7

Faecal sludge simulants: review of synthetic human faeces and faecal sludge for sanitation and wastewater research

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OBJECTIVES

The objectives of this chapter are to:

- Introduce the concept of simulants and their applications
- Present current state of the art in simulants for faecal sludge, faeces and urine
- Compare properties between simulants and typical values observed in the field
- Introduce customisation of simulants, including advantages and constraints.

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7.1 INTRODUCTION

Presented in this chapter is a critical literature review of two categories of simulants: synthetic faeces and faecal sludge (FS), together with how to select and further customise simulants for experimentation depending on the specific properties of interest. Simulants play an important role in research, and have a long history in wastewater research and other fields. The high variability of faeces (Rose *et al.,* 2015) and faecal sludge collected from onsite systems (Strande *et al.,* 2014) makes it difficult to obtain consistent samples and therefore execute repeatable experiments. Moreover, due to the potentially pathogenic content of human excreta, working with real faecal matter involves special safety precautions. Working with synthetic faecal matter can alleviate these challenges. Replicable experiments are important in order to gain an understanding of the specific role of different mechanisms. For example, faeces and faecal sludge simulants could be used to investigate rheological properties (*e.g.* pumpability), energy content, or anaerobic digestion. In addition, simulants could be used to investigate how flows in the sewer network affect operations and maintenance (*e.g.* clogging with solids). The applications are diverse, and demonstrate the range of applicability of simulants in faecal sludge and wastewater research. Although there are no 'perfect' simulants, they can be adapted depending on the specific physical, chemical, or thermal properties that are of interest, and allows for research of properties, when faecal sludge is not available.

Investigations involving human faeces are of great importance in many fields of research, such as medicine (Lewis and Heaton, 1997; Bekkali *et al.,* 2009), sanitary product development (such as diapers, toilets, etc.) (Stern and Holtman, 1987; Palumbo and D'acchioli, 2001), operation and maintenance of sewer systems (Butler *et al.,* 2003; Penn *et al.,* 2017), and implementation of faecal sludge collection and treatment for onsite sanitation systems (Wignarajah *et al.,* 2006; Bassan *et al.,* 2014; Colón *et al.,* 2015). Development of synthetic faeces and faecal sludge is a challenging task due to their high variability depending on diet, lifestyle and geographical location (Rose *et al.,* 2015). In this chapter, we focus on synthetic faeces and faecal sludge developed for sanitation research, hence resembling human faeces and faecal sludge in specific physical and chemical properties.

When discussing simulants, it is important to understand the difference between faeces and faecal sludge. Faecal sludge is the faecal waste stored within onsite sanitation technologies. In addition to faeces it includes everything that goes into the toilet, for example, urine, flush water, greywater, anal cleansing materials and municipal solid waste (Strande *et al.,* 2014). Faecal sludge differs significantly from fresh faeces alone; it is typically much more dilute due to the addition of liquids. Additionally, its characteristics are highly variable due to differences in storage duration, storage temperature and storage technology, and can range from fresh, to partially degraded, to completely stabilised (Strande *et al.,* 2014).

Three distinct recipes for synthetic faecal sludge have been reported in the literature. Their intended purposes include research into anaerobic digestion (Zuma, 2013; Colón *et al.,* 2015) and pit latrine emptying (Radford *et al.,* 2015). Together with the synthetic faeces recipes presented in this chapter, they could also be used as a basis for the development of improved faecal sludge simulants in the future.

Synthetic faeces have been developed to address many sanitation-related research questions. Most of the developed simulants mimic specific physical, chemical or thermal characteristics of human faeces important to the research objectives for which they are developed. Physical properties such as shape, size, density and rheology are of importance for simulating phenomena such as faeces settling, transport in sewer pipes, dewatering, viscous heating for pathogen destruction, and physical disintegration (*e.g.* Butler *et al.,* 2003; Veritec Consulting Inc. & Koeller and Company, 2010; Podichetty *et al.,* 2014). Chemical properties including chemical and biological oxygen demand, nutrient concentration, pH and conductivity are of importance for simulating biological disintegration, treatment of faeces and biogas production (*e.g.* Kaba *et al.,* 1989; Wignarajah *et al.,* 2006; Miller *et al*., 2015). Elemental composition (C, H, N, O) and heating properties are of importance for analysing energy recovery and for using the faeces for soil amendment *e.g.* biochar or compost production (*e.g.* Ward *et al.,* 2014; Colón *et al.,* 2015; Onabanjo *et al.,* 2016a). Studies on the fate of faeces in sewers and in onsite sanitation systems include their movement, settling and physical disintegration together with biochemical disintegration. For these kinds of investigations a simulant is required that represents closely a combination of chemical, biological and physical properties of faeces and faecal sludge. Such a simulant is still missing in the literature.

This chapter provides a critical literature review of synthetic faeces and faecal sludge used for human waste-related research. Based on this overview a modified simulant recipe is presented that is applicable for studying the fate of faeces in sewers and in onsite sanitation systems. A series of experimental results show how these properties can be selectively manipulated by making changes in the recipe and an explicit preparation procedure can be found in the appendix of this chapter.

7.2 CHARACTERISTICS OF FAECES AND FAECAL SLUDGE

7.2.1 Faeces

Faecal solids are composed of proteins, fats, fibre, bacterial biomass, inorganic materials and carbohydrates. Their chemical and physical characteristics vary widely depending on health and diet, as presented in Table 7.1.

Table 7.1 Chemical and physical properties of faeces identified in the literature.

Property	Parameter	Range (amount/cap.d)	Range (other units)	Median
Chemical	Wet mass	35-796 g[1,6]		128 g/cap.d[6]
	Water content		63-86 wt %[6]	75 wt %[6]
	Protein		2-25 wt % of solids weight (+50% of bacterial biomass)[6]	
	Fibre	0.5-24.8 g[6]		6 g/cap.d[6]
	Carbohydrates	4-24 g[6]	25 wt % of solids weight[6]	9 g/cap.d[6]
	Fats	1.9-6.4 g[6]	8.7-16 wt % of solids weight[6]	4.1 g/cap.d[6]
	Bacteria content		25-54 wt % of solids weight[6] $100\text{-}2{,}200 \cdot 10^{12}$ cells/kg[6]	
	BOD	14-33.5 g[6]		
	COD	46-96 g[6]		
	TN	0.9-4 g[6]	5-7% wt % of solids weight[6]	1.8 g/cap.d[6]
	VS		92 wt % of TS[6]	
	pH		5.3-7.5[6]	6.6[f], 7.15 (avg.)[2]
	Calorific value	0.21-1.45 MJ[6]		0.55 MJ/cap.d[6]
Physical	Shape		Type 1 (hard lumps) - type 7 (watery diarrhoea)[5]	3.6 (avg.) [6]
	Viscosity		3,500-5,500 cPs at 50 rpm[3]	
	Density		<1 g/mL for 10-15% of healthy humans[1]	1.06-1.09 (avg.)[2,4]

[1]Levitt and Duane, 1972; [2]Ciba-Geigy, 1977; [3]Yeo and Welchel, 1994; [4]Brown *et al.,* 1996; [5]Lewis and Heaton, 1997; [6]Rose *et al.,* 2015

The average number of stools produced by adults is one per day (Ciba-Geigy, 1977). The median daily wet mass of faeces produced per person is 128 g (Rose *et al.,* 2015), which falls within the reported full range of 35-796 g reported by Ciba-Geigy (1977) and Rose *et al.* (2015). Wyman *et al.* (1978) compared average stool sizes of 20 people (average of 10 samples from each individual). They identified that 250 g/stool and 111.3 g/stool were the maximum averaged weights for the male and female participants, respectively, in the study. In their review of faeces characteristics Rose *et al.* (2015) further report that live and dead bacteria comprise between 25 and 54% of the dry weight of faeces. The median water content in faeces is 75%, with a range of 63–86% across the mean values of the studies. Variations in water content and faecal mass are attributed to differences in fibre intake, as non-degradable fibre absorbs more water in the colon and degradable fibre stimulates growth of bacterial biomass (Eastwood, 1973; Garrow *et al.,* 1993; Reddy *et al.,* 1998). Rose *et al.* (2015) report that volatile solids comprise 92% of the total solids (TS) fraction of faeces. Faeces pH ranges between 5.3-7.5, with biological oxygen demand (BOD) between 14.0 and 33.5 g/cap.day and chemical oxygen demand (COD) between 46 and 96 g/cap.day (Rose *et al.,* 2015).

Faeces are also highly variable in their physical structure. This variability can be characterised by the Bristol Stool Form Scale introduced by Lewis and Heaton (1997) for assessing intestinal transit rate. The scale categorises stools into one of seven types, ranging from type 1 (hard lumps) to type 7 (watery diarrhoea). Types 3 and 4 ('hard, lumpy sausage' and 'loose, smooth snake') are classified as normal stool forms. Onabanjo *et al.* (2016 a) identified the moisture content of each stool classification ranging from ~50% (type 1) to >80% (type 7). The Bristol Scale has been used to assess stool form in the study of gastrointestinal disorders (*e.g.* Garsed *et al.,* 2014, Nolan *et al.,* 2015). Woolley *et al.* (2014) measured the rheological properties of fresh human faeces. They showed that with increasing shear rate the apparent viscosity measurements of the samples decreased. For any given shear rate, higher apparent viscosities were associated with lower moisture contents. Viscosity measurements of runny to solid faeces were found to be in the ranges of 3,500-5,500 cP (Yeo and Welchel, 1994). According to the US National Bureau of Standards (NBS) faeces are characterised by density of 1.06 g/mL (Brown *et al.,* 1996). 10-15% of healthy humans produce stools that float (have a density less than 1.0 g/mL) due to trapped gas in the faeces (Levitt and Duane, 1972).

7.2.2 Faecal sludge

Faecal sludge originates from onsite sanitation technologies, and has not been transported through a sewer. It is raw or partially digested, a slurry or semisolid, and results from the collection, storage or treatment of combinations of excreta and blackwater, with or without greywater (Strande *et al.,* 2014). Blackwater is defined as wastewater generated by the toilet, and includes excreta as well as flush water, anal cleansing water and/or dry anal cleansing materials (Tilley *et al.,* 2014). Greywater contains all other domestic wastewater flows including bathing, washing, laundry and kitchen (Gross *et al.,* 2015).

Typical quantities and qualities of faecal sludge are difficult to determine due to the variety of onsite sanitation technologies in use, such as pit latrines, septic tanks, aqua privies, and dry toilets. They further depend on the design and construction of the sanitation technology, how the technology is used, how the faecal sludge is collected, and the frequency of collection (Strande *et al.,* 2014). Recent findings have indicated that faecal sludge characteristics are correlated to the containment technology, but that there is not always a discernible difference between faecal sludge from public toilets and households (Strande *et al.,* 2018). The lack of standardised methods for the characterisation of faecal sludge further contributes to the variability in the measured parameters.

The important parameters to be considered for faecal sludge characteristics are similar to those of faeces and are presented in Table 7.2.

Figure 7.0 Prof. Chris Buckley of UKZN PRG presents the faeces simulant at the Reinvent the Toilet Fair in 2012, Bill & Melinda Gates Foundation, Seattle, U.S., (photo: D. Brdjanovic).

Table 7.2 Physical and chemical properties of human faeces and faecal sludge compared with simulants.

