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**TRANSFORMATION TOWARDS SUSTAINABLE
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Characterisation of faecal sludge simulants for drying experiments

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In order to optimize the drying process in covered, unplanted sludge drying beds more testing on faecal sludge drying and dewatering is required. Using real faecal sludge for drying and dewatering experiments is often not viable given the health and safety risk and its high variability. Following a thorough literature review of current synthetic simulants, an existing simulant (PRG, 2014) was prepared and tested to characterise its drying and dewatering behaviour in relation to real faecal sludge. It was found that the recipe proved robust to alterations and exhibited similar chemical characteristics as real faecal sludge; however, it was unlike real faecal sludge in terms of consistency and colour. It is concluded that further investigation is required to develop a synthetic simulant that replicates the chemical, physical and thermal properties of real faecal sludge for drying and dewatering experiments.

Introduction

Faecal sludge (FS) can be treated by drying in covered, unplanted sludge drying beds. FS is highly variable and can be hazardous to handle due to its high pathogen content. The purpose of this research is to develop a synthetic simulant which will replicate the drying and dewatering characteristics of real FS. This is required for laboratory-based experiments to optimise the drying process in covered, unplanted sludge drying beds.

Literature review

The literature review encompassed synthetic simulants developed for fresh faeces (FF), wastewater sludge and FS. In total 41 papers were found, of those 41, 11 used FS simulants and of those 11, 7 (Sung Ryong, Dwang Ho and Sang, 1986; Radford, 2011; Byrne, 2012; Radford and Fenner, 2013; Zuma, 2013; PRG, 2014; Radford et al., 2015; Penn et al., 2018) had developed original simulants.

As the focus of this research is the drying and dewatering behaviour of FS key parameters affecting this behaviour were identified from the literature. The moisture in sludges can be split into free and bound water content which will impact dewaterability and drying respectively. The water retention curve (WRC) was used by Vincent et al (2011) to investigate the dewatering and drying behaviour of FS on sludge drying reed beds (SDRBs). The shape of the WRC is affected predominantly by particle size distribution and compressibility (Vincent et al., 2011). The curve is also affected by organic matter content (volatile solids) to a lesser extent (Vincent et al., 2012). Volatile solids is often used as a parameter for the characterisation of wastewater sludge dewaterability (Kopp and Dichtl, 2000). pH has been noted to have a marginal effect on sludge dewaterability (Shao et al., 2009). Thermal properties such as specific heat capacity and thermal conductivity are likely to affect drying behaviour of sludge. These parameters in turn have been found to depend on moisture content, composition and density (Salomone and Kovacs, 1984; Salomone, Kovacs and Kusuda, 1984).

Methodology

The synthetic simulant should replicate the key parameters determining drying and dewatering behaviour of sludge; be made from readily available materials; have minimal health and safety and environmental risk

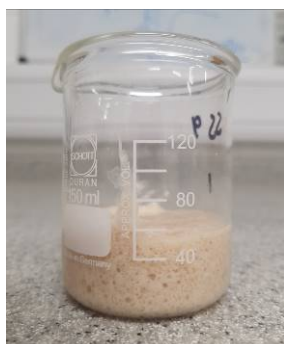
(Radford et al., 2015); and be cheap to produce as it will be made in bulk for drying and dewatering experiments.

Given these criteria, PRG SS9 (PRG, 2014) developed by Pollution Research Group (PRG) was selected as it was characterised for all of the key parameters and shown to match reasonably well. PRG SS9 was also made from cheap materials and provided a low health and safety and environmental risk.

PRG SS9 Original was altered several times as shown in Table 1. Based on availability PEG 3350, supplied by Sigma-Aldrich, was used instead of PEG 400. Cotton linters were only available in pressed sheets so PRG SS9 was made to ascertain whether the form of the cotton linters had any effect on the results of characterisation tests. Bath Mix 1 (BM1) replaced the cotton linters with hemp fibre on the basis that hemp fibre is predominantly made of cellulose and the fibrous material would better replicate the fibrous cotton linters used for the original recipe. Hemp fibre is also globally available. Bath Mix 2 (BM2) replaced all of the cellulose component with hemp fibre.

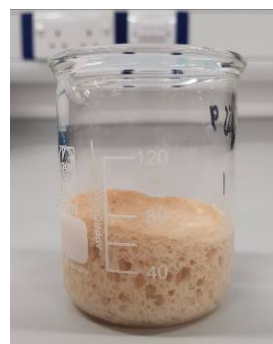
Component represents	PRG SS9 Orig. (PRG, 2014)	PRG SS9	BM1	BM2	BM3
Microorganisms	Instant yeast	Instant yeast	Instant yeast	Instant yeast	Brewer's Yeast
Cellulose	Half cotton linter/ half shredded tissue	Half cotton linter/ half shredded tissue	Half shredded tissue/ half hemp fibre	Hemp fibre	Half shredded tissue/ half hemp fibre
Water retention	PEG 400	PEG 3350	PEG 3350	PEG 3350	PEG 3350
Fibre/ Carbohydrate	Psyllium husk	Psyllium husk	Psyllium husk	Psyllium husk	Psyllium husk
Fat	Peanut oil	Peanut oil	Peanut oil	Peanut oil	Peanut oil
Fibre/ protein/ fat/ minerals	Miso paste	Miso paste	Miso paste	Miso paste	Miso paste
Minerals	Calcium phosphate	Calcium phosphate	Calcium phosphate	Calcium phosphate	Calcium phosphate
Water	Water	Water	Water	Water	Water

