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Article

Strength of Chemically Stabilized Sewage Sludge—Some Inferences from Recent Studies

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Abstract: Although there has been a substantial body of research on the chemical stabilization of sewage sludge, most of these results are project-specific and relate mainly to the use of new binders and sewage sludge from specific sources. In this sense, much of the work to date is context-specific. At present, there is still no general framework for estimating the strength of the chemically treated sludge. This paper proposes one such general framework, based on data from some recent studies. An in-depth re-interpretation of the data is first conducted, leading to the observation that sludge, which has coarse, hard particulate inclusions, such as sand, premixed into it, gives significantly higher strength. This was attributed to the hard coarse particles that lower the void ratio of treated soil, are much less susceptible to volume collapse under pressure, and contribute to the strength through frictional contacts and interlocking. This motivates the postulation of a general framework, based on the premise that coarse, hard particulate inclusions in the sludge which do not react with the binders can nonetheless contribute to the strength of the treated soil. The overall void ratio, defined as the volume of voids in the cementitious matrix normalised by the overall volume, is proposed as a parameter for quantifying the combined effect of the coarse particulate inclusions and the cementitious matrix. The binder-sludge ratio is another parameter which quantifies the strength of the cementitious matrix, excluding the hard particulate inclusions. Back-analysis of the data suggests that the significance of the binder-sludge ratio may diminish as the content of hard particulate inclusions increases.

Keywords: sewage sludge; stabilization; unconfined compressive strength; void ratio

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1. Introduction

The recycling and reuse of waste is now a grand challenge of global dimension (e.g., [1]). This challenge is complicated by the different waste streams generated, which include municipal solid waste, industrial waste which include chemical, toxic and hazardous waste, as well as sewage sludge. Each of these waste streams require different processing and treatment. This focus of this paper is on the stabilization of sewage sludge.

Sewage sludge is a mud-like semi-solid produced by wastewater treatment and the dewatering of sewage. It comprises mainly colloidal sediments containing organic material, microorganisms, toxic chemicals, and varying amounts of heavy metals. Sewage sludge differs significantly from dredged clay and silt, which are sometimes also termed "sludge" [2,3]. In general, sewage sludge has much higher organic content and plasticity index than dredged "sludge". Hence, the two cannot be considered together, and the focus of this paper is on sewage sludge. Various methods of disposing or re-using sewage sludge have been proposed, such as land spreading and agricultural purposes, land filling, re-use as construction material after treatment and incineration (e.g., [4–7]). Land spreading and agricultural usage of sludge are not major disposal avenues, since the agricultural usage and surface disposal of sludge are subjected to strict regulatory guidelines relating to the amount of toxic chemicals, heavy metals, and pathogens. Only sludge which meets strict criteria on toxicity and pathogenic organisms can be used as land spread and fertiliser. Incineration is often a preferred method of disposal, since the volume of ash produced is substantially smaller than that of the sludge, and is more readily disposed as landfill. However, sludge incineration facilities are still not available in many parts of the world. In such cases, chemical stabilization followed by burial as landfill is commonly adopted. Furthermore, sewage sludge that has been buried in un-incinerated form in previous landfills may need to be stabilized if the ground is to be re-developed.

Landfill disposal of sewage sludge is also subjected to regulatory guidelines regarding heavy metals and toxic chemicals, but this is often less stringent than land spreading and agricultural usage, since the sludge is often buried beneath the soil surface. In many applications involving the long-term use of treated sludge as a foundation or subgrade soil, however, strength is an important parameter.

Many studies have been conducted on different sewage sludge and soil admixtures with different binders and mix ratios (e.g., [8–12]). However, much of the studies are targeted towards sludge from specific sources and the use of specific new binders. Their results cannot be readily adopted for other sludge and binders. To date, guidelines for assessing the effects of binders and mix ratios on likely strength gain remain scarce. Indeed, the current understanding of the interaction between binder, sludge and water content remains nebulous. In most projects, binder is often selected on the basis of past experience, and binder performance is evaluated on a site-specific basis by trial mix testing, since there is still no well-established conceptual guideline or framework which can be used to give even a rough assessment of binder performance.

The objective of this paper is to assess the feasibility of establishing some general predictive framework for the strength gain of chemically stabilized sewage sludge, based on a study of data from previous studies on treated sewage sludge. The chemical stabilization approach dealt with herein typically involves chemical admixture at or near room temperature, since it can be readily applied in situ. Higher temperature processes such as incineration and pyrolysis are not readily applied in situ, and thus not considered herein. The results indicate that the resulting strength gain depends significantly on the void ratio, and thus water content as well as the binder-to-sludge ratio of the treated soil. By adding an inert coarse-grained filler such as sand, a significant decrease in void ratio can be achieved, with consequent increases in strength, without necessarily increasing the amount of binder.

2. Composition of Sewage and Wastewater Sludge

The composition of sewage and wastewater sludge varies considerably between sources. However, organic matter is commonly present in substantial concentrations. Typical organic content ranges from about 10% to more than 40% (e.g., [11,13,14]). Other constituents which are present in significant concentrations include nitrogen, calcium, phosphorus, silicon, potassium, magnesium (e.g., [15,16]). In addition, sewage sludge ash also contains significant amounts of silicon oxide, aluminium oxide, and iron oxide (e.g., [17,18]). This suggests that significant amounts of silicon, aluminium, and iron are also present in sludge. In addition, the presence of trace quantities of heavy metals, such as chromium, copper, nickel, zinc and lead, has also been widely reported (e.g., [15,19]).

Sewage sludge is typically characterized by high liquid limit and plasticity index, as well as natural water content, all of which are typically greater than 200%. This is similar to the behaviour of some soils with high organic content (e.g., [20,21]).

3. Previous Studies on the Strength of Treated Sewage Sludge

As Tables 1 and 2 show, recent works on chemical treatment of sewage sludge can be classified into two broad categories; those involving treatment of sewage sludge alone, hereafter termed “pure sewage sludge”, and those involving a mixture of sewage sludge with a substantial proportion of sand or sandy soil, hereafter termed “sandy sewage sludge”. Some studies involving non-sewage sludge were not included in this study. For instance, refs [2,3] used sludge which was dredged from the seabed rather than produced by wastewater or sewage treatment. The sludge used in [2,3] is comprised mainly of silt and clay and has significantly lower liquid limit than typical sewage sludge.

Table 1. Studies on treatment of pure sewage sludge.