Properties	Faeces	Synthetic faeces	Faecal sludge	Synthetic faecal sludge
Shape	From 'hard lump' to 'watery diarrhoea'; 'hard lump sausage' and 'loose smooth snake' are normal forms[c]	Cylinder[9]		
Length (cm)		8-10[9,21]		
Diameter (cm)		2.5-3.4[9,21]		
Volume (ml)	90-169 (for women)[3] 82-196 (for men)[3]			
Density (kg/L)	1.06-1.09[3,8]	1.02-1.06[9,21]	1.0-2.2[33]	0.8-2.2[33]
Viscosity (cP)	3,500-5,500[8]	1,000-40,000[8,28]	$8.9\cdot10^{-1}$-$6\cdot10^{9}$[29]	
Dewatering rate (g/m^2.min)	350-400 (for regular stool, very high for runny faeces)[6]	50-400[8]	11 (% of TS in the dewatered cake)[41,42]	4.5 (% of TS in the dewatered cake)[41,42]
Shear strength (Pa)			<1,760[33]	9-10,000[33]
COD_{total}	0.6-1.5 % of TS[17,32,34]	1.3 % of TS[30,32]	7,000-106,000 mg/L[24,26]	73[30] 12,500-72,800 mg/L[25,30]
$COD_{soluble}$	0.38 % of TS[30]			1,000-48,300 mg/L[25,30]
BOD	14-33.5 g/cap.d[34]		600-40,000· mg/L[13,26]	
TN	2-7 % of TS[17,20,32,34]	2.8 % of TS[30,32]	50-1,500 mg/L[21,28]	880-7,200 mg/L[25,30]
N-NH_3 (% of N_{total})	<7[32]	<3.02[32]		
C/N	5-16[32]	17.3[32]		
pH	4.6-8.4[5,30,32,34]	5.3[30,32]	6.7-8.5[19,26]	5.5-7.73[25,30]
EC (mS/cm)		5.7[30]	2.2-14.6[39]	14.4[30]
TS (%)	14-37[18,32,34]	18.4[16,32]	0.5-40[39,23]	1.7-85.0[25,30,33]
VS	80-92 % of TS[1,4,5,32,34,37]	86.8-88.5 % of TS[30,32,37]	7,000-52,000 mg/L[24,26]	78.9-79.9 % of TS[30] 1,600 -1,800 mg/L[25]
C (% of TS)	44-55[16,31,36,38]	43.4-47.3[11,32,36,37,38]	27.8-28.8[40]	
H (% of TS)	7.0-7.6[31,37,38]	6.2-7.2[11,32,36,37,38]	4.2[40]	
N (% of TS)	1.1-18[5,16,31,37,38]	2.1-7.2[11,36,37,32,38]	3.0-3.2[40]	
O (% of TS)	21-32[31,37,38]	30-42[11,32,36,37,38]		

Fe (μg/kgTS)	72,381-1,230,769(5)	59,950(30)		
Zn	64,762-660,256 μg/kgTS(5)	46,210 μg/kgTS(30)	646-918 ppm(40)	
Ni	1,016-34,615 μg/kgTS(5)	1,289(30)	24-30 ppm(40)	
Co (μg/kgTS)	254-3,846(5)	642(30)		
Mn (μg/kgTS)	46,857-236,539(5)	6,25(30)		
Mo (μg/kgTS)	1,148-12,180(5)	1,555(30)		
Cu (μg/kgTS)	24,889-125,641(5)	5,654(30)	114-216 ppm(40)	
B (μg/kgTS)		3,524(30)		
S	0.5-1.6 % of TS(5,31)	0.06-0.19 % of TS (11,22,32)		388-1,300 mg/L(25)
P (% of TS)	0.39-4.93(5)	0.28(11)	1.5-0.95(40)	
Calorific value (MJ/kg)	17.2-25.1(2,5,10,12,31,34,37)	17.5-22.36(35,37)	11-19(27,39)	
Ash (% of TS)	9.7-14.6(31,37)	13.15(37)	47-59(40)	
Biogas yield	0.16-0.53 NLbiogas/gCOD(1,5,15) 53.1 $mLCH_4/gVS$(43)	0.44 NLbiogas/gCOD(30)	45-50 $mLCH_4/gVS$(43,44)	0.24 $NLCH_4/gVS$(25) 0.12-0.37 NLbiogas/gCOD(30)
Average methane (% vol)		63(30)		38-60(30)
$Sulphate_{soluble}$ (mg/L)				88-392(25)
Total protein (mg/L)	3.2-16.2 g/cap.d(34)			2,874-8,835(25)
$Protein_{soluble}$ (mg/L)				497-1,723(25)
Total carbohydrates (mg/L)	4-24 g/cap.d(34)			660-3,812(25)
Lipids (g/gTS)	0.09-0.16(34), 4.2 g/d(5)			0.03-0.30(25)
Total fiber (g/gTS)	0.25(34)			0.33-0.79(25)
Hemicellulose (g/gTS)				0.15-0.31(25)
Cellulose (g/gTS)				0.03-0.34(25)
Lignin (g/gTS)				0.03-0.16(25)

[1]Snell, 1943; [2]Lovelady, 1970; [3]Levitt and Duane, 1972; [4]Fry, 1973; [5]Ciba-Geigy, 1977; [6]Wyman *et al.*, 1978 ; [7]Meher *et al.*, 1994; [8]Yeo and Welchel, 1994; [9]Brown *et al.*, 1996; [10]Girovich, 1996; [11]Tennakoon *et al.*, 1996; [12]Spellman, 1997; [13]Heinss *et al.*, 1999; [14]Koottatep *et al.*, 2001; [15]Park *et al.*, 2001; [16]Eawag, 2002; [17]Jönsson *et al.*, 2005; [18]Wignarajah *et al.*, 2006; [19]Henze *et al.*, 2008; [20]Barman *et al.*, 2009; [21]Veritec Consulting Inc. & Koeller and Company, 2010; [22]Serio *et al.*, 2012; [23]Still and Foxon, 2012; [24]Bassan *et al.*, 2013; [25]Zuma, 2013; [26]Appiah-Effah *et al.*, 2014; [27]Muspratt *et al.*, 2014; [28]Podichetty *et al.*, 2014; [29]Strande *et al.*, 2014; [30]Colón *et al.*, 2015; [31]Monhol and Martins, 2015; [32]Miller *et al.*, 2015; [33]Radford *et al.*, 2015; [34]Rose *et al.*, 2015; [35]Yerman *et al.*, 2015; [36]Ilango and Lefebvre, 2016; [37]Onabanjo *et al.*, 2016a; [38]Onabanjo *et al.*, 2016b; [39]Gold *et al.*, 2017a; [40]Gold *et al.*, 2017b, [41]Ward *et al.*, 2017a; [42]Ward *et al.*, 2017b; [43]Bourgault, 2019; [44]Rose *et al.*, 2014

Table 7.3 Recipes for faeces and faeces sludge simulants.

Component	Composition of solid content (wt %)																		
	Faeces simulant												Faecal sludge simulants						
Simulant number (#)	#4	#5	#6	#7	#8	#9	#10	#11	#12[E]	#13[F]	#14a	#14b	#15	#16	#17	#18	#19	#20	#21
Source	(2)	(2)	(1,3)	(4)	(5)	(13)	(11)	9,10)	(12)	(8)	(14)		(6)	(9)	(7)				
Cellulose	65.1[A]		33	15	37.5	12.4	15	10			10[G]	10[G]							
Wheat	11																		
Psyllium	6.6[B]	25[B]																	
Poly(oxyethylene)	11																		
Polyvinyl pyrrolidone		75																	
Potassium sorbate	0.7																		
Burnt sienna[C]	2.8																		
Yellow ochre[C]	1.4																		
Raw umber[D]	1.4																		
Torpulina			25																
E.coli			7	30															
Baker's yeast					37.5	32.8	10	30			0	3							
Yeast extract											30	27							
Casein			10																
Oleic acid			20					20			20	20							
KCl			2		4			2			2	2							
NaCl			2					2			2	2							
$CaCl_2$			1			11.3		1			1	1							
Polyethylene glycol				20															
Psyllium husk				5		24.3	15	17.5			17.5	17.5							
Peanut oil				20	20	17.5	5												
Miso paste				5		10.95	30	17.5			17.5	17.5							
Inorganics				5															
Dried coarsely ground vegetable matter (mg)				50															
$Ca_3(PO_4)_2$							5												

CaH_2PO_4					1														
Propylene glycol						10.95	20												
Soybean paste									62.6	52.2									
Rice									34.4	28.5									
Salt									0	19.3									
Ethanol									3										
Walnuts																20.23	39.08	62.83	77.6
Hay flour															79.4	60.56	39.08	20.94	
$Na_2HPO_4 \cdot 12H_2O$															6.35	6.71	6.14	7.41	6.29
NH_4HCO_3															14.25	12.49	15.71	8.82	16.11
Kaolin clay (ultra-fine particle size)													67						
Compost (by dry mass)													33						
1 ml synthetic urine (Table 7.5) + 0.4 g wet simulant #11														100					

[1]Kaba *et al.,* 1989; [2]Yeo and Welchel, 1994; [3]Tennakoon *et al.,* 1996; [4]Wignarajah *et al.,* 2006; [5]Danso-Boateng *et al.,* 2012; [6]Radford and Fenner, 2013; [7]Zuma, 2013; [8]Podichetty *et al.* 2014; [9]Colón *et al.,* 2015; [10]Miller *et al.,* 2015; [11]Yermán *et al.,* 2015; [12]Ilango and Lefebvre, 2016; [13]Onabanjo *et al.,* 2016a; [14]Penn *et al.,* 2019; [A]Powdered cellulose; [B]Fibrall® psyllium hydrophilic mucilloid; [C]Reddish brown and yellowish pigments; [D]Hydrous silicates and oxides of iron and manganese; [E]Water was added as 39.8% of total ingredients; [F]Water was added as 35.5% of total ingredients; [G]Microcrystalline cellulose. The components' composition is made up of dry solids. Water can be added in different amounts to adjust to various TS concentrations.

7.3 SYNTHETIC FAECES AND FAECAL SLUDGE FOUND IN THE LITERATURE

Appropriate simulants for faeces and faecal sludge should be able to reflect the range of physical, chemical, biological and thermal characteristics relevant for the research objective. This specifically includes:

- Physical characteristics *e.g.* represented by the Bristol Stool Form Scale (for faeces simulants).
- Shapability into the characteristic faeces cylinder, and can be made to float or sink (for faeces simulants).
- Viscosity and dewatering properties.
- Chemical and biological properties including COD, BOD, TN, pH, EC, TS, VS, elemental composition, biogas potential.
- Thermal properties, such as calorific value and ash content.
- Ability to physicality disintegrate with a resulting aqueous suspension having similar chemical properties to real disintegrated faeces (for faeces simulants) and biologically degrade in a typical way (for faecal sludge simulants).

This wide variety of faecal and faecal sludge properties poses a substantial challenge for creating a universal synthetic replacement and such an optimal simulant has not yet been developed. Simulants found in the literature were developed to reproduce specific characteristics of human faeces or faecal sludge, depending on the research objectives, with varying degrees of success. All the developments were successful in producing a simulant that is safe to use and does not represent any biohazard.

7.3.1 Physical parameters

The simulants discussed in the following sections are designed to reflect specific physical properties of human faeces and faecal sludge such as shape, rheology or density. As faeces are distinct from faecal sludge each type of simulant is discussed separately.

7.3.1.1 Faeces simulants

Butler *et al.* (2003) prepared artificial faeces for laboratory investigation of gross solids movement in sewers (referred to here as simulant #1). Solids were represented with plastic cylinders with a diameter of 3.4 cm, length of 8 cm and density of 1.06 g/ml, following the US NBS solid (Brown *et al.,* 1996). Penn *et al.* (2018) implemented similar solids for examining their movement in real sewers. Two techniques for tracking the gross solids were developed; using light sticks tracked by computerised light detector and RFID (radio frequency identification)-based tracking. They further analysed the effect of reduced sewer flows on the movement of the solids (Penn *et al.,* 2017).

Maximum Performance (Map) in the USA (Veritec Consulting Inc. & Koeller and Company, 2010) developed a media for testing toilet flush performance (simulant #2). In a Toilet Fixture Performance Testing Protocol, they define a test media (*i.e.* synthetic faeces) to comprise the following: 'one or more 50±4 g test specimen consisting of one of the following (*i*) soybean paste contained in latex casing (cased media), tied at each end forming a sausage shape or (*ii*) the same quantity consisting of extruded soybean paste (uncased raw media), and four loosely crumpled balls of toilet paper. Each test specimen will be approximately 100±13 mm in length and 25±6 mm in diameter.' A similar media was developed by DIN (German Industrial Norm/European Norm, 2006). The US Environmental Protection Agency's (EPA's) WaterSense program (EPA WaterSense, 2014) adopted Map's protocol and indicated that a 'high efficiency' toilet should successfully and completely clear 350 g of the test specimen from the fixture in a single flush in at least four out of five attempts.

All the above inert simulants were developed to reflect the shape, size and density of real faeces. These simulants were mainly used for investigating solids movement in sewers and in drainage pipes of buildings and for investigating the flushing performance of toilet user interfaces. Simulant faeces with varying densities and shapes as described in the Bristol Stool Form Chart (Lewis and Heaton, 1997) can be produced by modification of these physical simulants. Simulants can be further modified to represent other type of solids found in sewers such as FOGs (fats, oils and greases) by producing them from materials with various densities. With the increasing number of in-sink food waste disposals, the discharge of FOGs to sewers is widely increasing (Thyberg *et* *al.,* 2015) and hence investigating their transport in sewers is of significance. These simulants do not disintegrate and therefore are not impacted by the shear stress present in the system and their chemical properties are not reflected. It is also important to realise that the rheological properties of these simulants differ significantly from the real material.