Initial tests showed that the simulants became full of bubbles due to the reaction of the active yeast (Photograph 1a and 1b). Therefore Bath Mix 3 (BM3) was made using half hemp fibre and half shredded tissue as the cellulose component whilst replacing instant yeast with inactive brewer's yeast (Yesto-Seal® 004) in an attempt to prevent the bubbles forming.



Photograph 1a. PRG SS9 0hrs

Source: Deering 2018



Photograph 1b. PRG SS9 after 24hrs

Source: Deering 2018

Each simulant was characterised according to the parameters identified as significant in the literature review as shown in Table 2. Standardised tests (refer to Table 2) were used to characterise the simulants to ensure repeatability in testing and ease of comparison.

Table 2. Characterisation tests, methods and apparatus				
Test		Units	Methodology	Apparatus
Density	ρ	kg/m ³	Used apparatus as directed	AccuPyc 1330
Particle size distribution		%	Used apparatus as directed	Malvern X Mastersizer
pH			Standard methods for the examination of water and wastewater (1975) APHA-AWWA-WPCF pg 460, 424. pH value	Mettler Toledo LE409 pH Meter/ Hanna H1 208 pH Meter
Specific heat capacity	c	J/(kg·K)	ASTM E1269-11 Test method for determining specific heat capacity by differential scanning calorimetry (2011)	Differential scanning calorimeter
Total solids	TS	mg/L	Standard methods for the examination of water and wastewater (1975) APHA-AWWA-WPCF pg 91, 208 A. Total residue dried at 103-105 C	Oven
Thermal conductivity	k	W/(m·K)	ASTM D5334 Test method for the determination of thermal conductivity of soil and soft rock by thermal needle probe procedure (2014)	TP02 Hukseflux Thermal Sensor Temperature Sensor Type K
Volatile solids	VS	g/ g dry sample	Standard methods for the examination of water and wastewater (1975) APHA-AWWA-WPCF pg 95, 208 E. Total volatile and fixed residue at 550 C	Furnace
Water content	w	%	Standard methods for the examination of water and wastewater (1975) APHA-AWWA-WPCF pg 91, 208 A. Total residue dried at 103-105 C	Oven

Initial tests also showed that a smooth skin would form across the top of the sludge as it dried (Photograph 1 after 24hrs). This did not compare to the behaviour of real FS. Photograph 2 shows that real FS dried on drying beds had multiple cracks across the surface which would aid the drying process because a greater surface area was exposed to the atmosphere. It was hypothesised that the smooth skin could be causing a gas build up in the synthetic sludge so a test using BM3 was conducted during which holes were poked through the skin of the synthetic simulant.



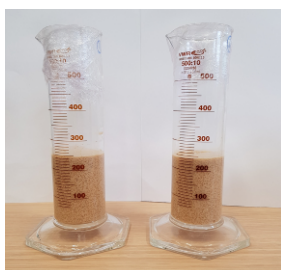
Photograph 2. Drying beds at Niayes faecal sludge treatment plant, Dakar, Senegal

Source: Strande, Ronteltap and Brdjanovic, 2014)

Discussion and results

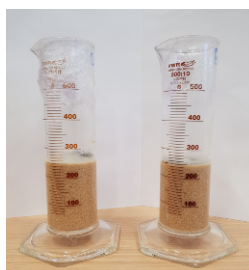
Each characterisation test was repeated three times for each sludge sample. The values reported in the following tables are an average of these three results. The results of the characterisation experiments were compared with the results of the original PRG SS9, as well as average values for fresh faeces (FF) and FS, kindly provided by PRG.

Photograph 3 shows the formation of bubbles in BM3 after 1 day (a), 5 days (b) and 8 days (c). BM3 used brewer's yeast in an attempt to counteract the bubble formation in the sludge. This was marginally successful as Photograph 3 shows; the use of brewer's yeast delayed the bubble formation significantly, from approximately 2 hours to almost 8 days, however, it did not prevent it completely.



Photograph 3a. BM3 Day 1

Source: Deering 2017



Photograph 3b. BM3 Day 5

Source: Deering 2017



Photograph 3c. BM3 Day 8

Source: Deering 2017

As can also be seen in Photograph 3 the use of the brewer's yeast did not prevent the formation of the smooth skin on top of the synthetic simulant. From day 5 it was noted that the skin on top of the synthetic simulant had thickened and there was mould growth present. The test shown in Photograph 3 also involved holes being poked through the smooth skin in an attempt to ascertain if the skin was causing the sludge to expand due to the gas bubbles not being released; however, results proved inconclusive as the sludge expanded very quickly overnight on day 8.

