

Supplementary information

Some energy and power calculations for results in Table 5 are made here to analyze some of the practical challenges that might arise. In South Africa, the average VIP pit moisture content ranges from 58 to 82 % (w/w) [21,48] and up to 95 % [47–49]. Data from Septien et al. [47] is reproduced here to indicate the technical challenges in the extraction of the VIP faecal sludge, outside of the interval 75 to 95 % of the moisture content and down to the value of 58 %. Two log-log linear dependencies of the power to empty a full VIP pit and the emptying time on the moisture content of the VIP faecal sludge, were derived from the data of Septien et al. [47], using linear regression and Microsoft Excel 2016 (Microsoft Inc., Johannesburg, South Africa). Results in Table 5 are based on Equations (S1) and (S2).

$$\log(ET) = 7.7335 \times \log(MC) - 13.523; R^2 = 0.9471 \quad (S1)$$

$$\log(P) = -27.445 \times \log(MC) + 55.765; R^2 = 0.9933 \quad (S2)$$

It is acknowledged, by the authors of the current study, that Equations (S1) and (S2) are based on an extrapolation outside of the calibration range of the dependence of P/ET on MC . This is likely to result in some error of the P estimation, but the extrapolation results clearly indicate that the power required to extract the VIP pit sludge with a lower moisture content than 75 % would pose practical problems. This will be based on the exponential increase in P , as the MC values decrease from 75 to 58 %. In addition, the scenario of Septien et al. [47] indicates that up to 11.2 m³ of H₂O might have to be pumped into the VIP to facilitate extraction of 2 m³ of faecal sludge from it. Linking to calculations from the current study, values of D would from approximately 1.151 to 2.429 m (see Table 3 and 4 for details). The volume of water required to mobilize more than 2 m³, e.g. volume of the VIP faecal sludge which had accumulated in the pit at the D values higher than 1.151 to 2.429 m (see Table 3 and 4 for details), would cause increase the water and power requirements of the faecal sludge extraction from the pits.

The financial implications of the maintenance of the VIP pits were evaluated based on Equation (S3).

$$FV = PV \times (1 + r)^n \quad (S3)$$

Equation (S3) is based on equation 1 from reference [36], but the authors of the current study replaced the exponent $t-1$ with n (years of the VIP is in operation/use or since the VIP construction), as the t being years would give immediate decrease in the FV in relation to PV at the start [36]. The change by the authors of the current study for Equation (S3) and n also reflects the different meaning of the two equations. In Equation (S3), r is the rate of interest on the cost of VIP, which is considered here a return on the VIP as an investment into the hygiene and public/environmental health of the users of the VIP as an improved sanitation facility. Practically, r will be equal to the cost of annual maintenance of the VIP as a fraction of the original investment to build a particular VIP. In other words, r is a compounded once over the period of 12 months. Finally, n is the number of years that the VIP is in use since the construction of the VIP had been completed. The reasoning behind application of Equation (S3) to the VIP as a sanitation technology is as follows. If the investment is made through construction of the VIP and the routine maintenance is done annually throughout the lifespan of the particular VIP, i.e. the maintenance of the VIP is equivalent to the positive investment interest r in Equation (S3). This investment in the VIP makes it an asset that appreciates in value throughout the lifespan of said VIP. If the investment of constructing a VIP is made and the maintenance is not performed, then the particular VIP depreciates in value as a sanitation facility throughout its lifespan. In that case, r is negative. It is hypothesized by the authors of the current study that if r is positive, then the value of the VIP increases with time during its lifespan and the cost/size of the public health and environmental burden decrease from the VIP. The VIP is also a

barrier to increasing sanitation H_{az} and R_i of the end-users. It is further hypothesized by the authors of the current study that if r is negative, then the value of the VIP decreases with time during its lifespan and the cost/size of the public health and environmental burden from the VIP increases. The VIP ceases to be a sanitation barrier to inferior hygiene and thus the VIP is a source of increasing sanitation H_{az} and R_i of the end-users and the surrounding environment. If r is positive there should be a higher probability to achieve buy-in of the end users of the VIPs as improved and appropriate sanitation facilities. If r is negative, then the financial burden of replacing the existing VIPs will increase and the 'legacy pits' will be formed. Those would require further investment in dealing with the environmental/public health burden on top of the construction and management of new sanitation facilities. As a result, the maintenance of VIPs and so a positive r value of VIPs in question increase $Prep$ and Res of the end users of VIPs and decrease Vul from Equation (1) for sanitation in South Africa.

