the fastest time to expedite construction.

The mean permeability value of the sintered product is determined to be 1.14×10^{-3} m/s, based on the equation:

$$k = \frac{VL}{Aht}$$

where

k = permeability;

V = collected volume of water;

L = length of sample;

A = Cross-section area of sample;

h = head difference; and

5 t = time required to collect volume, V .

The permeability of the sintered product from Test SL-1 falls in the category of gravel-sand mixtures. This high permeability value of the sintered product again proved that this material is truly “sand-like” and is very suitable to be used as the alternative infill material for land reclamation.

10 *Most loosely packed dry density*

The most loosely packed dry density was determined via the weight measurement of the loosely packed sintered product with a known volume. The most loosely packed dry density of sintered product from Test SL-1 is found to be in the range of 1139-1187kg/m³, which falls within the category of lightweight fine aggregate (<5mm size and <1200kg/m³).

15 *Density-Moisture Relationship*

A series of modified proctor tests were conducted according to ASTM D1557-91 to determine the density-moisture relationship, which indicates the compaction behaviour of SL-1 sintered product. Fig. 12 shows the relation between moisture content and dry unit weight of SL-1.

20 From Fig. 12, the optimum moisture content is 29%, while the maximum dry unit weight is 14.3kN/m³. By comparing these values with the typical soil type, the SL-1 sintered product can be categorised under diatomaceous or micaceous silts, which is slightly lower than the silty sands and gravels category (maximum dry unit =14.7 to 19.6kN/m³ and optimum moisture content = 10% to 20%).

25 This result shows that the SL-1 sintered product is sand-like and can be compacted, although slightly lighter than the typical silty sands and gravels based on the maximum dry unit weight.

X-ray Diffraction (XRD)

The mineralogy of the SL-1 sintered product was examined using X-ray diffraction (XRD). The XRD plot of the SL-1 sintered product was compared with the XRD plot of the raw excavated clayey soil, as shown in Fig. 13.

- 5 The primary minerals in the clayey soil are kaolinite, quartz and illite. In theory, kaolinite would transform into metakaolin at a temperature above 500°C, where metakaolin is a stronger mineral than kaolinite. Therefore, reduced kaolinite minerals in the SL-1 sintered product suggests that some kaolinite may have been changed to metakaolin.

Scanning Electron Microscopy (SEM)

- 10 In order to investigate the existence of metakaolin, a scanning electron microscope (SEM) was used because metakaolin is amorphous. The soil fabric of kaolinite and metakaolin is in layered structures, but the layer structure of metakaolin is more open than kaolinite.

Fig. 14 illustrates the SEM image of the SL-1 sintered product. Although the SEM image may not clearly show metakaolin's distinct microstructure, the square within the SEM image
15 indicates the suspected metakaolin formed in SL-1 sintered product.

Acid and Saltwater Dissolvability

- Since the sand-like material is likely to be used in the land reclamation works, it will be exposed to seawater and carbonic acid. Carbonic acid is formed when carbon dioxide in the air reacts with water. Hence, it is crucial to ensure that the sand-like material does not
20 dissolve in seawater and acidic conditions.

A quick check was carried out on the dissolvability of SL-1 sintered product in saltwater and acidic conditions. The SL-1 sintered product was soaked in seawater and pH 4 acid, in two separate columns for 28 days. The dry weight of the SL-1 sintered product before and after soaking was measured, and the difference was calculated.

- 25 The difference in dry weight of the SL-1 sintered product soaked in seawater is 0.6% of the original weight, while that of the SL-1 sintered product immersed in acid is 1.0% of the original weight. It was found that the SL-1 sintered product has almost negligible differences in dry weight after soaking in the seawater and acidic conditions. Hence, it can be concluded that sintered clay does not dissolve in seawater and acid after soaking for 28 days.

Example 2

For enabling industrial-scale production, the use of a rotary kiln for the sintering process is investigated and compared with a static furnace.