Table 3 shows that the average moisture content for all synthetic simulants were similar at approximately 80% but slightly higher than the average moisture content for dry and wet VIPs. In keeping with that trend, average total solids were slightly lower at approximately 19%. Average volatile solids were higher for all synthetic simulants. The difference in volatile solids in the simulants compared with real FS is thought to be on account of the organic nature of most of the ingredients for the simulants. Average pH was significantly lower for all simulants made and tested at the University of Bath. The average density of the synthetic simulants tested at the University of Bath were higher than that of the original PRG SS9 and BM3 was closest to the density of real FS in a dry VIP at 1365 kg/m³ but still significantly lower than FS in a wet VIP.

Synthetic sludge type	Units	PRG SS9	BM1	BM2	BM3	PRG SS9 Orig. (PRG, 2014)	Dry VIP (PRG, 2014)	Wet VIP (PRG, 2014)
W _{ave}	%	80.99	81.02	81.00	80.51	81.00	79.00	79.00
TS _{ave}	%	19.01	18.98	19.00	19.49	19.00	21.00	21.00
VS _{ave}	g/g dry sample	0.80	0.75	0.77	0.76	0.75	0.58	0.54
pH		5.14	5.11	5.17	5.26	5.92	7.60	7.59
ρ_{ave}	Kg/ m ³	1343.20	1343.67	1345.54	1365.20	1300.00	1379.72	1447.78
k _{ave}	W/ mK ³	0.04975	0.05191	0.05242	0.03280	0.50	0.54	0.55
C _p	J/kgK	2700.88	2723.58	2701.54	2609.35	2700.51	2530.54	2422.33

All of the mixes tested at Bath had a lower k_{ave} value; the reason for this is thought to be sample size as those mixes tested at Bath were 250ml whilst the sample size tested by PRG was approximately 1.25ml. k_{ave} results for PRG SS9, BM1 and BM2 were all very similar whilst BM3 was much lower; given the difference between the five mixes was the use of brewer's yeast it is assumed this is the reason for the lower k_{ave} . C_p results are similar to those of PRG SS9 and dry and wet VIPs; however it is difficult to draw any conclusion since C_p changes with temperature and moisture content.

Particle size distribution was also determined for the synthetic simulants; however, there is currently no published data to allow comparison of the synthetic simulant particle size distribution with that of real FS. There is a great deal of variance between the mixes as shown in Table 4.

Synthetic Sludge Type	PRG SS9	BM1	BM2	BM3
Obs' (%)	26.7	25.9	29.7	28.9
D[4,3] μm	139.04	82.73	79.26	49.73
D(v,0.1) μm	3.90	3.96	3.83	3.64
D(v,0.5) μm	54.22	5.51	5.36	8.35
D(v,0.9) μm	467.49	355.70	326.12	150.85

Over the course of the testing it was observed that the synthetic simulants all had a sticky, almost doughy, consistency and a light colour (Photograph 1) unlike real FS. Given the aim of the synthetic sludge is to mimic the drying and dewatering properties of real FS it is quite likely that the colour and consistency will play an important role, for example, a darker sludge is more likely to dry quicker than a lighter coloured sludge since it should conduct heat better; thus attention needs given to the colour of the simulant as well as chemical and thermal properties.

Summary

This paper describes the selection of PRG SS9 Original as a suitable synthetic simulant for real FS following a comprehensive literature review. PRG SS9 Original was adapted based on available ingredients and the results of preliminary tests, resulting in four iterations of the original recipe. These iterations were tested for key characteristics: moisture content (w), total solids (TS), volatile solids (VS), density (ρ), specific heat capacity (C_p), thermal conductivity (k) and particle size distribution (PSD).

The results of the testing showed that the instant yeast in PRG SS9 Original could be substituted for brewer's yeast and different cellulose components but still maintain similar chemical characteristics like water content, total solids and volatile solids. All mixes were markedly different from real FS in terms of colour and consistency, which may influence their drying behaviour. Thermal properties of the synthetic simulants were tested but comparisons with PRG results for real FS were difficult due to different testing methods used. This demonstrates the need for standard operating procedures for the testing of FS to

facilitate comparison between synthetic simulants and real FS. PSD of the mixes was measured; however, there are no published PSD results for real FS as yet there are no published PSD results for real FS for comparison.

The synthetic simulants behaved differently from real FS in several ways. First, the simulants developed a thick skin and did not crack, whereas real FS was observed to crack during drying. Secondly, although the synthetic simulants were able to mimic the chemical properties of the sludge they were a lighter colour, more aerated and stickier than real FS. This will affect their drying behaviour.

Further work

Further development of the synthetic simulants will be undertaken to better represent the physical and thermal properties of FS as well as to find a component to represent the microbial content of the synthetic simulant without causing it to 'rise'. Further research into the particle size distribution in FS is also required.

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