Podichetty *et al.* (2014) evaluated the application of viscous heating for the destruction of pathogens in faeces. Heat was generated within faecal simulants by applying shear stress with an extruder. They found, based on a literature review, several alternative materials displaying the same shear thinning behaviour as human stools, and demonstrating similar viscosity profiles with changing shear rate as reported by Woolley *et al.* (2013). The alternatives included contents from pig caecum (a section of the pig lower intestine) (Takahashi and Sakata, 2002), content from chicken caecum (Takahashi *et al.,* 2004), wheat flour (Podichetty *et al.,* 2014), different types of mashed potatoes (Podichetty *et al.,* 2014) and simulant stool (Susana.org, 2008), simulant #13 presented in Table 7.3. While wheat flour had the closest match to the rheological behaviour of human faeces, they selected red potato mash since it had a higher resemblance in terms of moisture content (simulant #3). Their choice of red potato mash as a faecal simulant was confirmed by its structural, thermal and viscoelastic properties (Singh *et al.,* 2008). Simulant #13 (Table 7.3) showed poor rheological resemblance to human faeces. Rheological behaviour of the various simulants is presented in Figure 7.1.

Viscous heating of the red potato mash (simulant #3) was not compared to viscous heating performance of real human faeces. Further, this simulant was not tested for its density or whether it could be representative of faeces shape. It can reasonably be assumed that this simulant will poorly represent the chemical characteristics of human faeces, as it lacks important components such as bacterial content, fibre, proteins and inorganic matter.

Yeo and Welchel (1994) patented a synthetic faeces for simulating the dewatering rate of human stools. It was developed to be used as a substitute for real faeces in the testing and development of diapers. They examined 32 formulations using different components. Many of their attempts were based on a commercially available synthetic faeces, FECLONE®BFPS-4 powder (simulant #4, Table 7.3*)* from Silicone Studio of Vallez Forge, Pa. FECLONE®BFPS-4 was reported to have a viscosity of 2,276-4,032 cP which is comparable to human stools, but a substantially higher dewatering rate of 524-535 $g_{water}/m^2_{simulant}$.min. In comparison, viscosity and dewatering values of human faeces were reported as 3,500-5,500 cp and 350-400 g_{water}/m^2_{faeces}.min for regular faeces (Table 7.1 and Table 7.2).

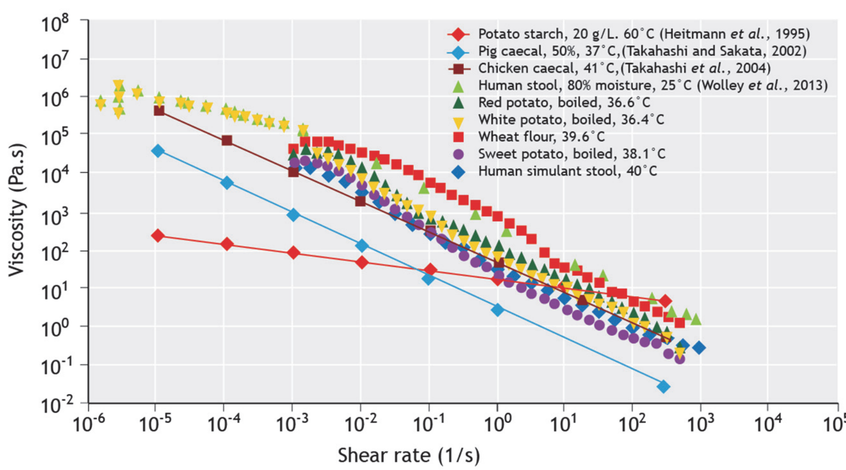

Figure 7.1 Rheological behaviour of the various simulants (Podichetty *et al.,* 2014).

The units of the dewatering rate (g/m^2.min) include m^2 of material, which is determined according to the measurement procedure reported in Yeo and Welchel (1994). Since such a unit is not applicable to be used easily for other research purposes, the authors of this paper converted the unit to $g_{water}/L_{material\ (simulant\ or\ real\ faeces)}$.min according to the methods described in Yeo and Welchel (1994). The converted results were found to be 110.1-125.9 g_{water}/L_{faeces}.min and 164.9-168.0 $g_{water}/L_{simulant}$.min for regular faecess and the simulant, respectively. The viscosity was measured in centipoise at 50 revolutions per minute using a model RVT viscometer manufactured by Brookfield Engineering Laboratories, Inc., Stoughton, Mass. The shear rate at which the viscosity was measured was not given.

Yeo and Welchel (1994)'s best-performing simulant (simulant #5, Table 7.3) was composed of 15% Polyvinylpyrrolidone (PVP), 5% psyllium mucilloid and 80% water. By varying the weight percentage of the soluble to insoluble components, the molecular weight of the soluble component (PVP) and the water content, the viscosity of the simulant could be varied along the Bristol Stool Scale. Therefore, the viscosity can be adjusted to between 1,000 to 40,000 cP covering the range of real human stools (Table 7.4 and Table 7.5). When the simulant was adjusted to a viscosity range of 3,500-5,500 cp (similar to that of human stools), a dewatering rate of 50-400 g/m^2.min (15.73-125.9 g/L.min after conversion) was reported. The simulant was found to bind water to a better extent than other commercially used alternatives. The alternatives included mashed potatoes, brownie mix, peanut butter and pumpkin filling, and were reported to have a dewatering rate of over 500 g/m^2.min (157.3 g/L.min after conversion), much higher than human faeces. A proper mixture of both water soluble (84 wt % of total solids) and water insoluble (16 wt % of total solids) components was necessary to achieve low dewatering rates while keeping the water content relatively constant at 70-90% of the total weight. The authors also found that water-soluble components which had an average molecular weight of over 10,000 g appeared to provide lower dewatering rates. They further reported that adding saturated fat to the solids portion at less than 2 wt % of total simulant weight resulted in reduction of both the surface tension and dewatering rate of the compound.

According to Wignarajah *et al.* (2006), the drawback of the simulant developed by Yeo and Welchel (1994) is its inability to act as a faeces-like substrate for microbial activity. The addition of PVP resulted in much higher nitrogen levels than are typically found in faeces.

7.3.1.2 Faecal sludge simulants

The physical properties of faecal sludge are different from faeces. Hence, investigations making use of faecal sludge require different simulants from those used for faeces. However, as faeces are an essential ingredient in faecal sludge, some of the simulants described in the previous section can be a base for the development of faecal sludge simulants.

Radford and Fenner (2013) developed a synthetic faecal sludge to represent the physical characteristics of pit latrine sludge (simulant #15, Table 7.3). It was developed for studying pit-emptying performance by vacuum trucks, specifically for systems in southern Africa. It was composed of a mixture of compost, kaolin clay, and water. The authors calculated the shear strength of faecal sludge as <400 Pa from a previous study of sludge densities in pit latrines (Boesch and Schertenleib, 1985). The simulant could be modified to have a shear strength from 60 to 900 Pa, which replicated and exceeded the full range of shear strengths found in faecal sludge. The simulant densities were in the range of some faecal sludges (800-1,200 kg/m^3) but were not representative of sludge with elevated sand content, which has a much higher density (up to 2,200 kg/m^3).

Radford *et al.* (2015) expanded the recipe developed by Radford and Fenner (2013) by proposing two simulants to cover the entire range of faecal sludge densities and shear strengths. The simulants were further developed to be used for research on emptying various types of containment systems (*e.g.* septic tanks, pour-flush systems, pit latrines, and urine-diverting dry toilets). While detailed recipes for these simulants were not described in the literature, their components were provided. Simulant 'a' replaced the compost in simulant #15 with topsoil, it further included (like simulant #15) kaolin clay and a range of water contents. Their second simulant (simulant 'b') contained milorganite organic fertiliser derived from sewage sludge, as well as salt, vinegar and a range of water contents. Both simulants were found to represent the full range of shear strengths reported for faecal sludge, but had different densities of 1,400 kg/m^3 and 980 kg/m^3 for simulants 'a' and 'b', respectively. Simulant 'a' was used for a Water for People-led research project in Uganda as those materials were locally available. Milorganite was recommended for faecal sludge processing technology development testing in the USA because it is easy to obtain in that country and can be standardised. Thorough validation of the faecal sludge simulants was impossible because there have been limited characterisation studies of the rheological properties and 'pumpability' of actual faecal sludge.

7.3.2 Chemical, biological, and thermal parameters

The previously discussed simulants were developed to mimic specific physical properties of human faeces and faecal sludge, and are unlikely to reflect their chemical properties. Various simulants reflecting specific chemical, biological, and thermal properties of human faeces and faecal sludge have also been developed. These chemical and biological properties are mostly defined as chemical oxygen demand (COD), total nitrogen (TN), pH, electrical conductivity (EC), total solids (TS), volatile solids (VS), elemental composition, and biogas potential. Important thermal properties are calorific value and ash content. Some of these simulants provide very high chemical, biological, and/or thermal resemblance to human stools and faecal sludge. However, many lack a physical resemblance to faeces and faecal sludge.

7.3.2.1 Faeces simulants

The first attempts to simulate the chemical composition of faeces were made by Kaba *et al.* (1989) for investigating faeces treatment by onsite oxidation (simulant #6, Table 7.3). The treatment was carried out by electrochemical incineration of waste. Bhardwaj *et al.* (1990) reported that oxidation of real faeces and oxidation of this simulant, with urine serving as an electrolyte, occurred at the same potential. Their simulant was developed based on the assumption that faeces solids are made up of one-third microorganisms from the intestinal flora, one-third undigested fibre and the rest is lipids and inorganic material. Tennakoon *et al.* (1996) made use of this simulant for investigating electrochemical treatment of human wastes in a packed bed reactor.

Based on the simulants developed by Kaba *et al.* (1989) (simulant #6 Table 7.3) and Yeo and Welchel (1994) (simulant #5 Table 7.3), Wignarajah *et al.* (2006) developed synthetic faeces formulations for NASA's development of onsite waste processing for its space missions (simulant #7, Table 7.3). These recipes focus primarily on representing the water-holding capacity, rheology and the chemical composition of real faeces. They replaced the oleic acid suggested by Kaba *et al.* (1989) with peanut oil due to its high fraction of oleic acid (50-80%). Additionally, they replaced the casein (protein) in the original recipe with miso paste, composed of 38% protein, 21% fat, 20% fibre and 4% minerals. *E.coli* was the only organism used. In their simulant, Wignarajah *et al.* (2006) opted to use the nitrogen-free polyethylene glycol to represent the water-holding capacity instead of PVP based on lessons learned from the high nitrogen content of simulant #5 (Table 7.3). The resulting product was reported to be more chemically similar to faeces than the previously developed simulants #5 and #6 (Table 7.3). Wignarajah *et al.* (2006) produced five different versions to represent different aspect of faeces: water-holding capacity, rheology and chemical composition. They indicated that each version may be best used for different studies. Table 7.4 presents the function of the different components in the basic recipe proposed by Wignarajah *et al.* (2006).

Table 7.4 Functions of the components in the synthetic faeces #7 (Wignarajah *et al.*, 2006).

Component	Function
E.coli	Bacteria debris
Cellulose	Fibre/carbohydrate
Polyethylene glycol	Water retention
Psyllium husk	Dietary fibre/carbohydrate
Peanut oil	Fat
Miso paste	Proteins/ fats/ fibre/minerals
Inorganics	Minerals
Dried coarsely ground vegetable matter	Undigested vegetable matter

It should be noted that even though some of the ingredients presented in Table 7.4 contain water (*e.g.* miso paste), 'solids content' refers to all of the recipe's ingredients excluding deionised water.