Authors	Sludge Type	Binder(s)	Results
[14]	Dewatered wastewater sludge. PI = 256%, water content = 314–357% [this is the water content of the raw, that is untreated, sludge]. Organic content = 42.8%.	Sludge:OPC:bentonite = 1:0:0.5 to 1:0.4:0.4.	Strength ranges from ~12 kPa to ~500 kPa [for OPC and bentonite content of 40% and 40%, respectively]. Initial water content has significant effect on final strength, especially at high OPC content.
[22]	Dewatered sewage sludge. Water content = 78%.	OPC and modified steel slag, which consists of steel slag, activator (consisting mainly of Al_2O_3, SiO_2 and CaO) and gypsum. Binder content ~20%.	14-day strength of treated sludge: With 20% modified steel slag 74.5 kPa With OPC 29.5 kPa).
[11]	Sewage sludge. Water content = 83%, organic content = 38%.	Proprietary binder Sulphoaluminate-based cement: OPC:CaO:gypsum:lithium salt = 0.30:0.60:0.05:0.049:0.001. Binder:sludge solids content = 118%.	Dependent upon initial moisture: (a) Initial moisture content = 56%, treated strength ~580 kPa. (b) Initial moisture content = 85%, treated strength ~60 kPa. Strength decreases rapidly with moisture content.
[12]	Sewage sludge. LL = 380%, PL = 63%, water content = 566%. SiO_2 45%, Al_2O_3 16.4%, CaO 5.6%. Sludge has a shortage of CaO.	Sludge solids:soda residue:GGBS:CaO = 1:2 to 3.33:1.33:0.8.Total binder:sludge solid ratio = 4.13 to 5.46:1. Total water content = 85.8% to 68.2%. Note: this is very high binder: sludge ratio.	Unconfined compressive strength range: (a) Mix ratio 1:2:1.33:0.8, water content 85.8% gives strength of ~220 kPa. (b) Mix ratio 1:2.66:1.33:0.8, water content 82.1% gives strength of ~280 kPa. (c) Mix ratio 1:3.33:1.33:0.8, water content 68.2% gives strength of ~410 kPa.

Table 2. Studies on treatment of sandy sewage sludge.

Authors	Sludge Type	Binder(s)	Results
[13]	Mixture of dried sewage sludge (from wastewater treatment plants Psyttalia and Metamorphosis) and sand. Total organic content 30% (Psyttalia) and 10% (Metamorphosis). Sand content (sand/(sludge + sand)) from 86%–95%.	OPC + jarosite/alunite. Binder:sludge ratio = 100% to 333%. Binder:(sludge + sand) = 14.4% to 15.8%. Total water content from ~18% to ~21%.	28-day strength range: ~86 kPa (for binder:pure sludge ratio of 100%) to 3000 kPa (binder:pure sludge ratio 300%).
[7]	Mixture of dried sewage sludge (from wastewater treatment plant Metamorphosis) and sand. Total organic content 10%. Sand content from 91.6% to 95.2%.	Binder consists of OPC with 0.5% to 1.5% of $CaCl_2$ (bihydrate) and $Ca(OH)_2$. Binder:sludge ratio = 100% to 333%. Binder:(sludge + sand) = 14.4% to 15.8%. Total water content from ~3.7% to ~11%.	28-day strength range: 80 kPa (for binder:sludge ratio of 1.82; binder/(sludge + sand) = 15.3%) to 1426 kPa (binder:sludge ratio of 333%; binder/(sludge + sand) = 15.9%).
[23]	Mixture of dried sewage sludge (from wastewater treatment plant Metamorphosis) and sand. Total organic content 10%. Sand content 96.5%.	OPC+jarosite/alunite. Binder: sludge ratio = 454%. Binder:(sludge + sand) = 16%. Total water content from ~8.3%.	28-day strength range: ~2.64 MPa to 4.814 MPa under different curing conditions.
[9]	Mixture of dried sewage sludge (from wastewater treatment plants Psyttalia and Metamorphosis) and sand. Total organic content 30% (Psyttalia) and 10% (Metamorphosis). Sand content from 86–95%. There is little or no Si or Al in the sludge	OPC and OPC+bentonite. Binder:sludge ratios: (a) 100% for sludge solids from Psyttalia or Metamorphosis; (b) 294% for wet Psyttalia sludge; (c) 333% for wet Metamorphosis sludge.	28-day strength range: 85 kPa (binder:sludge ratio 100% to 1.4 MPa (binder:sludge ratio 333%). showed higher compressive strength than the minimum limit of the 350 kPa at 28 days.
[10]	Sludge-soil containing 10% sewage sludge and 90% sandy soil. Sludge: LL = 40%, PL = 27%, natural water content = 22%. Silica content 28.5%. Alumina content 13.2%. Soil consists of 91% sand and 9% fines. LL~23%, PL~17%. Natural moisture content = 16%. Sand content in sludge-soil mixture = 81.9%.	3 types of binders used; lime, OPC and asphaltic emulsion. Binder content 2% to 8%.	28-day strength: Lime: 1000 kPa–1300 kPa. OPC: 489 kPa–1200 kPa [at low content, lime works better than cement. At higher content, they have similar strength] Asphaltic emulsion: 851 kPa to 1016 kPa.

Table 2. *Cont.*

Authors	Sludge Type	Binder(s)	Results
[24]	Mixture of (a) Sewage sludge. Organic content = 34.5%, water content = 198%; and (b) MSWI bottom ash. Water content = 14.9%. Bottom ash has large grain size, similar to sand. Ash:Sludge = 0.5 to 2.0. Ash content = 33.3% to 66.7%.	Three types of binders used: OPC, lime and gypsum, used separately. Binder:sludge ratio from 0.3 to 0.9. Total water content = ~48% to ~86% (roughly)	28-day strength of treated soil: (a) For lime: ~20 kPa to 55 kPa. (b) For OPC: ~80 kPa to ~90 kPa. (c) For gypsum: ~90 kPa to ~110 kPa.

Ref. [25] noted that the improvement of soft clay using ordinary Portland cement (OPC) arises from two chemical reactions, namely the hydration reaction between OPC and water, and the pozzolanic reaction between the binder chemicals and the soft clay minerals. Although various combinations of binders have been studied for sludge, the components of the binders used also rely on similar cementitious reactions, as follows:

(a) Hydration reaction. The main ingredient used for hydration-based hardening is OPC (e.g., [8–11,13,14,22–24]), which undergoes hydration-hardening to produce calcium silicate hydrate and calcium aluminate hydrate. Moreover, [11] used sulphoaluminate cement, which also undergoes hydration reaction to produce similar hydration products (e.g., [25]). In some studies, quicklime (CaO) and gypsum were also used (e.g., [11,12,22,24]). However, while quicklime hydrates under water, the reaction does not result in the hardening of admixture. Calcined gypsum, also known as "plaster of Paris", undergoes hydration-hardening in contact with water, but hydrated gypsum does not. It is unclear if these studies used calcined or hydrated gypsum. Moreover, they were used in relatively small quantities, typically 5% or less of the total mass of binder, as activators or dehydrating agent. Hence, their contribution to the production of cementitious chemicals is thus likely to be relatively small compared to the other components in the binder, such as OPC.