A rotary kiln is a cylindrical machine that rotates about its longitudinal axis and acts as a heat exchanger device. A rotary kiln is generally used to heat materials at temperatures high enough to bring about a chemical change, but the kiln can also be used as a rotary dryer to reduce the moisture content of materials. The heat required for sintering is delivered to the material by lifting and overturning each sample moving through the kiln. The sample in the kiln moves both radially and axially. The radial motion is controlled by rotational speed (rpm) and the amount of sample inserted, while the axial motion is governed by the kiln's inclination angle.

Heat transfer to the material in the rotary kiln occurs in three different ways: (a) heat transfer to material by convection and gas radiation, (b) heat transfer to material by brick radiation, and (c) conductive heat transfer to material from brick.

A comparison between a static furnace and a rotary kiln is summarised in Table 3.

Rotary Kiln Sintering

A series of sintering production studies were conducted using a rotating kiln and based largely on the method exemplified in Example 1, to obtain a set of optimal operating parameters for such production.

The parameters considered are sintering time (5, 10 & 15mins), kiln rotating frequency (36, 40, 44 & 48 rpm) and the initial mass of the granules (5, 10 & 15g).

Visual inspection and microscopic testing were carried out on the sintered products. As a first stage observation, visual inspection is carried out to determine whether the sintered products are completely sintered or un-sintered. The sintered products are broken for inspection, and the colour of the sintered product is noted down. A completely sintered product should have a uniform orange colour throughout. An un-sintered product is grey in colour. A partially sintered product is when the shell of the sintered product is orange in colour while the core of the sintered product is still grey (marine clay original colour).

	Static Furnace	Rotary Kiln
Heating process	The heat is transferred to the samples only through the convection process.	The heat is transferred to the sample by all three modes of heat transfer—conduction, convection, radiation.
Temperature heating sequence	Temperature will be ramping up to reach the target temperature. Once the target temperature is reached, there is a dwelling period followed by a cooling period.	The target temperature and the retention can be controlled.
Sample input/output	Samples are placed inside the furnace before starting the heating ramping stage when the furnace is at room temperature. The sintered product is collected after the cooling period.	Samples are inserted into the kiln while the target temperature is reached. The sintered product is collected immediately after retention time.
Parameters controlled	Sintering temperature, ramping rate, dwelling duration, and cooling down time.	Sintering temperature, retention time, and rpm of rotation.

Table 3: Comparison between a static furnace and rotary kiln.

Characterisation of Rotary Kiln Sintered Products

Visual Inspection

All the test series were carried out at 850°C sintering temperature. The operating parameter and visual inspection results are tabulated in Tables 4 and 5.

- 5 For Test T0, where granules each of 5g were used with a sintering temperature of 850°C, 36 rpm and 5 mins of retention time, the results show that the sintered product was disintegrated after the retention time. This disintegration is because the granules have a moisture content of around 40% entering the rotary kiln at 850°C; the water inside the granules vaporizes instantly and escapes the granules. This process of instant vaporization causes the granules to "explode", resulting in an undesirable fragmented sintered product.

In the testing series, T1, T2 and T3, the initial moisture content is close to 0%, only the retention time varies (5, 10 & 15 mins). Visual observation on T1 sintered product suggests that the surface of the granules is sintered, and the core of the granules is grey, suggesting that the retention time was too short for complete sintering. T2 and T3 sintered products seem to be completely sintered, indicating a minimum retention time required is about 10 minutes.

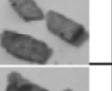
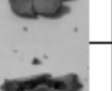
Testing series F0, F1, F2 and F3 were conducted with the rotation frequency of the rotary kiln at 0, 40, 44 & 48 rpm, respectively. All four test series have 10 minutes retention time. F0 simulates a static furnace, but the retention time of 10 minutes is too short for the granules to be fully sintered. Under F3 testing with 48 rpm, the granules are well sintered; however, some breakdown particles were observed due to particle-to-particle collision because of the high rotation speed. Both test series F1 and F2 with 40rpm and 44rpm seem to produce well sintered and intact products.

Under M1 and M2 testing series, the initial mass of the granule is varied at 10g and 15g, respectively, while the retention time is kept at 10 minutes, and rpm is kept as 40rpm. The sintered product in M2 series is poorly sintered due to the excessive size which blocks the heat, such that some granules do not receive adequate heat energy, thus resulting in a poor sintered product. M1 testing series with 10g initial mass produces good quality, well-sintered product.