Simulant #7 (see Table 7.3) is the basis of the synthetic faeces used by a number of research groups focusing on the energy recovery from faeces and its treatment in onsite sanitation systems. Ward *et al.* (2014) and Danso-Boateng *et al*. (2012) used it to simulate the energy content of carbonised faeces. Danso-Boateng *et al*. (2012) modified this simulant for investigating the conversion of biomass within faeces into char using hydrothermal carbonisation (HTC). Their modified recipe is presented as simulant #8 in Table 7.3. No information on the purpose of their modification or the simulant's resemblance to faeces was reported. Ward *et al*. (2014) evaluated solid fuel char briquettes produced from faeces. They found that although both the faeces and the simulant (simulant #7 as in Table 7.3) had similar calorific values, the char produced from synthetic faeces had a higher calorific value compared to char produced from real faeces. They attributed this difference to the low inorganic content of the simulant in comparison with real faeces. They further showed that the faecal char had a comparable calorific value to wood char. The energy content was reported as 25.57 MJ/kg and 29.53 MJ/kg for chars produced from faeces and synthetic faeces, respectively at a pyrolysis temperature of 300 °C. Increasing the pyrolysis temperature to 750 °C decreased the energy content of the chars to 13.83 MJ/kg and 18.92 MJ/kg for faeces and synthetic faeces, respectively. Onabanjo *et al*. (2016a) and Yermàn *et al.* (2015) adapted simulant #7 (Table 7.3) to investigate the combustion performances of faeces. Their modifications can be found as simulants #9 and #10 in Table 7.3. The result presented by Onabanjo *et al*. (2016a) showed good representation of human faeces regarding parameters effecting combustion including calorific value, VS, ash content and element chemical composition (as shown in Table 7.2). Yermàn *et al*. (2015) validated the combustion performance of the simulants with the performance of dog faeces.

Colón *et al*. (2015) modified simulant #7 to investigate anaerobic digestion of undiluted synthetic faeces and urine, and Miller *et al*. (2015) looked at supercritical oxidation of a similar simulant to treat faecal sludge. This simulant (simulant #11), shows high chemical and biological resemblance to human faeces (Table 7.2). Colón *et al*. (2015) further adjusted the simulant for trace metal contents since trace metals play an important role in the growth of methanogens and methane formation. The adjustment was made by adding a trace element solution with the following composition: $FeCl_2{\cdot}4H_2O$, 28.6 mg/kgTS; H_3BO_3, 1.14 mg/kgTS; $MnCl_2{\cdot}4H_2O$, 1.91 mg/kgTS; $CoCl_2{\cdot}6H_2O$, 2.29 mg/kgTS; $ZnCl_2$, 1.34 mg/kgTS; $NiCl_2{\cdot}6H_2O$, 0.48 mg/kgTS; $CuCl_2{\cdot}2H_2O$, 0.29 mg/kgTS; $NaMoO_4{\cdot}2H_2O$, 0.48 mg/kgTS $FeCl_2{\cdot}4H_2O$, 28.6 mg/kgTS; H_3BO_3, 1.14 mg/kgTS. The results shown by Colón *et al.* (2015) demonstrated that anaerobic digestion of undiluted human simulant excreta in simple unmixed digesters is feasible and yields biogas, which is a valuable by-product of the treatment. As it was not relevant to their studies, no attempt was made to match the physical properties of their simulant to that of real human stools.

Of the previously addressed modifications to simulant #7, four of them use active baker's yeast instead of *E.coli* to represent microbial material (see Table 7.3). The inorganic fraction was supplied by various salts including calcium phosphate (Ward *et al.,* 2014), a mixture of calcium phosphate and potassium chloride (simulant #8, Table 7.3), or a mixture of calcium chloride, sodium chloride, and potassium chloride (simulant #11, Table 7.3). The quantities of the other components of simulant #7 were only slightly modified (Table 7.3) and no further information was given for those modifications.

Simulant #11, developed by Colón *et al*. (2015), was the only one thoroughly analysed for chemical properties important for wastewater treatment (including COD_{total}, $COD_{soluble}$ TN, pH, EC, TS VS and elemental composition). It showed a high chemical resemblance to human faeces (Table 7.2). It further showed adequate potential for production of biogas. However, based on the personal experience of the authors of this chapter, the large amount of baker's yeast included in this recipe makes it physically very different from real human faeces as it inflates like bread dough, and yields a sticky, unshapable slime.

Ilango and Lefebvre (2016) used miso paste (a mixture of soybean paste, rice, salt, ethanol and water) as a chemical approximation of faeces for a study of biochar production from faeces (simulant #12, Table 7.3). This simulant was found to have a similar elemental composition to faeces along with comparable moisture content and calorific value (as shown in Table 7.2). While this recipe produced a successful simulant for pyrolysis studies, a similar simulant was also evaluated by Podichetty *et al.* (2014) (simulant #13, Table 7.3) in the previously discussed rheology studies and deemed to be a poor physical representation of human faeces. Both studies provide similar compositions for a miso paste-based simulant.

Simulant #11 and simulant #12 (Table 7.3) appear to provide good approximations of faeces in terms of the chemical properties (as indicated in Table 7.2), while Simulant #11 (Table 7.3) showed good resemblance to the chemical properties important for wastewater treatment. It further showed high compatibility in terms of its elemental content important for energy and nutrient recovery and similar biogas production to faeces. Simulant #12 had similar elemental composition and heating properties to faeces, both important factors for energy recovery from faeces. However, they both proved to poorly resemble the physical properties of faeces.

7.3.2.2 Faecal sludge simulants

Fresh faecal sludge can be represented as a combination of faeces and urine with the option to include flush water, greywater, anal cleansing material, municipal solid waste, or other constituents depending on the system. Faecal sludge emptied from onsite containment or arriving at a treatment facility undergoes biological degradation, contributing to the various chemical and physical characteristics that a simulant will need to address. Two simulants were found in the literature intended to represent the chemical and biological properties of faecal sludge for anaerobic digestion research (Zuma, 2013; Colón *et al.,* 2015). In addition, a recipe for synthetic urine (Colón *et al.,* 2015) and a few recipes for synthetic greywater were developed (Gross *et al.,* 2015). These can be combined with synthetic faeces for the preparation of synthetic faecal sludge. Examples for these simulants are presented in tables 7.5 and 7.6.

Table 7.5 Synthetic urine (Colón *et al.*, 2015).

Component	Amount (g/L)
Urea	14.2
Creatinine	3
Ammonium citrate	2
NaCl	8
KCl	1.65
$KHSO_4$	0.5
$MgSO_4$	0.2
KH_2PO_4	1.75
$KHCO_3$	0.5

Colón *et al.* (2015) mixed 300 ml of a modified urine simulant (Table 7.5) developed by Putnam (1971) with 120 g of wet simulant #11 in their studies of onsite anaerobic digestion of undiluted fresh faecal sludge (to produce simulant #16, Table 7.13). Their simulant was required to have chemical similarity to facilitate growth of anaerobic bacteria (specifically, COD_{total}, $COD_{soluble}$, N, N-NH_3, C:N, pH, EC, P, Fe, Zn, Ni, Co, Mn, Mo, B, Cu). For adjusting the simulant to contain missing trace elements (important for methanogen growth), the same trace element solution described with the discussion of their faeces simulant (simulant #11, Table 7.3), was added. The simulant had specific gas production of 0.12-0.37 NL biogas/gCOD (gas volume at 237 K and 1 atm). Since the time that this study was originally published, biomethane potential values of 47.3 mLCH_4/gVS for faecal sludge, and 53.1 mLCH_4/gVS for faeces have been published, suggesting that further characterisation of may be necessary to establish realistic biomethane potential targets for faeces and faecal sludge simulants (Bourgault, 2019).

Zuma (2013) developed synthetic faecal sludge for representing the chemical and biological properties of faecal sludge for anaerobic digestion testing. Five different recipes were developed by varying the proportions of hayflour, ground walnuts, sodium phosphate ($Na_2HPO_4 \cdot 12H_2O$), and ammonium bicarbonate (NH_4HCO_3) (simulants #17-21, Table 7.3). This simulant was found to have a comparable biomethane potential to dairy manure, with 0.237 NLCH_4/gVS after 24 days and 0.24 NL CH_4/gVS after 40 days at 37 °C for the simulant and the dairy manure, respectively. Sludge parameters

TS, VS, TSS, and VSS were easily adjusted for the entire ranges present in faecal sludge by varying the ingredient ratios. COD could be varied with hay flour content. Nutrients could be adjusted with sodium phosphate and ammonium carbonate, and sulphate content was adjustable by varying the walnut content. Recipes with more hay flour had higher lignin and cellulose, and recipes with more walnut had higher lipid levels. The range of values achievable for these simulants is presented in Table 7.2. This simulant needs further development to be able to model a broader range of faecal sludge characteristics. The authors found that they were unable to replicate sludge with a VS/TS ratio lower than 0.85, which seriously limits applicability in the case of more stabilised faecal sludge. VS/TS ratios for faecal sludge samples collected during discharge at treatment facilities typically range between 0.43 and 0.73 (Gold *et al.,* 2017a. The physical properties of this simulant were not reported.

Table 7.6 Recipes for synthetic greywater (adopted from Gross *et al.,* 2015)

Constituent	Greywater(1) (mg/L)	Greywater(2) (g/100 L)	Bath(3) (g/100 L)	Laundry(3) (amount/100 L)	Laundry and bath(4) (amount/100 L)
Ammonium chlorine	75				
Soluble starch	55				
Potassium sulphate	4.5				
Sodium sulphate Na_2SO_4		3.5		4 g	
Na_2PO_4				4 g	
Sodium dihydrogen phosphate	11.4	3.9			
Sodium bicarbonate $NaHCO_3$		2.5		2 g	
Boric acid		0.14			
Lactic acid		2.8	3		
Synthetic soap					
Body wash with moisturiser			30		
Conditioner			21		
Shampoo	0.022	72	19		86 mL
Liquid hand soap			23		
Bath cleaner			10		
Liquid laundry fabric softener				21 mL	
Liquid laundry detergent				40 mL	
Laundry		15			At recommended concentrations for hard water
Kaolin	25				
Clay		5			
Test dust			10	10 g	
Sunscreen/moisturiser		1/1.5			
Toothpaste		3.25	3		
Deodorant		1	2		
Vegetable oil		0.7			1 mL
Secondary effluent		2 L	2 L	2 L	To give final concentration of 10^5-10^6 CFU of total coliforms

[1]Friedler *et al.,* 2008; [2]Diaper *et al.,* 2008; [3]NSF, 2011; [4]BSI, 2010; CFU: colony-forming unit.

In addition to faeces and urine, greywater is an important component of some faecal sludge, especially within higher economic brackets that are likely to have piped water and septic tanks (Strande *et al*., 2014; Schoebitz *et al*., 2016). Recipes for synthetic greywater contain ingredients typically found in real greywater such as a variety of personal hygiene products, chemicals used in the home, and bacteria. The mixture of these substances typically yield similar levels of pH, COD, BOD_5, TSS and surfactants usually found in greywater. Greywater characteristics are influenced by the type of flows contained within the greywater (*e.g.* kitchens, showers, sinks, laundry etc.), cultural and socioeconomic variables, climate and geographical variables and quality of the source water (Gross *et al.,* 2015). Recipes for synthetic greywater found in the literature and in government standards are presented in Table 7.6.

7.4 DISCUSSION

Based on the literature review, there have been successful simulants mimicking specific physical and chemical properties of human faeces and faecal sludge. A summary of the reviewed simulants and their similarity to human faeces and faecal sludge is presented in Table 7.7 and 7.8. The differences in the simulant properties are readily apparent in Table 7.8, since each was developed to mimic specific faeces and faecal sludge characteristics applicable to the study undertaken, but ignore most others. A clear distinction can be made between the physical (simulants #1 to#5 and #15) and chemical, biological, and thermal simulants (#6 to #14, #16 to #21). Almost none of the simulants adequately represent both chemical and physical properties. The information provided in Table 7.8 can support the selection of the simulant to be used or to be further developed for any intended research. For example, in wastewater research of sewer systems and onsite sanitation systems a combination of some of these properties is of importance. Such investigations include faeces movement and faeces and faecal sludge settling, dewatering, and physical and biochemical disintegration. A first attempt to combine these properties in one faecal simulant is described in detail in Section 7.4.1.

To date, constituents of interest, such as odour, pathogens, pharmaceuticals, hormones and comprehensive COD fractionation, have not been included in faecal sludge simulants. The development of simulants including COD fractionation (*e.g.* inert and slowly and readily biodegradable fractions of COD is important for the study of biochemical properties of faecal sludge during onsite storage and treatment. Odours can be simulated by real or synthetic components, such as hydrogen sulphides, methyl sulphides and benzopyrrole derivatives (Moore *et al.,* 1987). Sato *et al.* (2001a,b) found that sulphur-containing components were 2.2% of the total gaseous fraction, while the nitrogenous benzopyrrole compounds were only about 0.3%. Ammonia occurred at 6.3%.