(b) Pozzolanic reaction. The pozzolanic materials used for treatment include OPC, ground granulated blast furnace slag (GGBS) (e.g., [12]), steel slag, lime (e.g., [10,18,24]), and bentonite (e.g., [14,26]). The pozzolanic reaction typically occurs between lime (CaO) and pozzolans, in the presence of water. The main pozzolans are silica (SiO_2) and alumina (Al_2O_3). The reaction between silica and hydrated lime can be summarized by the equation

$$Ca(OH)_2 + H_4SiO_4 \rightarrow CaH_2SiO_4{\cdot}2H_2O \quad (1)$$

which also produces calcium silicate hydrate ($CaH_2SiO_4{\cdot}2\,H_2O$). The primary components of GGBS and steel slag are quicklime and silica, which will undergo pozzolanic reaction in the presence of water. The hydration of OPC also produces lime, which will undergo pozzolanic reaction if silica or alumina is available. Bentonite comprises mainly montmorillonite, which is also rich in silica and alumina, and may be able to react with lime. Alunite [$KAl_3(SO_4)_2(OH)_6$], which was used as a binder component by [13], is a hydroxylated aluminium potassium sulphate mineral. Furthermore, [26] noted that alunite can enhance the strength of cement, owing to the pozzolanic reaction between the lime produced by the hydration reaction and the Al^{3+} ions released by alunite dissolution, which forms calcium aluminate hydrate, a cementitious material. In addition, [27] noted that lime produced by the hydration of OPC undergoes pozzolanic reaction with the silica and alumina in kaolinite, until the latter is exhausted. This suggests that there may be an optimal proportion of binder and sludge, which would ensure that all of the active ingredients are utilized. Furthermore, unused ingredients which are uncemented may weaken, rather than strengthen, the soil matrix.

Non-hydration and non-pozzolanic binders have also been studied. Moreover, [10] used asphaltic emulsion, which relies on the hardening of the asphalt to solidify sewage sludge. This appears to yield comparable performance to lime and OPC, but is probably only applicable to unsaturated sludge-sand admixture in a compacted state. However, such binders are not in wide use, and [10] were investigating it in relation to usage as pavement base or subgrade layers. For these reasons, asphaltic emulsion will be excluded from subsequent discussion.

In many studies, sand has also been included in the admixture, Table 2. Although silica, the primary mineral of quartz sand, is pozzolanic, sand is unable to sustain the pozzolanic reaction, since its surface area for chemical reaction is limited by its large grain size. Hence, it is likely to be an inert filler material. Furthermore, ref. [24] also added bottom ash derived from incineration of municipal solid waste, termed "MSWI ash", instead of sand, into the sludge admixture. Bottom ash is typically rich in silica, lime, and alumina (e.g., [28]), and is pozzolanic [29]. However, the particle size of the MSWI ash used by [24] ranges from 0.1 mm to 10 mm, which implies that the particles are sand and gravel-sized. Hence, the ratio of surface area to volume is similar to that of coarse sand, and the particles are unlikely to be surface active chemically. For this reason, it is likely to behave similarly to a mixture of sludge and sand.

4. Bases of Comparison

As Tables 1 and 2 show, the binder types and compositions differ significantly between studies. The sludge properties and its water content also vary significantly. Finally, the unconfined compressive strength (UCS) of the treated sludge also varies over a wide range from about 20 kPa to more than 4.8 MPa. This greatly complicates an in-depth study of the interaction between binders and sludge. In order to assess the effect of the different types of binders and sludge, the effect of binder and water contents was first investigated.

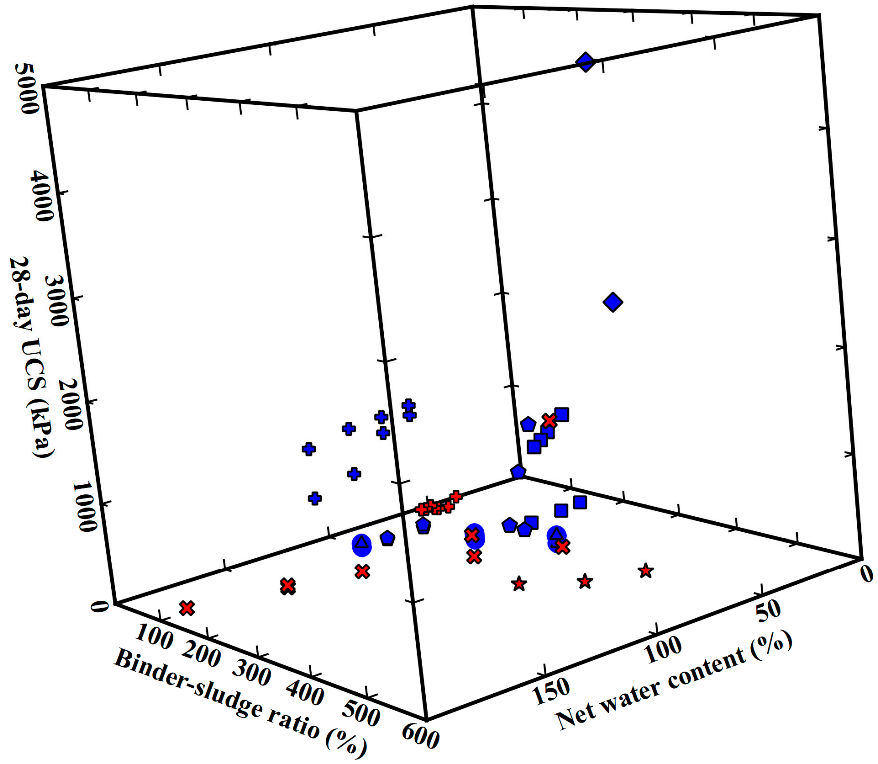
Two measures of binder mass ratio are used herein. The first, termed hereafter as binder-sludge ratio, is defined hereafter as the ratio of the mass of binder to the mass of sludge solids, but excluding sand and other "inert" particles, such as bottom ash. This measure is applicable to pure and sandy sewage sludge. The second, termed hereafter as binder content (e.g., [27,30]), is defined as the ratio of the mass of binder to the mass of all other solids, inclusive of sludge and sand. For the pure sewage sludge, both measures are equivalent.