The authors of the current study performed calculations of the value of the VIP as a function of its lifespan for two scenarios. Scenario 1 included the building of a single VIP on a land which does not have to be bought or which has been occupied already with South African residents. For scenario 1, the price of building one single VIP is assumed to be equal to PV in Equation (S3). FV is the value of the single VIP at time n based on positive or negative value of r . This value was set to the average of the price to build a single VIP without the cost of land, as reported by Manga et al. [36], and thus PV was equal to an average of 399 and 448 USD, i.e. 423.5 USD. The r value was estimated to be equal to 56.5 USD annually [36] and it is converted into the r value as a fraction of the PV value. Thus r is equal to 0.133 and the FV calculation results are shown in the main body of the article, namely in Tables 6–9. The PV and FV values from scenario 1 are referred to as no-land values in further text and PV is assumed to be constant during the lifespan of the VIP.

Scenario 2 included the building of a single VIP on a land that needs to be bought in an area for residential occupation in South African residents. For scenario 2, the price of building one single VIP is assumed to be equal to PV in Equation (S3). FV is the value of the single VIP at time n based on positive or negative value of r . This value was set to the average of the price to build a single VIP without the cost of land, as reported by Manga et al. [36], and thus PV was equal to 823 USD. The r value was estimated to be equal to 56.5 USD annually [36] and it is converted into the r value as a fraction of the PV value. Thus r is equal to 0.069 and the FV calculation results are shown below in Tables 8 and 9. The PV and FV values from scenario 2 are referred to as constant during the lifespan of the VIP.

The fly ash chemical composition is described here based on the FTIR spectra. FTIR subjects' samples to infrared radiation, which impacts molecules' atomic vibrations, leading to specific absorption or transmission of energy. The respective FTIR spectra are shown in Figures S1 and S2.

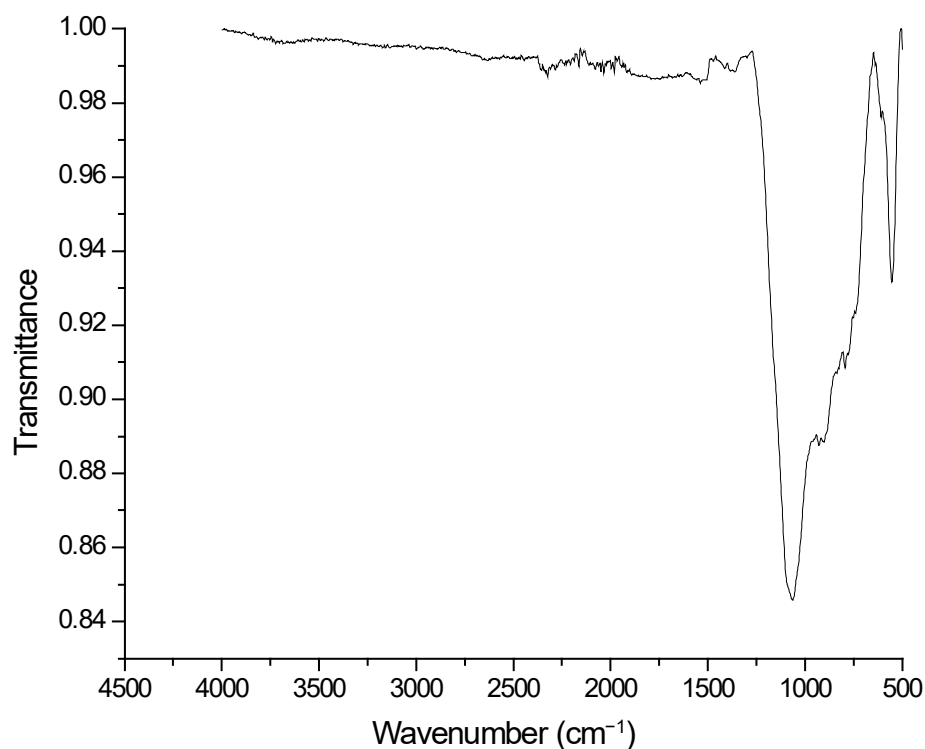


Figure S1. FTIR spectra of unmodified coal-fly ash from South Africa as described by Madikizela et al. [94].