It is important to note that faecal sludge is highly variable and it differs significantly from fresh faeces. As seen in this review, the development of faecal sludge simulants is in its preliminary stages. The importance of FSM has only been acknowledged relatively recently (Moe *et al*., 2006; WHO, 2017), which is a possible reason for the comparative lag in simulant development. One reason for the complexity of developing representative simulants is due to the lack of comprehensive characterisation data for faecal sludge, although, with the increasing awareness of the importance of FSM, this data is becoming more readily available (Gold *et al.,* 2017a). The lack of available information on faecal sludge characteristics makes it difficult to validate simulant performance. Faeces is an important constituent of faecal sludge, which typically also includes additional components such as urine, greywater, flush water, and/or solid waste, and with varying levels of biological and physical degradation (Chapter 2). The comprehensive review of faeces, urine, and greywater simulants presented in this paper will support the further development of faecal sludge simulants. This will be valuable for conducting research to understand what is occurring during onsite storage of faecal sludge, to develop treatment technologies, and to enhance potential for resource recovery (Diener *et al.,* 2014; Muspratt *et al.,* 2014; Gold *et al.,* 2017a,b).

In the discussion on faeces and faecal sludge simulant development it is also important that average values are targeted for desired simulant characteristics. However, in reality, the characteristics of faeces and faecal sludge vary widely depending on health and diet, storage time, containment technology, and usage patterns (Chapter 2). Further research is necessary prior to the development of simulants that reflect regional and dietary dependent variations. To achieve this, it will be important to identify which parameters are most sensitive to such effects and how much impact they have on the purpose of the simulant.

Table 7.7 Summary description of all the simulants.

	Sim. #	Reference	Description	Investigation
Faeces simulants	1	(4,17)	Plastic cylinders with detecting device	Investigating gross solids movement in sewers
	2	(5, 7, 11)	Soybean paste in a latex casing	Testing toilet performance (connected to sewers and off-grid)
	3	(12)	Red potato mash	Viscous heating of faeces for pathogen destruction
	4	(2)	Water soluble polymer (for water-holding capacity), fibre and water	For testing diapers
	5	(2)		
	6	(1,3)	Variations on a recipe containing bacteria, water, retention component, fibre, fat, proteins and minerals	Electrochemical oxidation for treatment of faeces
	7	(6,13)		Wastewater treatment in space vehicles (6) Production of char briquettes from faeces (13)
	8	(8)		Production of char briquettes from faeces through hydrothermal carbonisation
	9	(19)		Combustion performance of human faeces
	10	(19)		
	11	(14,15)		Anaerobic digestion of faeces and urine (14) Supercritical oxidation to treat FS (15)
	14	(20)		Physical disintegration of faeces under sewer flow conditions, biological disintegration of faeces in onsite systems and optimisation of FS treatment
	12	(18)	Mixture of soybean paste, rice, salt, ethanol and water	Biochar production from faeces
	13	(11)		
Faecal sludge simulants	15	(9,16)	Mixture of compost, kaolin clay and water	For studying pit-emptying procedure
	16	(14)	Same as simulant #11 + addition of synthetic urine	Anaerobic digestion of FS
	17-21	(10)	Mixture of hay flour, ground walnuts, sodium phosphate and ammonium carbonate	
	22	(20)	Same as simulant #14 + addition of synthetic urine	Dewatering studies of FS

[1]Kaba *et al.,* 1989; [2]Yeo and Welchel, 1994; [3]Tennakoon *et al.,* 1996; [4]Butler *et al.,* 2003; [5]German Industrial Norm/European Norm, 2006; [6]Wignarajah *et al.,* 2006; [7]Veritec Consulting Inc. & Koeller and Company, 2010; [8]Danso-Boateng *et al.,* 2012; [9]Radford and Fenner, 2013; [10]Zuma, 2013; [11]EPA WaterSense, 2014; [12]Podichetty *et al.,* 2014; [13]Ward *et al.,* 2014; [14]Colon *et al.,* 2015; [15]Miller *et al.,* 2015; [16]Radford *et al.,* 2015; [17] Yermán *et al.,* 2015; [18]Ilango and Lefebvre 2016; [19]Onabanjo *et al.,* 2016a; [20]Penn *et al.,* 2018.

Table 7.8 Summary comparison of human faeces simulants.

Simulant #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17-21	22
Reference	(4,20)	(5,7,11)	(5)	(2)	(2)	(1,3)	(6)	(8)	(19)	(17)	(14,15)	(18)	(12)	(21)	(9,16)	(14)	(10)	(21)
Shape	+	+									–			+				
Density	+	+												+	+			
Physical disintegration	–	–												+				
Viscosity	–	–	+	+	+		○					–	–	+	+			+
Dewatering	–	–		–	+		○											–
Water content	–	–	+	+	+	+	○	+	+	+	+	+	+	+	+	+	+	+
COD_{total}	–	–					○				+			+		+	+	+
$COD_{soluble}$	–	–									□			□		□	□	□
TN	–	–					○				+			+		+	+	+
NH_3-N and NH_4-N	–	–					○				+			+		+	+	+
C/N	–	–									+					+		
BOD	–	–																
PH	–	–					○				+			+		+	+	+
EC	–	–					○				□			□		+		+
TS	–	–	+	+	+	+	○	+	+	+	+			+		+	+	+
VS	–	–					○		+		+			+		+	–	+
Elemental composition	–	–				+	+		+		+	+	+					
S	–	–				+					+							
P	–	–															+	
Fe	–	–									+					+		
Zn	–	–									+					+		
Ni	–	–									+					+		
Co	–	–									+					+		
Mn	–	–									+					+		
Mo	–	–									+					+		
Cu	–	–									+					+		
B	–	–									+					+		
Calorific value	–	–					+	+	+			+	+					
Ash content	–	–							+				+					
Biogas yield											+					+		
Odour	–	–	–	–		–	–	–	–	–	–	–	–	–	–	–	–	–
Pathogens	–	–	–	–		+	+	–	–	–	–	–	–	–	–	–	–	–

[1]Kaba *et al.,* 1989; [2]Yeo and Welchel, 1994; [3]Tennakoon *et al.,* 1996; [4]Butler *et al.,* 2003; [5]German Industrial Norm/European Norm, 2006; [6]Wignarajah *et al.,* 2006; [7]Veritec Consulting Inc. & Koeller and Company, 2010; [8]Danso-Boateng *et al.,* 2013; [9]Radford and Fenner, 2013; [10]Zuma, 2013; [11]EPA WaterSense, 2014; [12]Podichetty *et al.* 2014; [13]Ward *et al.,* 2014; [14]Colón *et al.,* 2015; [15]Miller *et al.,* 2015; [16]Radford *et al.,* 2015; [17]Yermán *et al.,* 2015; [18]Ilango and Lefebvre, 2016; [19]Onabanjo *et al.,* 2016a; [20]Penn *et al.,* 2017; [21]Penn *et al.,* 2018.

+ Validated with real faeces or faecal sludge;

□ Reported value for synthetic, but no available data to compare to real faeces or faecal sludge;

– Not expected to be comparable to real faeces or faecal sludge (based on reported literature, other literature values, and experiences of authors; blank box: not enough data to make a conclusion;

○ Reported to be comparable to faeces or faecal sludge but no results provided (simulants #7-10 and simulant #13 are based on this recipe);

Blank box: not enough data to make a conclusion.

7.4.1 Development of a new simulant

For research into the fate of excreta in urban sewers and in onsite sanitation systems, both the chemical/biological aspects of faeces and faecal sludge and their physical properties are important. Investigations of their fate include their physical motion (movement, settling, sedimentation, and dewatering) and their physical and biochemical disintegration in sewer pipes and in onsite sanitation systems. Based on the information gained in the literature review, it is possible to create an adapted simulant with mixed physical and chemical properties that can be used for such investigations. Detailed instructions on the simulant preparation and recommended storage practices can be found in Example 7.1 in the appendix of this chapter.

7.4.1.1 Synthetic faeces

It is required that the new simulant represents a range of physical characteristics based on the Bristol Stool Form Scale. It should be able to be modified from soft to hard by adding different amounts of water, should be shaped into the characteristic faeces cylinder, sausage, or snake, and be able to be controlled as to whether it floats or sinks. The desired simulant should also possess a similar viscosity and dewatering rate to real faeces. Additionally, it should have similar chemical composition to faeces including COD, TN, pH, EC, TS, VS and elemental composition. It should be able to disintegrate in water and the resulting aqueous suspension should have similar chemical properties to disintegrated faeces. By looking at Table 7.8, one can see that both simulant #11 and simulant #12 (from Table 7.3) showed high chemical and biological resemblance in their elemental composition but poor physical resemblance in their shape and rheological properties. Indeed, none of the simulants with proper physical parameters has a representative chemical composition. The modification of the physically-related simulants to represent additional chemical properties was found to be impracticable. Simulants #11 and #12 were therefore the best candidates for further development. Simulant #11 shows high compatibility in its chemical properties important for wastewater-related research, including COD, TN, TS, and VS. Baker's yeast is used to represent microbial biomass and to produce floating stools (due to gas produced by the yeast). However, the quantity included in this recipe creates an unfavourable physical structure. It produced a gassy and sticky material that floated when added to water, but was too sticky to be shaped into a cylinder. Figure 7.2A illustrates the high gas production, shown by the many bubbles in the beaker. The stickiness of the material is shown in Figure 7.2B. Use of active yeast also contributes to quick biological changes within the synthetic material, which is undesirable if reduced sample variability is a priority. An ideal simulant would be storable and resistant to physical or biological change over a span of at least several days in order to maximise reproducibility of experiments. We hypothesised that by adapting the baker's yeast content of simulant #11 (Table 7.3), a physically representative simulant could be produced, while still maintaining its chemical and biological resemblance.

Although Simulant #12 also looks like a good candidate for further development efforts were focussed on simulant #11 at this stage.

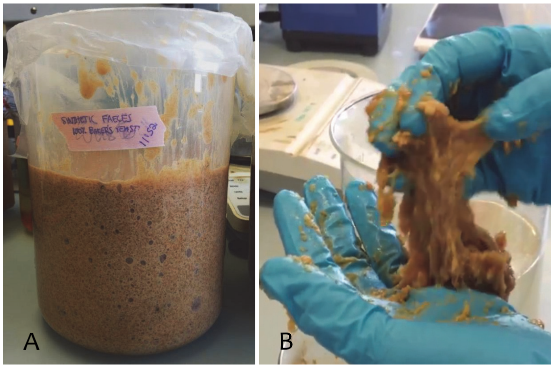

Figure 7.2 Synthetic faeces containing 30 wt % of the solids content baker's yeast. Photo A shows the mixture after standing at room temperature for 1.5 hours and photo B shows a sample of the mixture.

Two substitutions for the bacterial content (*i.e.* baker's yeast) of the adapted simulant were evaluated for shape formation (*i.e.* whether it could be shaped into a cylinder) and density. These substitutions include yeast extract and baking soda. The resulting optimal recipe was then analysed for its chemical and physical properties.

Replacing baker's yeast with yeast extract resulted in a simulant with representative physical properties (shape formation, viscosity, and density) and chemical properties (COD, TN, ES, pH, TS and VS). These results are shown in Table 7.9. Compared to simulant #11 the physical properties of the modified simulant were improved while the well-represented chemical properties were not affected. In addition, the disintegration of the modified simulant in turbulent flow revealed a disintegration mode similar to that of human faeces, with a similar time span (Penn *et al.,* 2019).

The density of this modified simulant was found to be 1.07 g/mL. Since faeces densities can be <1 g/mL (Table 7.2), two rising agents were tested as to whether they could be used to manipulate the density without losing the shaping capabilities. The two rising agents used were: (*i*) baker's yeast, which generates gas through fermentation, and (*ii*) sodium bicarbonate, which produces gas through a chemical reaction with acids in the mixture. The optimum quantity of baker's yeast was identified as 3 wt % of solids content. This amount of baker's yeast produced faeces with roughly the same buoyancy as water, with an average density of 0.99 g/mL. A range of water contents can be added to represent the span present in human faeces: from 65-80% moisture. When lower than 80 wt % water content is required, the portion of baker's yeast can be increased to a maximum of 5 wt % of solids content (in the case of a solid containing 65 wt % water) in order to facilitate quicker gas production. The density and viscosity of the modified simulant could be altered with varied yeast extract and water content fractions, respectively.