Similarly, two measures of water content are used herein. The first, termed hereafter as total water content, is defined as the ratio of the mass of water to the mass of all other solids, inclusive of sludge and sand. This also follows the definition of water content used by previous researchers (e.g., [27,30]). The second measure, termed hereafter as net water content, is defined hereafter as the ratio of the mass of water to the mass of sludge and binder solids, but excluding sand and bottom ash. The use of these two measures of binder and water contents is to facilitate direct comparison between the studies on pure sewage sludge, and those which include sand and other inert filler particles. It is also to allow the effect of the inert filler particles to be assessed.

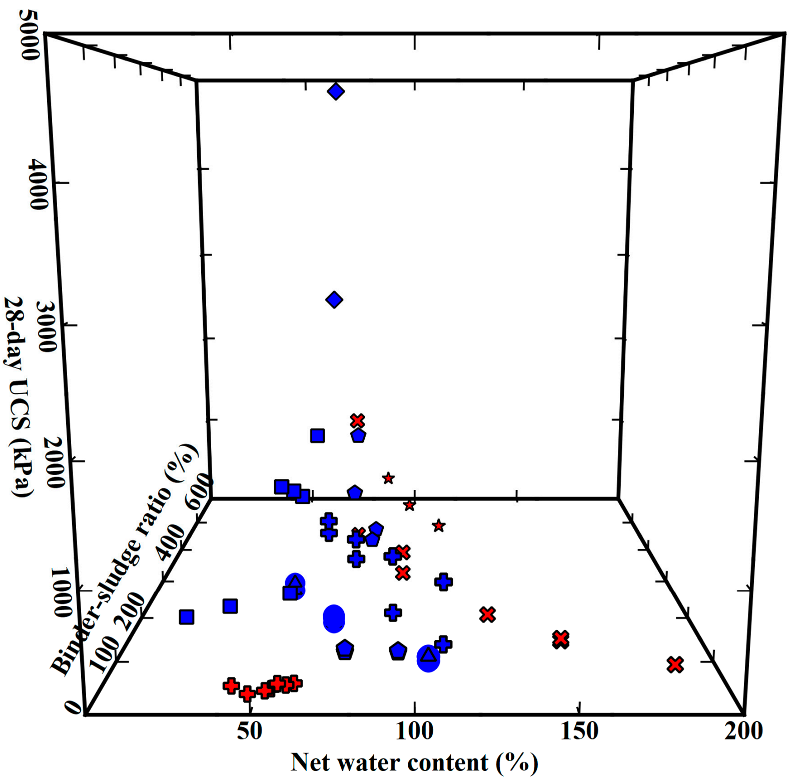
5. Proposed Framework

5.1. Binder Content and Binder-Sludge Ratio

Figure 1a–c show the three-dimensional plots of 28-day UCS against the binder content and net water contents, in a different perspective. The data in [22] cannot be included, since they only measured 14-day UCS. As the plots show, there is a general trend of UCS increasing with binder-sludge ratio and decreasing with net water content. However, the data show considerable scatter, which suggests that the influential factors may not have been adequately accounted for.

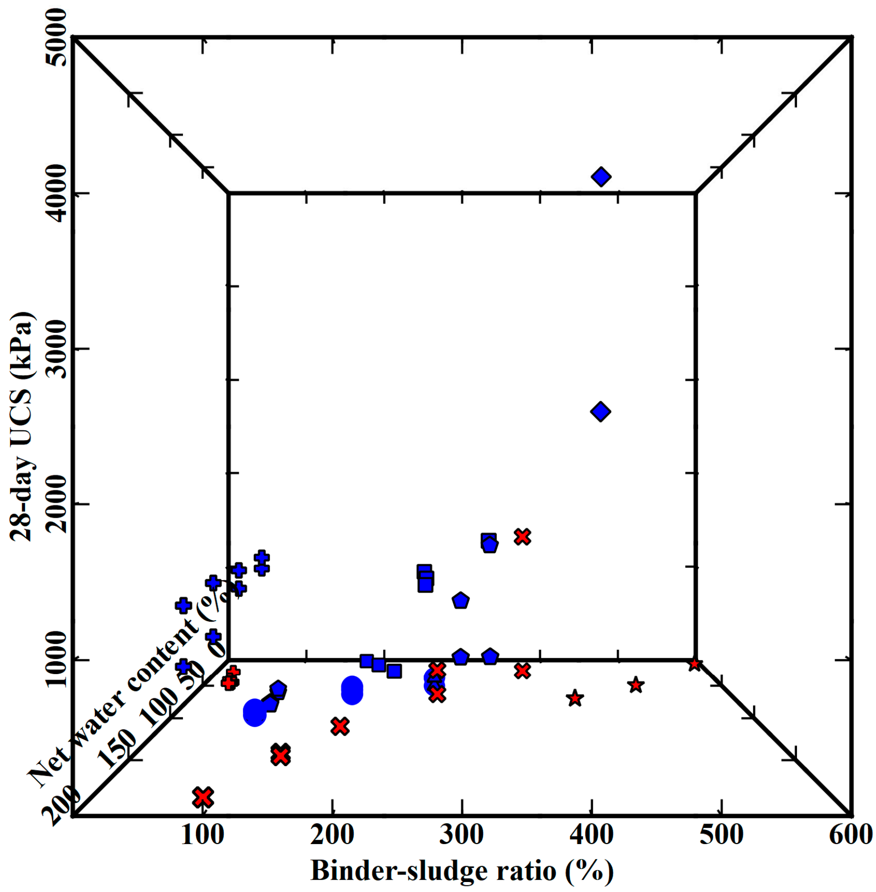


(**a**)



(**b**)

Figure 1. *Cont.*



(**c**)

Legend:

Pure sewage sludge

✖ [14]

✚ [11]

★ [12]

Sandy sewage sludge (including sludge and bottom ash)

● [13]

✚ [10]

■ [8]

◆ [23]

▲ [24]

⬟ [9]

Figure 1. 28-day UCS against binder-sludge ratio and water content. (**a**) axonometric (**b**) frontal and (**c**) side perspectives. Red and blue data points represent data from pure and sandy sewage sludge, respectively.

Figures 2 and 3 show the 28-day UCS against binder content for different ranges of total and net water content. As can be seen, the data are highly polarized, with a cluster of data banded around the horizontal axis, indicating high binder content and low UCS, and another cluster banded around the vertical axis, indicating low binder content and high UCS. This suggests that binder content may not be an appropriate parameter to harmonise the effect of binder and other components on UCS.