The main purpose of the FTIR measurements was to examine the structural changes in the amorphous aluminosilicates in the coal-fly ash and the alkali-hydrothermally-modified coal-fly ash. The spectra of raw/virgin coal-fly ash show peaks between 1060 and 950 cm^{-1} due to the asymmetric stretching vibrations of Si-O-Si or Si-O-Al bonds (Figure 1). The unmodified coal-fly ash is known to be composed of mainly quartz (SiO_2) and mullite ($\text{Al}_2\text{Si}_2\text{O}_7$), along with other mineral reported in the literature before the current study [90,104,105]. The bands at 1060 and 950 cm^{-1} are respectively associated with Si-O and Si-O-Si molecular vibrations and correspond to the presence of quartz in the unmodified fly ash. The absorption band at 550 cm^{-1} is associated with the octahedral coordinated aluminum of Al-O vibrations and indicates the presence of mullite in the FA structure. The FTIR spectra of the coal-fly ash, which had been subjected to hydrothermal alkaline treatment (the modified coal-fly ash), is presented in Figure 2. After alkali activation (7M NaOH), additional peaks appeared between 500 and 900 cm^{-1} , indicating a shift in the position of Si-O-Si and Si-O-Al bond to the lower frequencies, which might be attributed to the additional -OH groups on the surface, including the substitution of SiO_4^{4-} by AlO_4^{3-} [106; 107]. All absorption bands related to the presence of an Al-based structure (mullite) vanished or almost disappeared, suggesting the incorporation of Al ions into the described structural changes during alkali-activated materialization. The absorption band that appeared at 1645 cm^{-1} in all samples was attributed to the presence of H-O-H bending vibration. This band indicates that water present during alkali activation was absorbed at the surface or entrapped in the pores of the alkali-activated material products [108].

Adsorption sites include highly active Al_2O_3 , SiO_2 , and other oxides [109]. The silica surface in fly ash is thought to have a strong affinity for metal ions. Silicates' core ion, Si^{4+} , attracts electrons quite aggressively. Another significant structural feature observed by FTIR analysis suggests that atmospheric carbonation was common in all specimens at any age, as seen by registered transmission bands at 1440 cm^{-1} and 873 cm^{-1} , ascribed to the stretching vibration of O-C-O. These spectral features confirm that the process of carbonization undoubtedly happened during alkali activation of fly ash. The shape and intensity

of the absorption band appearing at 870 cm^{-1} could indicate that carbonization of the modified coal-fly ash could be more pronounced, as compared to the unmodified coal-fly ash. Adsorption of wide range of organic pollutants might be possible from wastewater is possible because to the unburned carbon in coal-fly ash [110]. Similar adsorption could provide an additional mechanism for the elimination of organic pollutants and microorganisms from the VIP faecal sludge. Recent papers on the use of the chemically-modified fly ash from coal have indicated that such materials have anti-bacterial properties against indicator microorganisms, e.g. *E. coli* [111].