Replacing baker's yeast with sodium bicarbonate did not provide satisfying results. The minimum quantity of bicarbonate required for sufficient gas production to yield floating was 3 wt % of solids content in the recipe. However, the resulting product had an undesirable fluffy, sticky structure, and did not pass the shape formatting test.

Table 7.9 Comparison of chemical and physical properties of synthetic faeces from this study simulants #14a and #14b (Table 7.3) with real and artificial faeces from the literature.

Properties	Parameters	This chapter		Literature	
		Simulant #14a	Simulant #14b	Human faeces	Simulant faeces
Chemical	COD_{total} (gCOD/gTS)	1.117±0.056	1.194±0.162	0.567-1.450[10]	
	$COD_{soluble}$ (gCOD/gTS)	0.624±0.017	0.551±0.048	1.24[6]	1.33[9]
	TN (% of TS)	3.56±0.13	4.05±0.22		
	pH	5.4	5.2	5-7[10]	
	EC	6.06±0.17	6.40±0.25	2-3[6,8]	2.75[9]
	TS (%)	20.65±0.29	20.79±0.30	5.0-8.0 (avg. 6)[10]	
	VS (% of TS)	87.61±0.13	87.93±0.07	4.6-8.4[9]	5.3[9]
Physical	Viscosity (cPs at 50 rpm)	6,360	4,640		5.7[9]
	Density (g/ml)	1.07±0.02	0.98±0.05	14-37[10]	

[1]Snell, 1943; [2]Fry, 1973; [3]Meher *et al.,* 1994; [4]Yeo and Welchel, 1994; [5]Brown *et al.,* 1996; [6]Jönsson *et al.,* 2005; [7]Wignarajah *et al.,* 2006; [8]Barman *et al.,* 2009; [9]Colón *et al.,* 2015; [10]Rose *et al.,* 2015;
Note: Average ± standard deviation were calculated from three replicates;
Note: Results are for synthetic faeces containing 80 wt % water.

7.4.1.2 Synthetic faecal sludge

The synthetic faeces developed by the authors as described in Section 7.4.1.1 (simulant #14(a), Table 7.3) was combined with synthetic urine (Table 7.5) and water to produce a synthetic faecal sludge for dewatering studies. The simulant was chemically very similar to simulant #16 (Table 7.3) and to fresh faecal sludge, however it displayed a 60% reduced dewaterability compared to real fresh faecal sludge. In this case, dewaterability is defined as the percentage of dry solids in the dewatered cake after centrifugation, which was 11% and 4.5% for fresh faecal sludge and synthetic fresh faecal sludge, respectively (Ward *et al*., 2017a, b). This is likely due to the high water-binding affinity of the psyllium husk included in the simulant. For further dewatering experiments, a faeces simulant with a reduced proportion of water-binding components could be evaluated.

7.5 CONCLUSIONS

The use of synthetic faeces and synthetic faecal sludge enables replicable experimentation, while simultaneously reducing health risks. There are a multitude of simulants for faeces in the literature, however, they are still relatively scarce for faecal sludge. At this stage, simulants have for the most part been developed for specific purposes, and simulants that are mutually representative of physical, chemical, biological and thermal properties are still lacking. It is important to develop recipes including COD fractionations for detailed biochemical process, and potentially other properties such as pharmaceuticals and hormones, pathogens and odours. The compilation of existing simulants in this chapter has been valuable for the identification of strengths and weaknesses of simulants, and areas for further research.

A critical analysis of the literature yields the following conclusions:

- Synthetic faeces and faecal sludge are very useful for conducting research, but cannot entirely replace research with real faeces and faecal sluge.
- As with any surrogate, the results have to be validated with real faeces and faecal sludge.
- Standardisation and validation of other results can be significantly increased through the use of standard methods for the characterisation of faeces and faecal sludge.

APPENDIX 7.1 EXAMPLES FOR THE DEVELOPMENT OF FAECES AND FAECAL SLUDGE SIMULANTS

Example 7.1 *Development of a new faeces simulant by Eawag, Switzerland*

For research into the fate of excreta in urban sewers and in onsite sanitation systems, both the chemical/biological aspects of faeces and its physical properties are important. Investigations of its fate include its physical motion (movement, settling and sedimentation) and its physical and biochemical disintegration in sewer pipes and in onsite sanitation systems. Both types of chemically related simulants (simulant #11 (Table 7.3) and simulant #12 (Table 7.3) showed poor physical resemblance, as discussed above (Table 7.8). Similarly, none of the simulants with proper physical parameters have an adequate chemical composition. In the following experimental sections, substitutions for the bacterial content (*i.e.* baker's yeast) of the adapted simulant were evaluated for shaping capability and density. These substitutions include yeast extract and baking soda. The resulting optimal recipe was then analysed for its chemical and physical properties.

Material and methods

Chemicals and materials used

Table 7.10 lists the materials and chemicals used for preparation of the simulant.

Table 7.10 Chemicals and materials used for the simulant

Component	Chemical/material	CAS number
Yeast extract	Sigma Aldrich	8013-01-2
Cellulose	Sigma Aldrich	9004-34-6
Oleic acid	MP Biomedicals LLC	112-80-1
NaCl	Merck KGaA	7647-14-5
KCl	Fluka Chemika GmbH	7447-40-7
$CaCl_2 \cdot 2H_2O$	E. Merck	10035-04-8
Baker's yeast	Dry, Betty Bossi, COOP, Switzerland	
Psyllium husk	Govinda Nature GmbH	
Miso paste	Seasoned soybean paste HACCP, TS content ~48%	

Measurement methods

Total chemical oxygen demand (COD_{total}), soluble COD ($COD_{soluble}$), total nitrogen (TN), ammonium nitrogen (NH4-N), total solids (TS), volatile solids (VS), pH, and electrical conductivity (EC) were determined based on standard methods (Rice *et al.,* 2017). Hach LCK test kits were used to measure COD_{total} and $COD_{soluble}$, TN, and NH_4-N with a Hach DR 6000 spectrophotometer. EC and pH were measured using a WTW Multi 3320 following the procedure described in Colón *et al*. (2015), by diluting synthetic faeces in DI water at a 1:5 w:v ratio. Viscosity was measured with a Brookfield DVII-LV viscometer using a #64 spindle at 50 rpm with a 30-second measurement time.

Physical structure of the synthetic faeces, *i.e.* its shaping capabilities, was evaluated by attempting to shape it into a cylinder, following the normal stool form according to the Bristol Stool Form Chart (Lewis and Heaton, 1997). Approximately 100 g of synthetic faeces was handled and rolled gently into a cylinder, while wearing wetted nitrile gloves. If the material was too sticky, gooey, or liquid to form a cylinder, it failed the shape test.

Buoyancy of the synthetic faeces was evaluated by placing a piece of prepared substance in a beaker filled with water. Floating or sinking performance of the faeces was recorded.

The estimated density was measured by weighing a 40 g portion of simulant and placing it in a 1,000 mL graduated cylinder filled with 600 mL of deionised water. The increase in volume was measured, and the density was calculated. In order to reduce the uncertainty in this measurement, a pycnometer could be used in future experiments. An average and standard deviation from three repetitions was calculated.

Base synthetic faeces recipe

The range of recipes for preparation of 1 kg of synthetic faeces is presented in Table 7.11.

Table 7.11 Ingredients for basic recipe of the simulants S80 and S65, all quantities are in grams.

Water content (% TS)[A]	80% (S80)		65% (S65)	
	SB80[B]	SE80[C]	SB65[B]	SE65[C]
Yeast extract	65.06	72.29	105.42	126.51
Baker's yeast	7.23	0.00	21.08	0.00
Microcrystalline cellulose	24.10	24.10	42.17	42.17
Psyllium	42.17	42.17	73.80	73.80
Miso paste	42.17	42.17	73.80	73.80
Oleic acid	48.19	48.19	84.34	84.34
NaCl	4.82	4.82	8.43	8.43
KCl	4.82	4.82	8.43	8.43
$CaCl_2 \cdot H_2O$	2.75	2.41	4.81	4.81
DI Water	758.7	758.7	577.72	577.72
Final mass 'faeces'	1,000.00	1,000.00	1,000.00	1,000.00

[A]The water content was determined by TS measurements; [B]Simulants starting with SB contain baker's yeast and yeast extract; [C]Simulants starting with SE contain only yeast extract.

Table 7.12 Results of physical testing for synthetic faeces S80 with different quantities of rising agents (baker's yeast and sodium bicarbonate).

Rising agent	Amount of rising agent added (wt % of solids content in recipe[A])	Shapable?[B]	Floats?[B]	Waiting time (h)[C]
None	0.0	yes	no	1.5
Baker's yeast	30.0*	no	yes	1.5
	15.0	no	yes	1.5
	10.0	no	yes	1.5
	5.0	no	yes	1.5
	3.0	yes	yes	1.5
	1.4	yes	yes	3.0
	0.9	yes	yes	48.0
Baking soda	15.0	no	yes	1.5
	3.0	no	yes	1.5
	1.0	no	no	1.5
	0.4	yes	no	1.5

[A]Original recipe from Colón *et al.* (2015); [B]Results from synthetic faeces made with 80% water (actual water content obtained from TS measurements of the simulant). In each recipe, wt % rising agent + wt % yeast extract = 30 wt % of solids content; [C]Time needed for the mixture to stand at room temperature

Experiments

Identification of the base recipe

With the goal of producing a simulant to be used for investigating the fate of faeces in sewer systems and in onsite sanitation systems, which will resemble human faeces in both its physical and chemical properties, an adaption of one of the reviewed simulants was undertaken. Modifying the physical simulants also represent also the chemical properties of human faeces was found to be impracticable. Both simulant #11 (Table 7.3) and simulant #12 (Table 7.3) showed high compatibility in terms of elemental content but poor physical resemblance in terms of shapable capabilities and rheology (Table 7.8).

Simulant #11 shows high compatibility in its chemical properties important for wastewater related research, including COD, TN, TS, and VS. Baker's yeast is used to represent microbial biomass and to produce floating stool (due to gas produced by the yeast). However, the quantity included in this recipe creates an unfavourable physical structure, as explained above and later demonstrated in the results. It was hypothesised that by adapting the baker's yeast content of simulant #11 (Table 7.3), a physical representative simulant can be produced, while still maintaining its chemical resemblance.

In order to consider simulant #12 (Table 7.3) as a good base for further development, its additional wastewater-related chemical properties (*i.e.* COD, TN, TS, VS) would first need to be analysed. If these results showed a close resemblance to human faeces, its shaping capabilities and density would then need to be further adjusted to replicate those of human faeces. However, since the results from adapting simulant #11 showed good chemical and physical resemblance, modification of simulant #12 was not investigated further.

Density adjustments

After identifying the base recipe, a series of experiments were performed to adjust the density of the simulants. For each formulation of yeast and baking soda, shapable capability and floating tests were conducted. The time required for the simulant to float was recorded.

Quantities of two rising agents, baker's yeast, which generates gas through fermentation, and sodium bicarbonate, which produces gas through a chemical reaction with acids in the mixture, were tested to determine whether they could be used to manipulate the density without losing the shapable capabilities. These tests were conducted on simulants containing 80% and 65% water, S80 and S65 respectively, corresponding to the reported maximum and minimum water content expected in human faeces. The corresponding ingredients are listed in Table 7.11. The water content was determined by TS measurements and not only by the volume of water added, since miso paste also contains water.

Different formulations of baker's yeast and yeast extract were tested. The total yeast content was held constant at 30% (dry weight by dry weight), but the ratio of these two forms of yeast were varied. Reduced quantities of baker's yeast were replaced by respective quantities of yeast extract. Quantities of baker's yeast examined were 0, 0.9, 1.4, 3, 5, 10, 15, and 30 wt % of the recipe's solids content. The activity of the yeast depends on the temperature, amount of yeast added and substrate availability. The optimal quantity of baker's yeast was determined when a simulant obtained the desired cylinder shape and buoyancy properties after approximately 1.5 h at room temperature (23 °C). 1.5 hours is the minimum time required for the psyllium husks to gel. It further should enable a relatively 'comfortable' time range (not less than an hour with preference for longer) in which the simulant maintains its physical structure.

Replacing baker's yeast with sodium bicarbonate as an alternative to the biological gas production was further examined. Quantities of bicarbonate examined were 0.4, 1, 3, 5 and 15 wt % of the recipe's solids content.