Test ID	Sample Weight (g)	Moisture Content- Before Sintering (%)	Rotating speed (rpm)	Retention Time (mins)	Visual Observation	Comments	*S/U
Original	-	~40	-	-		Original Pre-dried Sample (Grey colour)	N.A.
T0	5	~40	36	5		Sintered product "explodes" and breaks into small pieces	U
T1	5	~0	36	5		Some samples showed poor sintering	U
T2	5	~0	36	10		Clay sintered uniformly	S
T3	5	~0	36	15		Clay sintered uniformly	S

*S – Satisfactory, U - Unsatisfactory

Table 4: Operating parameter and visual inspection results for original clay and Test series T.

Test ID	Sample Weight (g)	Moisture Content- Before Sintering (%)	Rotating speed (rpm)	Retention Time (mins)	Visual Observation	Comments	*S/U
F0	5	~0	0	10		Not fully sintered	U
F1	5	~0	40	10		Clay sintered uniformly	S
F2	5	~0	44	10		Clay sintered uniformly	S
F3	5	~0	48	10		Inter-particle breaking is observed due to high rotating frequency	U
M1	10	~0	40	10		Clay sintered uniformly	S
M2	15	~0	40	10		Very Poorly Sintered	U

*S – Satisfactory, U - Unsatisfactory

Table 5: Operating parameter and visual inspection results for original clay and Test series F and M.

X-ray Diffraction (XRD)

The mineralogy of the fully sintered products (i.e. M1, F1, F2, T2 and T3) were examined using X-ray diffraction (XRD) and the results are shown in Fig. 15 against the original clayey soil.

- 5 The mineral phase transformation of kaolinite to metakaolinite is expected when the clay sample is subjected to a sintering temperature of 850°C - 900°C. As seen in Fig. 15, kaolinite was found in the original sample, which, upon sintering, is no longer detected by XRD testing. This change is consistent across all the samples deemed fully sintered by visual inspection. The presence of metakaolinite is not detected by XRD Test as it is an amorphous
10 aluminosilicate (Panesar, 2019) but can be identified using a Scanning Electron Microscope (SEM).

Scanning Electron Microscopy (SEM)

Once it was established that kaolinite was no longer present in sintered clay sample by XRD testing, a SEM inspection was conducted to detect the presence of metakaolinite, if any.

- 15 Fig. 16 shows the SEM picture of one sintered product, which clearly shows the presence of metakaolinite. Thus, based on the visual observations XRD and SEM results, it can be concluded that parametric combinations M1, F1, F2, T2 and T3 will produce a well-sintered product.

- Among these well-sintered testing series, Test M1 is chosen to represent the optimum
20 operating condition because more samples can be well sintered in a lesser duration, thereby being energy efficient and saving the operating cost.

Comparison with Static Furnace Sintered Products

- Test M1 sintered product (i.e. sintering temperature of 850°C, retention time of 10mins and initial mass of 10g) was compared with SL-1 sintered product of Example 1 (i.e. sintering
25 temperature of 900°C, ramp rate of 300°C/hr and dwelling period of 1hr).

Static Compression Strength

A Zwick Roell Z100 universal testing machine with a maximum testing load of 100 kN was used to obtain the ultimate compressive strength of sintered clay product.

Ten (10) randomly chosen samples kept in longitudinal direction were subjected to the static compression test with a 1 mm/min strain rate. Besides the static compressive strength testing on the sintered product, another series of static compressive strength testing is carried out on sintered products soaked in saltwater for ten (10) days and 30 days. Soaking test is carried out to determine the effect of saltwater soaking (either no effect or detrimental) on the sintered product.

The strength of the product produced using the static furnace, and rotary kiln is shown in Fig. 17. The results show that the strength of the sintered product produced using the rotary kiln is 5MPa higher than the sintered produced using the static furnace for all un-soaked and soaked conditions consistently. This increase in strength of the sintered product from the rotary kiln could be due to the more effective heat transfer modes involved in the rotary kiln.