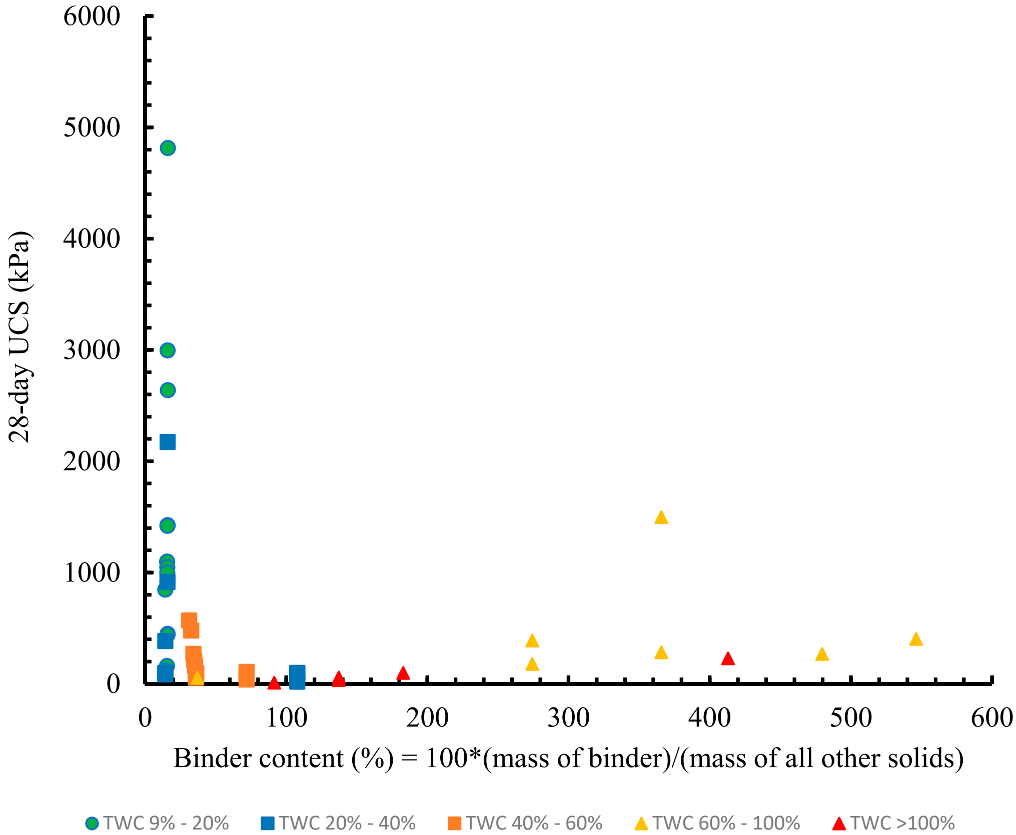


Figure 2. 28-day UCS against binder content $= \left(100 * \frac{\text{mass of binder}}{\text{mass of all other solids}}\right)\%$ for different ranges of total water content (TWC).

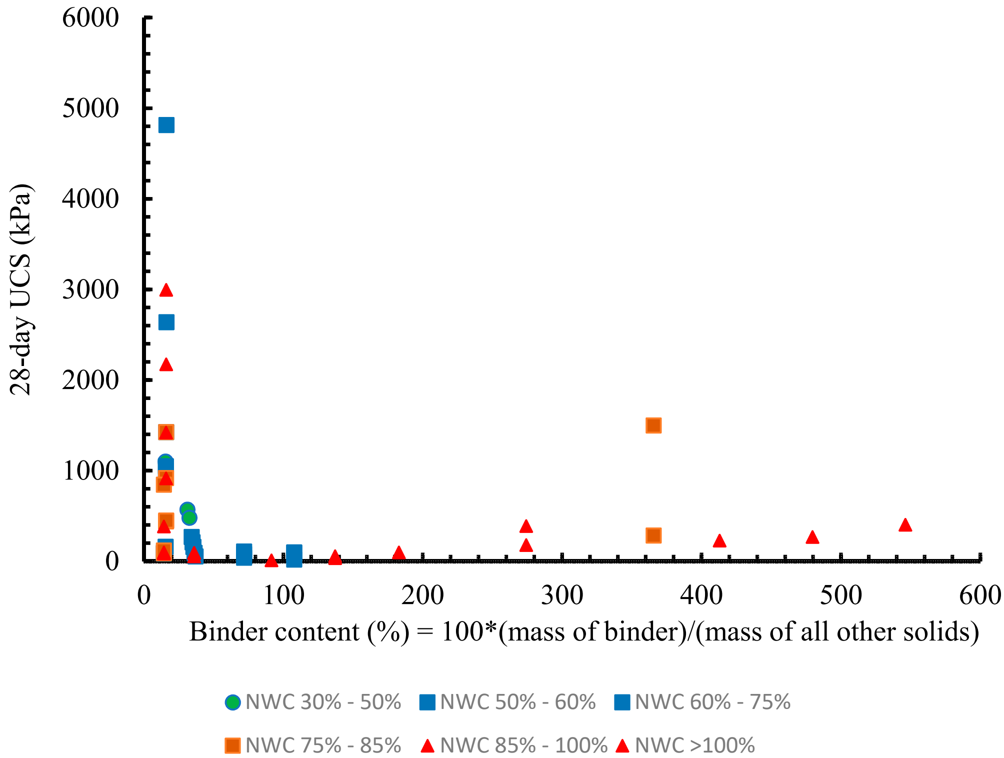


Figure 3. 28-day UCS against binder content $= \left(100 * \frac{\text{mass of binder}}{\text{mass of all other solids}}\right)\%$ for different ranges of net water content (NWC).

Examination of the data indicates that the cluster which is banded around the horizontal axis comprises mainly data from the pure sewage sludge, whereas the cluster which is banded around the vertical axis comprises mainly data from the sandy sewage sludge. This indicates that the effects of the binder on the sludge and sand solids differ significantly, so that sludge and sand solids cannot be considered together as materials to be improved.

Figures 4 and 5 show the 28-day UCS against the binder-sludge ratio banded according to the total and net water contents. As can be seen, there is much better merging of the data points, and the trend of UCS increasing with binder-sludge ratio is much clearer than that with binder content. As these two figures show, for binder-sludge ratio below about 250%, the trends for treated pure and sandy sewage sludge are well-merged, indicating no significant difference in strength gain characteristic. For binder-sludge ratio about 250%, the trend bifurcates into two, with the sandy sewage sludge showing much higher strength gain than the pure sewage sludge for the same binder-sludge ratio. The separation in the trends is reflected, to some degree, in the total water content, Figure 4, where the sandy sewage sludge specimens with uptrending strength generally show lower total water content than the pure sewage sludge, for the same binder-sludge ratio. On the other hand, there is no clear distinction in net water content between the data in the two trends. All this indicates that, at high binder-sludge ratio, the introduction of sand into the sludge can result in significantly higher strength gain compared to pure sewage sludge.