Physical and chemical properties

Once the optimum formulation was obtained, chemical properties and viscosity of two types of simulant S80 were evaluated. These simulants include SB80, made with baker's yeast and yeast extract, and SE80, made with only yeast extract. As addition of bicarbonate showed poor results, simulants containing bicarbonate were not analysed further for their chemical properties and viscosity. Density was evaluated for these two types and for SB65 and SE65, *i.e.* simulant S65 made with baker's yeast and yeast extract, and only yeast extract, respectively.

Results and discussion

Physical structure

Synthetic faeces SE80 and SE65, *i.e.* both simulants not containing baker's yeast, immediately sank when added to water, with an average density of 1.07 g/ml and standard deviation (SD) of 0.02 for SE80 and a density of 1.12 g/ml with SD of 0.05 for SE65. Densities resemble the density of an NBS solid

(Brown *et al.,* 1996). These simulants were easily shaped (Figure 7.3) and sank when placed in standing water.

Figure 7.3 Simulants with 30 wt % of solids content yeast extract and no baker's yeast: A) SE65; B) SE80.

A summary of the physical characteristics of synthetic faeces made with the different amounts of rising agents (baker's yeast and sodium bicarbonate) is shown in Table 7.12. The results presented are for simulant S80. Adding baker's yeast contents of more than 3 wt % created a gassy and sticky material that floated when added to water, but was too sticky to be shaped into a cylinder. The resultant simulant did not represent the physical structure of human faeces. An extreme example can be depicted in Figure 7.2 where one can observe high gas quantities, shown by the many bubbles in the beaker (Figure 7.2A) and a very sticky material that could not be shaped into a cylinder (Figure 7.2B). Addition of smaller quantities of baker's yeast (1.4 wt % of solids content or lower) resulted in a long delay in yeast activation. These simulants eventually floated in water, but only standing at room temperature for between 3 hours to 2 days.

The optimum quantity of baker's yeast was therefore identified as 3 wt % of solids content, *i.e.* simulant SB80. This amount of baker's yeast produced faeces with roughly the same buoyancy as water, with an average density of 0.99 g/mL and SD of 0.05 (Figure 7.4). Simulants SB65 required a longer period of 4 hours (compared to the 1.5 hours mentioned above) for the yeast to produce sufficient gas to enable floating of the stool. Increasing baker's yeast quantity to 5 wt % of solids content enabled floating of the simulant, while maintaining its physical properties, in a shorter period of 2 hours. The average density of this simulant was found to be 0.96 g/ml with SD of 0.005. Replacing baker's yeast with sodium bicarbonate did not provide satisfying results. For simulant S80 the minimum quantity of bicarbonate required for sufficient gas production to yield floating was 3 wt % of solids content in the recipe. However, the resulting product had an undesirable fluffy, sticky structure, and did not pass the shapable capability test.

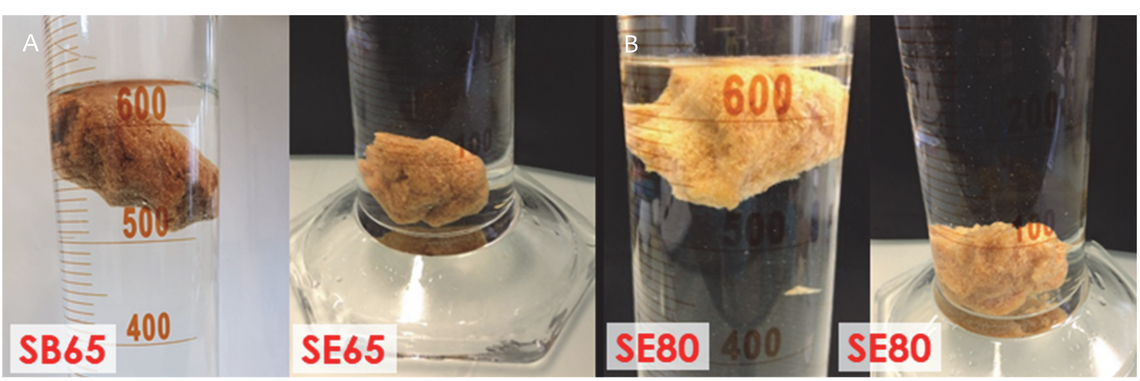

Figure 7.4 Density tests for synthetic faeces (A) S65 and (B) S80.

Table 7.13 Properties of the two simulants identified as most closely representing the range of human faeces.

Simulant		Density (g/mL)	
		Average	SD
Sinking stool (baker's yeast is not added)	SE80	1.07	0.020
	SE65	1.12	0.050
Floating stool (baker's yeast is added)	SB80	0.99	0.050
	SB65	0.96	0.005

As a result of these physical tests, two recipes were identified to most closely represent the range of human faeces, according to Table 7.13.

The addition of baker's yeast resulted in a simulant with a weaker structure, corresponding to the lower viscosity measured. Simulant made with baker's yeast was less robust to handle, and disintegrated more rapidly upon immersion in water than simulant made without baker's yeast. Higher water content also resulted in a simulant with decreased structural strength. Ongoing research conducted by the authors of this paper includes examination of physical disintegration of faeces in turbulent flow conditions. The experiments are being conducted on the reported simulant and verified by real human faeces.

Chemical composition

The modified simulant was analysed for chemical properties of interest to wastewater treatment and compared to properties found in the literature as presented in Table 7.14 (Snell, 1943; Fry, 1973; Meher *et al.,* 1994; Jönsson *et al.,* 2005; Wignarajah *et al.,* 2006; Barman *et al.,* 2009; Colón *et al.,* 2015; Rose *et al.,* 2015). Results are presented only for simulants S80. The synthetic faeces developed in this study provide compatible chemical and physical properties resembling real human faeces. The simulants are appropriate candidates for replacing human faeces in investigations into faeces physical and biochemical disintegration in sewer systems and in onsite sanitation systems.

Table 7.14 Comparison of chemical and physical properties of synthetic faeces SE80 and SB80 with real and simulant faeces from the literature.

Properties	Parameters	This chapter		Literature	
		SE80 (Table 7.10)	SB80 (Table 7.10)	Human faeces	Simulant faeces
Chemical	COD_{total} (gCOD/gTS)	1.117±0.056	1.194±0.162	0.567-1.450[10], 1.24[6]	1.33[9]
	$COD_{soluble}$ (gCOD/gTS)	0.624±0.017	0.551±0.048		
	TN (% of TS)	3.56±0.13	4.05±0.22	5-7[10], 2-3[6,8]	2.75[9]
	pH	5.4	5.2	5.0-8.0[10], 4.6-8.4[9]	5.3[9]
	EC	6.06±0.17	6.40±0.25		5.7[9]
	TS (%)	20.65±0.29	20.79±0.30	14-37[10], 15-35[7]	18.4[9]
	VS (% of TS)	87.61±0.13	87.93±0.07	92[10], 80-92[1,2,3]	88.5[9]
Physical	Viscosity (cP)	6,360	4,640	3,500-5,500[4]	
	Density (g/mL)	1.07±0.02	0.98±0.05		1.06[5]

[1]Snell, 1943; [2]Fry, 1973; [3]Meher *et al.,* 1994; [4]Yeo and Welchel, 1994; [5]Brown *et al.,* 1996; [6]Jönsson *et al.,* 2005; [7]Wignarajah *et al.,* 2006; [8]Barman *et al.,* 2009; [9]Colón *et al.,* 2015; [10]Rose *et al.,* 2015; Note: Average ± standard deviation calculated from three replicates; Note: Results are for synthetic faeces S80.

Recommendation for recipes

Based on detailed chemical and physical characterisation, the two most suitable recipes have been selected for providing chemical and physical properties similar to those of human faeces. Recommended recipes are presented in Table 7.15.

Table 7.15 Recommended recipes for synthetic faeces solids.

Component	Composition of solids content (wt %)	
	Yeast extract	Baker's yeast + yeast extract
Baker's yeast	0.0	3.0
Yeast extract	30.0	27.0
Microcrystalline cellulose	10.0	10.0
Psyllium husk	17.5	17.5
Miso paste	17.5	17.5
Oleic acid	20.0	20.0
NaCl	2.0	2.0
KCl	2.0	2.0
$CaCl_2$	1.0	1.0

A range of water contents can be added to represent the range present in human faeces: from 65 to 80% moisture. Baker's yeast should be added if floating faeces are desired. When lower than 80 wt % water content is required, the portion of baker's yeast can be increased to a maximum of 5 wt % of solids content in order to facilitate quicker gas production.

Figure 7.5 presents the steps for making synthetic faeces as outlined in this case study.

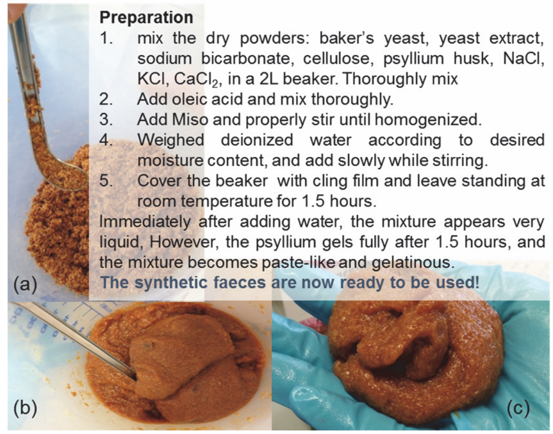

Figure 7.5 Procedure for preparation of synthetic faeces; (a) mixture of synthetic faeces prior to addition of water; (b and c) mixture of prepared synthetic faeces containing ~80% water (b) prepared mixture after standing for 1.5 hours; (c) structured faeces. Tip: Use wet hands, preferable gloves, because the synthetic faeces contain substantial amount of oil.

Recommended storage practices

Baker's yeast produces gas via a biological process which is time and temperature sensitive. It was observed that the mixture should be held at room temperature for at least 1.5 hours but not more than 4 hours in order to produce the required amount of gas for floating synthetic faeces. Results were obtained at room temperature of ~23 °C; higher temperatures will shorten the time interval, and lower temperatures will lengthen it. The synthetic faeces can be refrigerated for a period of not more than 24 hours if they contain baker's yeast or one week if they do not contain baker's yeast. Additionally, both mixtures can be held in the freezer for a longer period of time (not evaluated for more than one month). The frozen synthetic faeces containing baker's yeast should be allowed to reach room temperature, until the point at which the yeast will again become active. Activity can be confirmed by examining the floating of the simulant. Further investigations are needed to verify that chemical and physical properties of the simulant will not change due to freezing as freezing and thawing may change the properties of the recipe material.

Example 7.2 *Development of new simulants by the Pollution Research Group of UKZN, S. Africa*

The Pollution Research Group based at the University of KwaZulu-Natal (UKZN PRG) in Durban, South Africa, has developed, tested and characterised synthetic simulants for fresh faeces and faecal sludge for use in laboratory trials to test treatment methods and processes. In addition to making reproducible substrates for laboratory experimentation, another need for a faecal sludge simulant that arose was health and safety in the handling of faecal matter, for example testing and demonstrating new toilet technologies during the Reinvent the Toilet Fair in India in 2014. Presented in this example are the evolution of the developed synthetic simulants and their comparison to faecal sludge, faeces and other synthetic simulants reported in the literature. The process of simulant development is presented in two stages - the development of a synthetic simulant for the Reinvent the Toilet Fair, and the further development of simulants for laboratory testing.

Development of a synthetic simulant for prototype testing of innovative toilet technologies

The purpose of this study was to develop a uniform simulant that matched as closely as possible with the properties of faecal sludge, to be used for the demonstration of innovative sanitation treatment systems during the Reinvent the Toilet Fair. The properties are presented in Table 7.16, and the appearance of the final simulant is shown in Figure 7.6.

During this study, experiments were carried out with various recipes for faecal simulants found in the literature, mainly from the University of Colorado Boulder, Duke University and Wignarajah *et al.* (2006). All the simulants were tested for the following properties: moisture content; total, fixed, volatile and suspended solids; sludge volume index; chemical oxygen demand; pH; density; thermal conductivity; heat capacity; calorific value; rheology and particle size distribution, and then compared to the same properties for faecal sludge and fresh faeces. The faecal sludge and faeces samples were obtained from onsite sanitation facilities (dry and wet ventilated improved pit latrines, community ablution blocks and urine diversion toilets) in the eThekwini Municipal area around Durban, South Africa (Velkushanova *et al.*, 2019, Zuma *et al*, 2015). Standard operational procedures were followed for all the analysed properties and repeated for all samples in order to ensure compatibility.