Permeability

A constant head permeability test is carried out in accordance with ASTM D 2434-19. The permeameter is 60mm in diameter and 102 mm in length. The sintered product is compacted in three layers to achieve a density of 15kN/m³. The time taken for 100mL of water to flow under a constant head of 100 cm is noted down and the permeability is calculated using Darcy's law.

Fig. 18 shows the permeability of sintered product from the static furnace and rotary kiln, which shows that the permeabilities of the sintered products are the same ($k = 1 \times 10^{-3}$ m/s). Unlike static compressive strength, which depends on microscopic properties, the permeability of granular soil primarily depends on the packing arrangement and the particle size of the sintered product. The particle size and density of the sintered product were maintained to be the same, thereby leading to similar permeability results between sintered products. It is noted that the permeability of the sintered products lies in the range of fine to coarse sand.

Friction Angle

A consolidated drained triaxial testing, similar to Example 1, is carried out on the well-sintered product samples, and the friction angle is determined. The samples are prepared inside the membrane with vacuum pressure applied from bottom pedestal, before the confining pressure is applied. The sintered product is compacted in three layers to achieve a

density of 15kN/m^3 . Once the top cap is placed in position and the confining pressure is applied, the vacuum pressure is released. Three series of testing is carried out with confining pressures of 100kPa, 200kPa and 300 kPa. The deviatoric stress under each confining pressure is recorded and the friction angle is calculated using Mohr's circle.

- 5 The sintered product from the rotary kiln had a friction angle of 39° . With this value of friction angle, the sintered product can be classified as coarse-grained uniform sand. The effective friction angle of sintered product produced from the static furnace was 33.7° . A high friction angle of 39° is essential for a land reclamation material, and its classification also proves that the rotary kiln can sinter clayey soil into a sand-like material effectively.
- 10 The result also shows that the rotary kiln can produce sintered products of a higher friction angle than those produced by the static furnace.

Example 3

In this example, a mid-sized rotary kiln that enables a further parameter, i.e. inclination I of the kiln to be controlled is used.

15 Preparation of sintered products

Clayey soil, similar to Examples 1 and 2, was obtained and sieved through 1mm sieve to remove shells, roots and coarse sand particles. The liquid limit and plastic limit of the clayey soil are 80% and 36%, respectively. The soil classifies as “CH” clay of high plasticity according to Universal Soil Classification System (USCS).

- 20 The clayey soil obtained after initial screening has a moisture content of 80-100%. The clayey soil is dewatered to a lumpy clay by reducing the moisture content closer to plastic limit (35%) to make it suitable for next stage, where the lumpy clay is turned into smaller clay balls.

- 25 Low moisture content would result in formation of crack and high moisture content would make the clay balls sticky. The dewatered clay is then put inside an extruder with cutting blades to produce clay balls of 3mm size.

The moisture content of the clay balls is further reduced in the next pre-heating stage, whereby the clay balls are preheated in a drying rotary kiln at 100°C or higher for at least 5-10 mins.

The pre-heated clay balls are then sintered using a mid-sized rotary kiln to produce the sintered product. The mid-sized rotary kiln used in this study has a rotary furnace which is 2.2m in length and 240 mm in diameter.

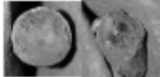
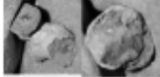
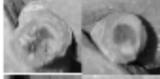
Target sintering temperature (T), kiln inclination (I) and the kiln rotation frequency (R) could be controlled by the user. The kiln inclination and rotation frequency are important parameters that control the amount of time the clay balls are retained in the rotary kiln. In other words, the parameters R and I control the retention time (t) of the clay balls in the rotary kiln.

It is important to find the optimum operating parameters for the rotary kiln to make the process energy efficient.

Characterisation of Sintered Products

Visual Inspection

First series (Test series A) of testing was carried out by maintaining the target temperature at 800°C and varying the angle of inclination ($I = 2.0^\circ, 3.0^\circ, 3.6^\circ, 4.2^\circ$ & 5.6°) and rotation frequency ($R = 8, 10$ & 12 rpm). Table 6 summarizes the visual observation of the sintered product obtained from the parametric study.