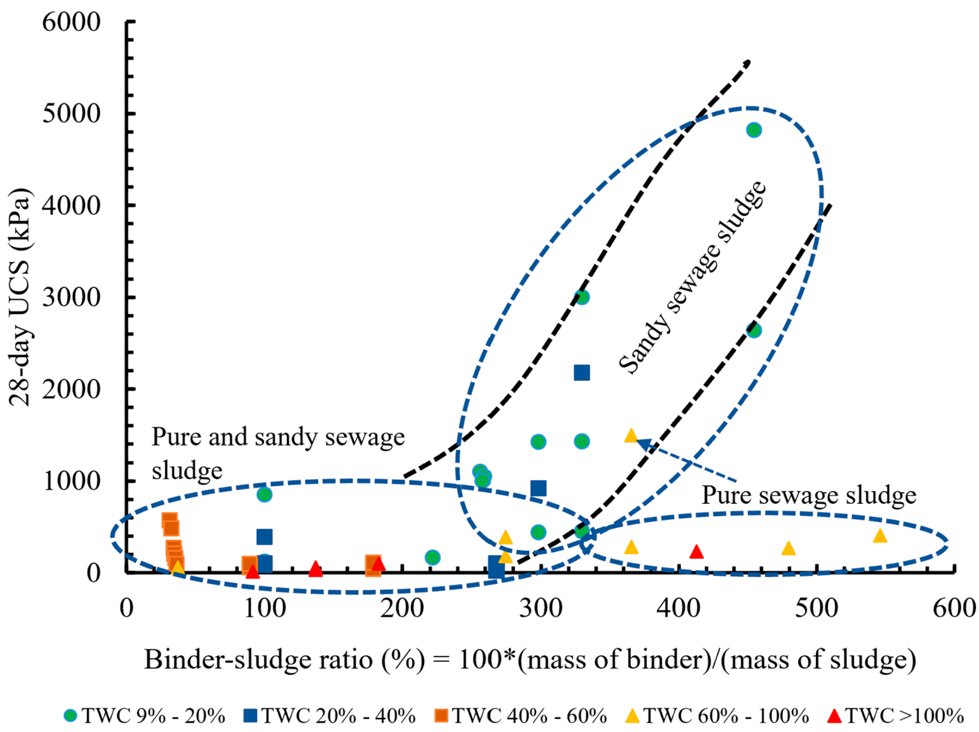


Figure 4. 28-day UCS against binder-sludge ratio $= \left(100 * \frac{\text{mass of binder}}{\text{mass of sludge solids}}\right)\%$ for different ranges of total water content (TWC).

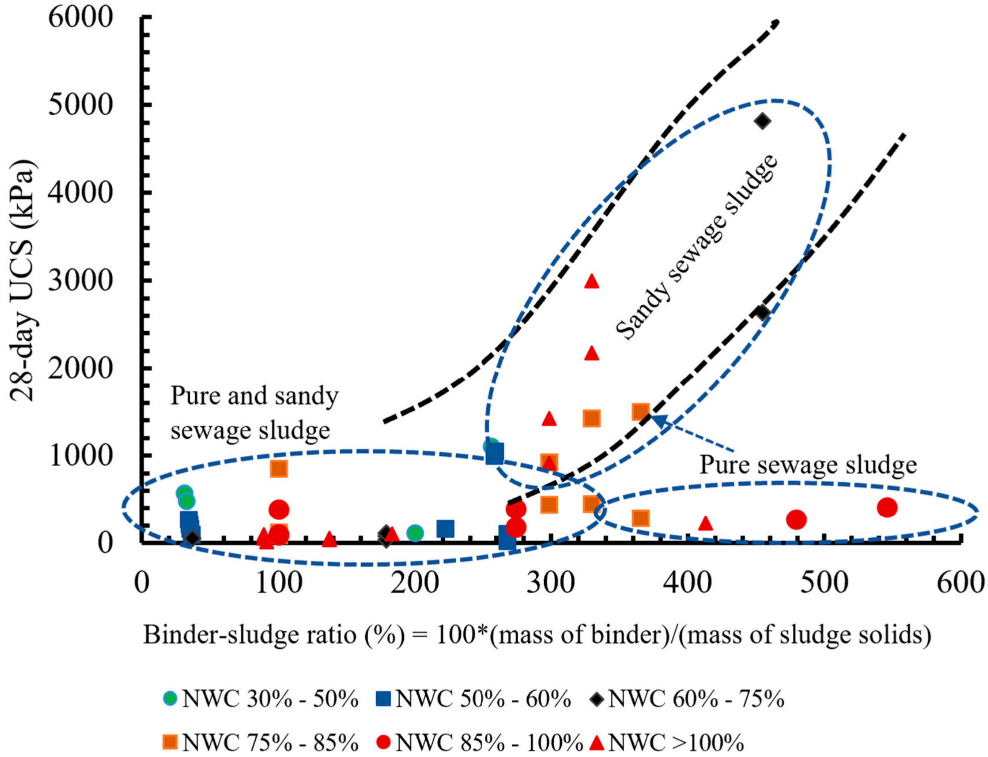


Figure 5. 28-day UCS against binder-sludge ratio $= \left(100 * \frac{\text{mass of binder}}{\text{mass of sludge solids}}\right)\%$ for different ranges of net water content (NWC).

As Figures 4 and 5 show, some scatter in the data still remains. This is not surprising and is readily attributable to the differing efficacy and hardening rates of the various binders used, in relation to the type and amount of sludge solids. For instance, data from [13] showed that, for approximately the same total water content, sandy sewage sludge with binder-sludge ratio of approximately 100% shows higher strength gain with a binder mixture of cement and jarosite/alunite than with just cement. On the other hand, for binder-sludge ratio of approximately 300% or higher, the cement-jarosite mix gives lower strength gain than just cement for the same binder content. This indicates that binder efficacy has a significant influence, and may vary as the binder-sludge ratio changes.

5.2. Postulated Structure and Strength of Treated Sandy Sewage Sludge (Coarse, Hard Particulate Inclusion in Sludge)

The above observations may be explained by a conceptual framework relating to the structure and strength of chemically treated sandy sewage sludge. The fact that binder-sludge ratio harmonises the trend for the pure and sandy sewage sludge better than binder content supports the assumption that the sand and other coarse particles do not participate actively in the chemical reactions involved in the stabilization process. The crushing strength of silicaceous sand particles ranges from about 10 MPa to about 70 MPa [31]. This is much higher than the strength of stabilised sewage sludge. Hence, treated sandy sewage sludge is a composite material comprising an assemblage of hard coarse particles embedded within a cementitious matrix produced by the binder-sludge reaction.