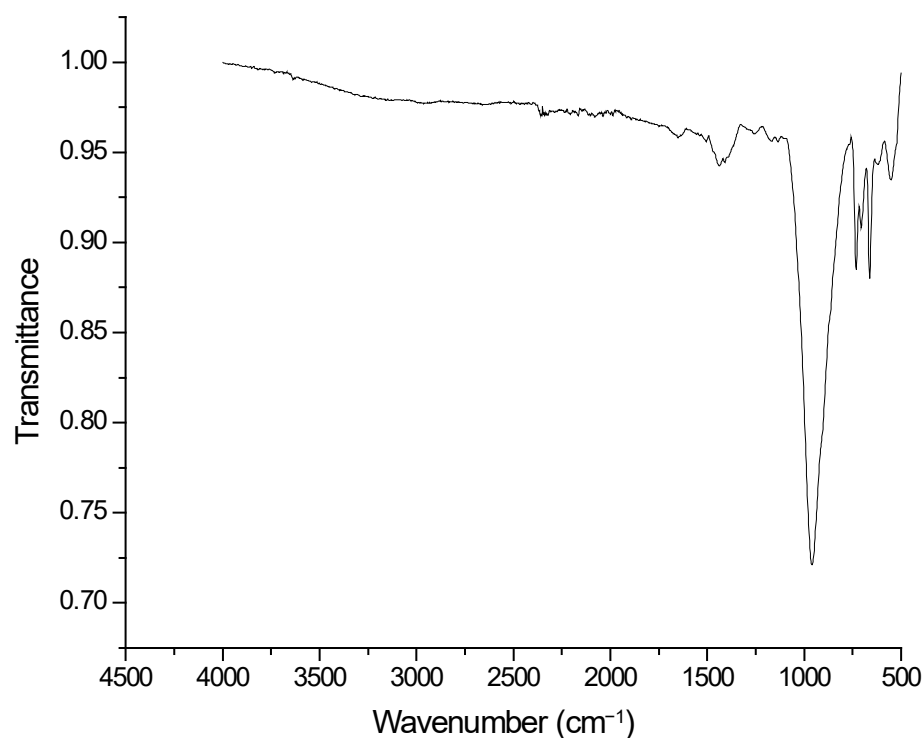


Figure S2. FTIR spectra of the modified coal-fly ash after alkaline hydrothermal treatment with 7 M NaOH, as described in more detail by Madikizela et al. [94].

The data of Getahun et al. [49] was analysed, using the Graphpad online calculator (see <https://www.graphpad.com/quickcalcs/ttest1/?format=SD> for details; website accessed on 4th February 2022). The (specific) drying heats were statistically significantly different at 5 % level of significance, when the unpaired *t*-test was performed for drying temperatures of 50 and 100 °C (*p*-value = 0.0085). The (specific) drying heats were not statistically significantly different at 5 % level of significance, when the unpaired *t*-test was performed for drying temperatures of 100 and 150 °C (*p*-value = 0.2458). The drying heats were not statistically significantly different at 5 % level of significance, when the unpaired *t*-test was performed for drying temperatures of 150 and 200 °C (*p*-value = 0.3151). Therefore the drying heat for the VIP faecal sludge was constant at temperatures of 100–200 °C. The average (specific) drying heat (designated as $H_{\text{spec}}^{\text{mean}}$ in further text) was calculated as the arithmetic mean of the (specific) drying heats for 100, 150 and 200 °C. The value was equal to 4.0 ± 0.3 MJ/kg evaporated water. The average specific drying heat was used to calculate the unit energy needed to stabilise one kilogram of faecal sludge (designated as $H_{\text{spec}}^{\text{unit}}$), i.e. to evaporate all the moisture from the VIP faecal sludge.

The $H_{\text{spec}}^{\text{unit}}$ values can be calculated using the following reasoning. One kilogram of the VIP faecal sludge studied by Getahun et al. [49] was 95 % water and 5 % solid/particulate matter. In South Africa, results of other studies indicate that the average pit moisture content ranges from 58 to 82 % (w/w) [21,48]. Ash content of the VIP faecal sludge, i.e. a measure of the inorganic residue in the particulate matter of the VIP pit contents, ranged

from 28 to around 60 % of dry weight of the VIP faecal sludge [47]. Therefore 1 kg of the VIP faecal sludge dried in that study was composed of between 580 and 950 g of H₂O, as well as between 50 to 420 g of solid/particulate matter [21,48,49]. As a result, the $H_{\text{spec}}^{\text{unit}}$ (MJ/kg) values can be calculated as shown in Equation (S4).

$$H_{\text{spec}}^{\text{unit}} = Z \times H_{\text{spec}}^{\text{mean}} \quad (\text{S4})$$

In Equation (S4), Z stands for the volume fraction of water in the VIP faecal sludge and it ranged from 0.58 to 0.95. The $H_{\text{spec}}^{\text{unit}}$ values were calculated and are shown in Table 10 (see the main text of the article). To continue the argument, the energy to stabilise and remove moisture from 1 kg of VIP faecal sludge (E) can be estimated from Equation (S5). The average time to achieve drying time was set to 20 minutes and the energy for complete water evaporation (E) was calculated in units of be W/kg.

$$E = \frac{H_{\text{spec}}^{\text{unit}}}{\text{Drying time}} = \frac{H_{\text{spec}}^{\text{unit}} \text{ J}}{20 \times 60 \text{ s}} \quad (\text{S5})$$

Density of the VIP faecal sludge is equal to 1.0–2.2 g/cm³ or 1000–2200 kg/m³ (see Table 2 in reference [113]). Therefore the weight of 2 m³ of the VIP faecal sludge ranged from 2000–4200 kg. The energy to dry and stabilise 2 m³ of the VIP faecal sludge will be equal to the *Total E*, as shown in Equation (S6).

$$\text{Total } E = \langle 2000; 4200 \rangle \times E \quad (\text{S6})$$