Test No.	I°	R rpm	t mins	Visual Inspection	S/U
A1	4.2	8	6.0		U
A2	3.6	8	7.67		U
A3	4.2	10	5.0		U
A4	3.6	10	6.0		U
A5	3.0	10	8.5		S
A6	5.2	12	3.0		U
A7	2.2	12	10.5		U

Note: S=Successful and U=Unsuccessful

Table 6: Operating parameters and visual inspection results for Test series A.

The retention time (t) defined here is the difference between the time of arrival of first sintered product and the time of arrival of last sintered product. In these series of testing, 50g of clay balls were used.

For example, when the 50g of clay balls are put inside the rotary kiln, the stopwatch was started. The first sintered product would arrive at 2 mins elapsed time and the last sintered product would arrive at 12 mins elapsed time. Thereby the retention time would be 10 mins.

Comparing test A1 and A2, an increase in inclination angle (I) reduces the retention time (t) of clay balls in the kiln. Similar trends are observed while comparing A3, A4 and A5, where the increase in inclination angle reduced the retention time of the clay balls.

Similarly, higher kiln rotation frequency (R) results in shorter retention time of clay balls in the rotary kiln (comparing A1 & A3 and A2 & A4). In some series of tests, there is a black core observed when the sintered product is cut open. It was thought in the beginning that this black core could be due to incomplete sintering process, where the clay balls did not have sufficient exposure to the heat energy. A more detailed analysis on the black core was carried out in the later section.

It is important to find a suitable combination of inclination and rotation frequency thereby optimizing the retention time that produces well sintered clay. Shorter retention time would result in less energy consumption of the rotary kiln. Based on visual observations, Test A5 produces well sintered clay.

Series A focuses on the importance of the retention time of the clay balls in the rotary kiln.

Apart from retention time, the other way to achieve better sintering while keeping the retention time shorter is to increase the sintering temperature.

Increasing sintering temperature would expose clay balls to more heat energy thereby reducing the time required for complete sintering. Series B testing is carried out with a sintering temperature of 900°C and the results are tabulated in Table 7.

The visual inspection of the 900°C sintered samples show black coring as well. Hence a detailed investigation of this black core was carried out via microscopic investigations (TGA and XRD) to investigate whether the 'black core' is acceptable (maybe a by-product of sintering) or unacceptable (un-sintered product).

Test No.	I°	R rpm	t mins	Visual Inspection	S/U
B1	4.2	6	6.67		U
B2	3.6	6	7.83		U
B3	3.0	6	10.50		U
B4	1.6	14	9.50		U
B5	1.6	8	13.16		U
B6	1.3	12	14.83		U
B7	1.0	10	>26		U

Table 7: Operating parameters and visual inspection results for Test series B.

Thermogravimetric Analysis (TGA) and X-ray Diffraction (XRD)

A new series of testing was carried out (Series C) to conduct the microscopic analysis. The parameters considered are summarized in Table 8. Thermogravimetric analysis (TGA) and X-Ray diffraction (XRD) testing were conducted to study the mineralogical composition of the black core and the sintered product. The results obtained from TGA and XRD analysis are shown in Fig. 19 and Fig. 20 respectively.

Test No.	Mass g	I°	R rpm	$T^\circ C$	t mins
C1	50	1.56	10	800	12.67
C2	100				14.67
C3	50			900	13.00
C4	100				15.00

Table 8: Operating parameters for Test series C.

As seen from Fig. 19, a rapid loss of weight occurs between 350°C - 700°C and a peak in the derivative of weight loss indicates that decomposition occurs at approximately 500°C. The change in mass is attributed to the process of dehydroxylation, where evaporation of chemically bounded water occurs during the decomposition of kaolinite to metakaolinite. The reduction in mass stabilizes at 800°C, indicating the completion of dehydroxylation process. Since a complete dehydroxylation is necessary to prevent the potential

disintegration of clay in water, a minimum temperature of 800°C must be used for sintering. Sintered clay without sufficient resistance against water would be unusable at land reclamation sites due to exposure to seawater and rain.