The crushing strength of the bottom ash particles used by [24] is probably lower than that of sand. However, they have been proposed for use as aggregates in high-strength concrete with compressive strength of 60 MPa to 80 MPa [32]. This suggests that the crushing strength of the bottom ash particle is likely to be still much higher than the strength of the treated sewage sludge. Hence, the bottom ash particles are also likely to behave as hard inclusion in a cementitious matrix in [24] study.

Ref. [33] noted that, if the volume ratio of coarse particle exceeds about 70% of the total volume, then the coarse particles will be in contact. Based on this, the sand particles in [8,9,13,23] are likely to be in contact with one another. Coarse particles which are in contact will probably be able to contribute to the strength of the soil through frictional contacts. In addition, densely packed particulate assemblage can also produce substantial enhancement to its strength through the additional work required to overcome interlocking under ambient effective confining stress (e.g., [34,35]) generated by the hardened cementitious matrix encapsulating and infilling these sandy particles. In contrast to [8,9,13,23], the proportion of bottom ash used by [24] is below 70%. Hence, the coarse bottom ash particles may not be in contact with one another; they would behave as inclusions floating in a treated sludge matrix. For this reason, the strength contribution by the bottom ash in [24] test specimens is likely to be smaller than in [8,9,13,23] specimens.

Moreover, since the sand particles have much higher crushing strength and lower void ratio than the cementitious matrix, the overall compressive stiffness and isotropic yield stress of the composite material are also likely to be higher than those of the cementitious matrix alone. Finally, rupture planes which would otherwise be able to propagate through the cementitious matrix may be obstructed by sand particles, thereby resulting in further enhancement to the strength. Any failure mechanism is thus likely to involve relative movement between the sand particles, rather than the shearing and crushing of the sand particles themselves.

5.3. Void Ratio as a Possible Characterising Parameter

The fact that the presence of the sand particles will lower the void ratio and raise the strength of the composite material suggests that, at a phenomenological level, it may be possible to use the overall void ratio of the composite as a characterising parameter. Figure 6 shows the 28-day UCS against the void ratio at the point of mixing. The post-curing void ratio was generally not reported. Moreover, refs [36,37] proposed a method for estimating the post-curing unit weight and void ratio of cement-treated soil, but this only applies to the hydration reaction of OPC. Based on the [36,37] model, the void ratio may decrease by up to about 15% during curing. This implies that the void ratio at the point of mixing is not equal to, but may serve as, a reasonable first approximation of the post-curing void ratio.

In calculating the overall void ratio, the sand and bottom ash particles are assumed to have a void ratio of zero. While this is not strictly correct, it is consistent with the assumption that the sand and bottom ash behave as hard particles which do not undergo crushing during loading. Hence, the void ratio defined herein is that of the cementitious matrix normalised over the entire volume of the composite matrix.

As Figure 6 shows, the data indicate an inverse relationship between 28-day UCS and void ratio, which is to be expected. However, the data are also dual-banded, with the sandy sewage sludge data and [11] pure sewage sludge data on the left, and the rest of the pure sewage sludge data on the right. Examination of the data shows that the binder-sludge ratio and water content used by [11] are far lower than those used by the other pure sewage sludge studies. The lower water content leads to a low void ratio, but the low binder-sludge ratio prevents a higher strength from being attained. This indicates that the binder-sludge ratio should be included in order to approximately account for the strength of the stabilised binder-sludge admixture.

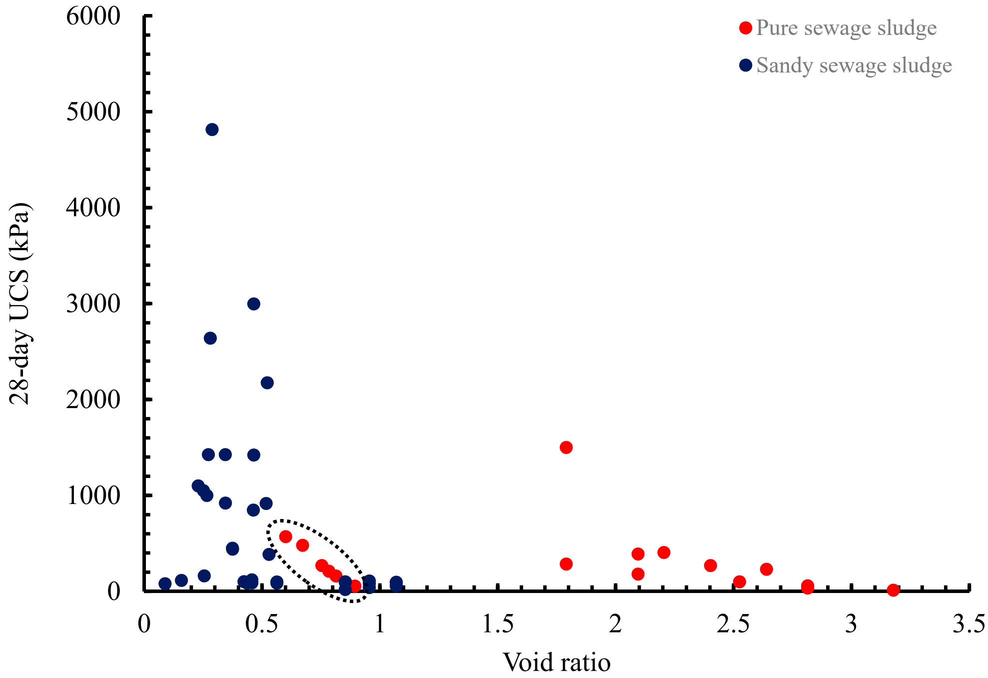


Figure 6. 28-day UCS against void ratio at the point of mixing. Red points within broken. Ellipse is data from [11].

Figure 7 shows the 28-day UCS against a composite parameter Π, defined as

$$\Pi = \frac{e}{\eta^{a}} \tag{2}$$

in which e is the void ratio, η is the binder-sludge ratio expressed as a fraction instead of percentage, and a is the significance index. The higher the value of a, the more significant is the binder-sludge ratio η in influencing the 28-day UCS. Using a = 0.47 allows [11] data to fall into the same band as the rest of the pure sewage sludge, albeit there is still some spread in the data points. This data scatter can be attributed to the different efficacy of different binder-sludge mixes.

As Figure 7 shows, sandy sewage sludge can also be merged into the same band as the pure sewage sludge by using a = 0.31. This is lower than the a-value for pure sewage sludge, and suggests reduced reliance on the binder-sludge ratio. This is not surprising since, as discussed earlier, the high sand content in all these studies, typically 86% to 96%, would allow the sand particles to come into contact and contribute significantly to the strength of the composite material. Finally, ref [24] data harmonise better with a slightly higher a-value of 0.35; this being consistent with the fact that, since the ash content is below 70%, the ash particles may not behave as an assemblage of rough particles in contact with one another, and their contribution to the overall strength is correspondingly reduced. For this reason, greater reliance is placed on the binder-sludge ratio as a contributory factor to the strength of the cementitious matrix. The curved upper boundary formed by the data points may be surmised to be representative of the upper limit in strength gain, which can be achieved in the chemical stabilization of sewage sludge. The data scatter below this upper limit may be attributed to the different efficacy of binder types and mix ratios.

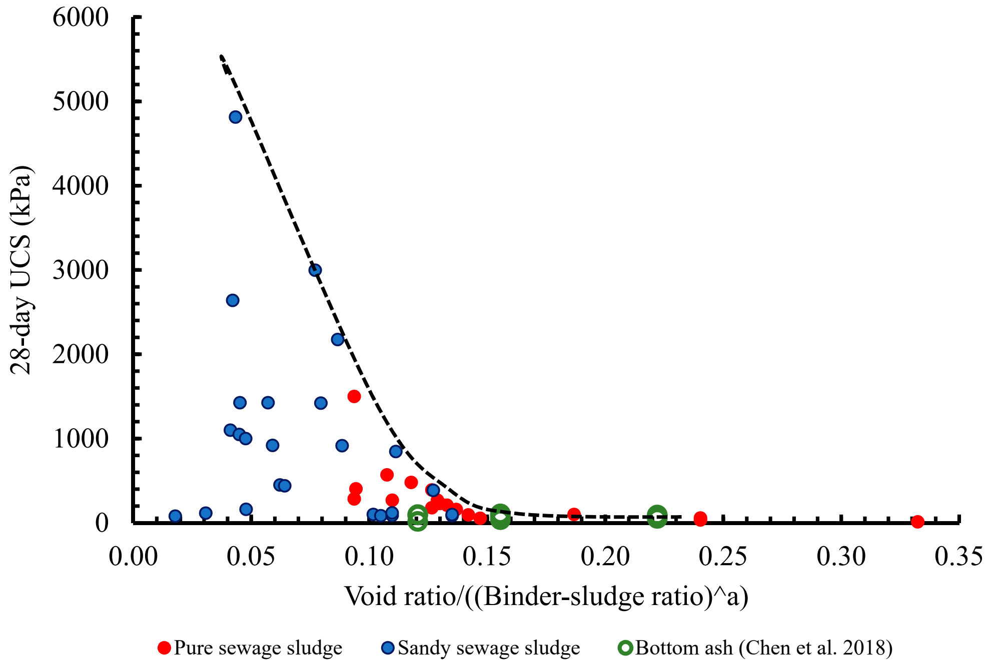


Figure 7. 28-day UCS against Π at the point of mixing [25].

Figure 8 shows the variation of the *a*-value with the content of sand (coarse particles) in the sludge. The sand content is defined as the weight of sand divided by the weight of sand and sludge. The dashed horizontal arrows denote the spread in coarse particle content in the various studies. As can be seen, there is a consistent decrease in the value of *a* as the percentage of coarse particles increase. Based on the conceptual framework of strength contribution by the coarse particles postulated above, this indicates that, as the percentage of coarse particles increases, the strength contribution from friction and interlocking of the coarse particles also increases, leading to a decreased reliance on the binder-sludge ratio, and thereby the strength, of the cementitious matrix itself.

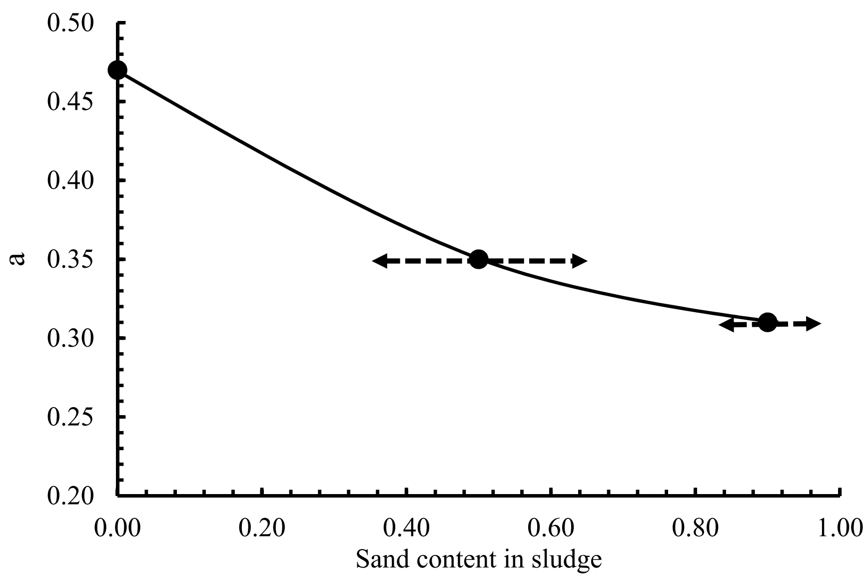


Figure 8. Variation of significance index *a* with the content of coarse particles in sludge. Dashed arrows show the range of sand content.

6. Conclusions

The foregoing discussion shows that, notwithstanding the large variety of sludge and binder types and mix ratios, it may still be possible to harmonise the results of these studies under a general framework, based on the following premises:

(a) The binder-sludge ratio is a relevant parameter, as it quantifies a contributory factor to the strength of the cementitious matrix. This may diminish in significance as the content of coarse, hard particles increases.
(b) Coarse, hard particulate inclusions in the sludge do not participate in the cementitious reactions, but their presence can enhance strength gain through frictional contacts and interlocking.
(c) The overall void ratio, defined as the volume of voids in the cementitious matrix normalised by the overall volume, is also a relevant parameter which quantifies the combined effect of the coarse particulate inclusions and the cementitious matrix.

Another likely beneficial effect of the introduction of sand is to lower the plasticity index and liquid limit of the sludge-sand mixture. In general, the higher the liquid limit of the soil, the higher is the water content required to facilitate mixing. Water content lower than the liquid limit does not usually facilitate good mixing, and the resulting heterogeneity of the mix can degrade the overall performance of the treated soil mass. Hence, the issue of strength of the treated soil may also be inter-related to that of miscibility; this has still not been widely investigated.

The attention on the chemical treatment of sludge and other waste soils has produced a deluge of research relating to the use of new binders and new sludge or soil types. Hence, a general framework for estimating and interpreting the results of chemical treatment of such materials is now all the more relevant. This paper hopes to stimulate more research into this direction in the future.

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