Fig. 20 (S2 & S3) shows that at sintering temperatures of 800°C and 900°C dihydroxylation has occurred, converting kaolinite into metakaolinite. As noted previously, metakaolinite is undetectable by XRD due to it being an amorphous aluminosilicate. The absence of hematite in the black core in S4 and its presence in S2 and S3 samples validates that the hematite gives the red appearance in thermally treated clay. Furthermore, the absence of kaolinite in the black core in S4 sample indicates that a certain degree of heat treatment has occurred in the black core of the clay, bringing about the process of dehydroxylation. Therefore, the presence of a black core is determined to be not due to incomplete sintering. Even with the presence of black core the sintered product would not disintegrate in water (dehydroxylation has taken place).

The microscopic analysis through TGA and XRD has proved that the black core formation does not indicate un-sintered product. Kaolinite has been converted to metakaolinite in the black core, thereby resulting in a stable sintered product.

Compressive Strength

The compressive strength of individual sintered product was tested in a Zwick compression machine at a strain rate of 1 mm/minute. Fig. 21 shows the compressive strength of individual sintered product.

The strength of sintered product obtained from the rotary kiln is 7 MPa higher than that of sintered product obtained from static furnace. This could be the result of more effective heat transfer occurring in rotary kiln.

Although various embodiments of the present invention have been shown and described in the above, the present invention is not limited to the described embodiments. Instead, it would be appreciated by those skilled in the art that changes may be made to the embodiments without departing from the scope of the invention, the scope of which is set forth in the following claims.

CLAIMS

1. A method of producing a sand-like material, the method comprising:
obtaining a clayey soil, wherein the clayey soil comprises a first mineral;
5 granulating the clayey soil to form a plurality of granules;
sintering the plurality of granules to convert the first mineral completely or partially
to a second mineral; and
cooling the plurality of sintered granules.
- 10 2. The method of claim 1, wherein the first mineral is kaolinite.
3. The method of claim 2, wherein the second mineral is metakaolinite.
4. The method of any one of claims 1 to 3, wherein a size of the plurality of granules is
15 in the range of 3mm to 5mm.
5. The method of any one of claims 1 to 4, further comprising filtering the clayey soil
to remove debris and particles before granulating.
- 20 6. The method of claim 5, wherein the step of filtering screens out debris and particles
that are more than 0.6 mm in size (coarse sand).
7. The method of claim 5 or 6, further comprising mixing the clayey soil with water to
obtain a homogenous slurry before filtering.
- 25 8. The method of any one of claims 1 to 7, further comprising dewatering the clayey
soil to reduce a moisture content of the clayey soil before granulating.
9. The method of claim 8, wherein the moisture content of the clayey soil is reduced to
30 the range of 30% to 50% by mass.
10. The method of any one of claims 1 to 9, wherein the step of granulating comprises
extruding and cutting the clayey soil.

11. The method of claim 10, wherein the extruded clayey soil has a diameter in the range of 1mm to 3mm.
12. The method of any one of claims 1 to 11, wherein the step of sintering comprises heating the plurality of granules at a temperature in the range 800°C to 900°C.
13. The method of claim 12, wherein the plurality of granules is sintered in a rotary kiln for 5 to 10 mins.
14. The method of claim 12 or 13, further comprising preheating the plurality of granules in a drying rotary kiln prior to the step of sintering.
15. The method of claim 14, wherein the plurality of granules is preheated at 100 °C or higher for at least 5-10 mins.
16. The method of any one of claims 1 to 15, wherein the step of cooling is performed in a heat exchanger to harvest heat from the plurality of sintered granules.
17. A sand-like material obtained from the method of any one of claims 1 to 16.
18. The sand-like material of claim 17, wherein the sand-like material has a static compressive strength in the range of 10MPa to 20MPa; a permeability in the range of 1×10^{-3} to 1×10^{-4} m/s; and/or a friction angle in the range of 30° to 39°.
19. Use of the sand-like material of claim 17 or 18 in land reclamation.
20. Use of the sand-like material of claim 17 or 18 to produce concrete.