Figure 7.6 Faecal sludge simulant developed for prototype technologies at the Reinvent the Toilet Fair in India, 2014 (www.mentalfloss.com/article/56003/recipe-fake-poop).

Thirteen trial recipes, named Simulant Trials (ST) 1 to 13 (Table 7.16) were prepared, and modified in order to match more closely the properties of faecal sludge and faeces. The recipe for each simulant was prepared by adding the ingredients following the sequence presented in Figure 7.7.

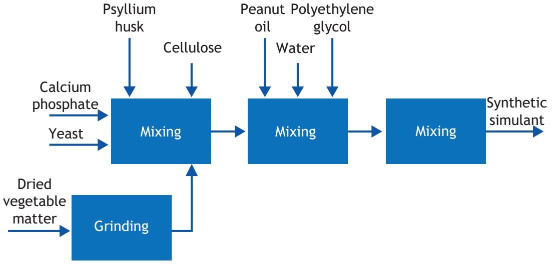

Figure 7.7 Process flow diagram showing the procedure followed in the preparation of synthetic faecal simulants at UKZN PRG.

Table 7.16 A list of ingredients and the respective quantities used in the trials /development of a simulant for the RTT Fair in India (2014).

Component used	Simulant trials												
	ST1	ST2	ST3	ST4	ST5	ST6	ST7	ST8	ST9	ST10	ST11	ST12	ST13
Instant yeast (g)			50			50				18.8	18.8	37.5	37.5
Nutritional yeast (g)	75			75.0			75	75	18.8				
Fresh yeast (g)		30			30								
Baker's yeast (g)													
Cotton balls & paper towels (g)	37.5												
Sawdust (g)								37.5					
Shredded tissue paper (g)		10	75	37.5	10		37.5						
Cotton linters & tissue paper (g)											37.5	6.25	37.5
Sawdust & tissue paper (g)									37.5				
Paper towels (g)						75							
Cotton linters (g)										37.5			
PEG-400 (g)	50		100	50		100	50	50	12.5	14	7	12.5	14
Psyllium husk (g)	12.5	17.5	75	12.5	17.5	75	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Peanut oil (g)	50		25	12.5		25	12.5	25	25	25	25	20	20
Oleic acid/olive oil (g)		20			5								
Miso paste (g)	12.5	17.5	150	12.5	17.5	150	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Calcium phosphate (g)	12.5		25	12.5		25	12.5	12.5	12.5	6.25	6.25	12.5	12.5
NaCl (g)		2			2								
KCl (g)		2			2								
$CaCl_2$ (g)		1			1								
Water (mL)	400	400	400	400	400	400	500	500	450	900	900	400	360

Table 7.17 Comparison of properties of faecal sludge simulants with real faecal sludge and faeces.

Type of onsite sanitation facility	Total solids	Moisture content	Suspended solids	Volatile solids	Ash	Sludge Volume Index	pH	COD	Heat capacity	Thermal conductivity	Calorific value	Density
	%	%	(mg/L)	(g/g)[A]	(g/g)[A]	(mL/mg)		(g/g)[A]	(J/kg.K)	(W/m.K)	(MJ/kg)	(kg/m^3)
Dry VIP	21	79	577	0.58	0.42	0.04	7.60	0.69	2,530	0.54	14.06	1,379
Wet VIP	21	79	402	0.54	0.46	0.06	7.59	0.69	2,422	0.55	13.08	1,447
UDT	40	60	245	0.45	0.27	0.23	7.54	0.49	2,150	0.38	12.93	1,450
CAB	23	77	139	0.49	0.51	0.51	7.44	0.65	3,268	0.60	14.31	1,350
Fresh faeces	24	76		0.87	0.13			0.66			22.64	
ST1	35	65	109	0.96	0.04	0.09	6.37	0.97	2,337	0.45	24.22	1,384
ST2	11	89	121	0.87	0.13	0.82	5.08	0.65	2,878	0.52	24.38	1,272
ST3	42	58	396	0.90	0.10	0.01	4.96	0.83	2,573	0.44	19.37	1,232
ST4	34	66	105	0.91	0.09	0.19	5.54	2.28	2,281	0.42	18.94	1,268
ST5	11	89	88	0.86	0.14	0.91	5.03	0.73	2,920	0.53	17.48	936
ST6	42	58	121	0.86	0.14	0.41	4.10	2.15	3,001	0.38	20.30	1,340
ST7	14	86	78	0.93	0.07		6.37		2,181	0.56		1,756
ST8	29	71	27	0.92	0.08	4.36	5.52	14.51	2,691	0.49	24.14	1,756
ST9	24	76	20	0.89	0.11	2.42	5.64	2.16	3,312	0.50	21.89	1,308
ST10	13	87	144	0.88	0.11	1.73	5.95	2.70	2,868	0.55	21.95	1,068
ST11	15	85	113	0.88	0.12	1.32	5.97	1.80	3,199	0.52	24.18	1,316
ST12	**19**	**81**	**141**	**0.75**	**0.12**	**1.76**	**5.92**	**1.59**	**2,700**	**0.50**	**22.17**	**1,300**
ST13	23	77	177	0.85	0.25	1.52	5.91	1.04	3,040	0.50	22.17	1,156

[A](g/g dry sample)

The comparative results between faecal sludge and faeces, and the simulant faecal sludge are presented in Table 7.17 and Figure 7.8. On the basis of these results, the recommended simulant for the Reinvent the Toilet Fair was ST12 (Table 7.16). It was recommended that the recipe should be prepared by adding the ingredients in the indicated sequence with constant stirring until a smooth and homogeneous texture is achieved.

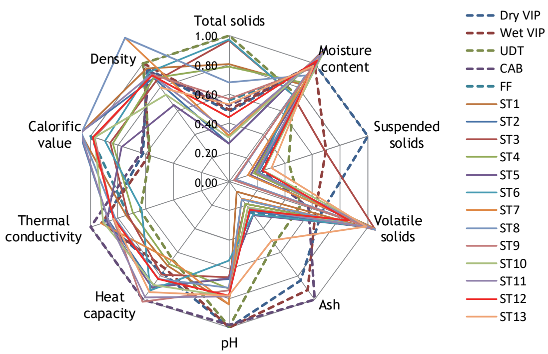

Figure 7.8 Comparison between different properties of faecal sludge with the synthetic simulants to establish which of the developed simulants had the best match with faecal sludge from different onsite sanitation facilities.

Further development and improvement of synthetic simulant for laboratory experiments and testing of pilot technologies

Following the Reinvent the Toilet Fair, the UKZN PRG continued to conduct experiments to improve the simulant ST12. The modifications were based on feedback for improvement by users of the simulant, and also to simplify the preparation process. For the sake of simplicity, in the following text simulant ST12 is hereafter referred to as S1, and the subsequent modified simulant as S2 (Table 7.18). The goal was that S1 would resemble more closely properties of faecal sludge from onsite containments, and S2 would resemble more closely properties of fresh faeces with a smoother consistency. S1 (Figure 7.10) was consecutively modified by the substitution of ingredients and adjustment of ratios of ingredients to create S2. In addition, five other synthetic simulants based on recipes in Wignarajah *et al.* (2006) were produced (Figure 7.9) in order to compare their properties with the developed S2, and to verify the properties of S2. These simulants were selected as they were used as a base for the development of S1. They represented different simulants of fresh faeces, but actual characteristics/properties were not reported in Wignarajah *et al.* (2006). Based on the characterisation carried out by UKZN PRG, the two simulant recipes S6 and S7 (Wignarajah *et al.*, 2006) were selected for comparison with the rest of the simulants in this study as they had the closest match to properties of fresh faeces, and they are presented in this case study.

Table 7.18 A list of recipes used in the formulation of synthetic faecal simulants S1 and S2.

Ingredient represents	Component used (in g)	S1	S2
Micro-organisms	Instant yeast	18.20	18.21
Cellulose	Cellulose (powder)		2.13
	Cotton linters (50%) and shredded paper (50%)	3.10	
Water retention	PEG (polyethene glycol) 400	6.08	6.08
Fibre/carbohydrate	Psyllium husk	6.08	6.09
Fat	Peanut oil	9.70	9.71
Fibre/protein/fats	Miso paste	6.08	6.08
Minerals	Calcium phosphate	6.08	6.08
Vegetable matter	Vegetable matter		1.04
Water	Water	194.03	113.76

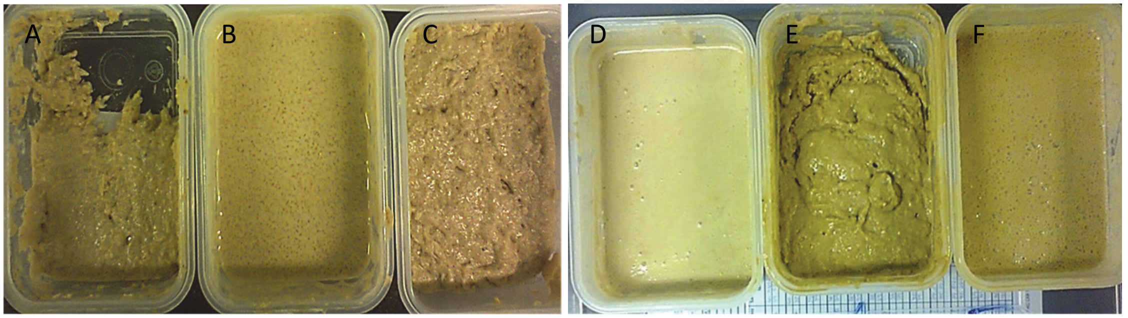

Figure 7.9 Mixed simulants for analysis at the UKZN PRG laboratory: A) PRG (S2), B) NASA2 (S6), C) NASA1, D) NASA3, E) NASA5 and F) NASA4 (S7).

Figure 7.10 Faecal sludge simulant S1.

A description of all the synthetic simulants that were compared with faeces and faecal sludge in this case study are included in Table 7.19.

Table 7.19 A description of the labels of simulants, real fresh faeces and faecal sludge.

Label	Description
S1	Simulant developed by UKZN PRG in 2014 for the RTT Fair in India (2014).
S2	Simulant developed by UKZN PRG in 2015 based on modifying the simulant, S1.
S3	Faecal sludge simulant developed by Deering et al. (2018), based on modifying the simulant, S1.
S4	Fresh faeces simulant #14 (a) developed by Penn *et al.,* 2017.
S5	Fresh faeces simulant developed by Colón *et al*., 2015.
S6	Fresh faeces simulant developed by Wignarajah *et al.,* 2006 (combination 2).
S7	Fresh faeces simulant developed by Wignarajah *et al.,* 2006 (combination 4).
FF1	Fresh faeces properties reported by Nwaneri, 2009.
FF2	Fresh faeces properties reported by Jönsson *et al.,* 2005.
FF3	A set of eight fresh faeces samples (a-h) on rheological properties reported by Woolley *et al*., 2014.
FS1	Faecal sludge properties from dry VIPs reported by UKZN PRG, 2014.
FS2	Faecal sludge properties from CABs reported by UKZN PRG, 2014.

Samples of the selected simulants were analysed to provide a characterisation of the following properties: pH, COD_{total}, density, total solids, moisture content, volatile solids, ash, viscosity, thermal conductivity, heat capacity, calorific value and rheology. These properties were compared against properties of faecal sludge collected from ventilated improved pit (VIPs) latrines in Durban. All the samples were analysed using the standard operational procedures (SOPs) that are presented in this book. The source of fresh faeces (FF) samples used for comparison with simulants is presented in Table 7.19. Table 7.20 summarises some of the data available in the literature on variations of properties. A comparison of the properties of simulants S1 and S2 to other simulants and faeces and faecal sludge is presented in Table 7.21.

Table 7.20 Physical, chemical and thermal properties of fresh human faeces and faecal sludge found in the literature.

Faecal matter type	Parameter / property	
	Fresh faeces	Faecal sludge
Total solids (%)	14-37[1,2,3]	4-91[9,10]
Moisture content (%)	63-86[1,2,3]	9-96[9,10]
Volatile solids (g/g dry sample)	0.80-0.92[1]	0.01-0.84[9,10]
Ash (g/g dry sample)	0.08-0.20[1]	0.16-0.99[9,10]
Density (kg/L)	1.06-1.09[4]	0.54-2.34[2,9,10]
COD (gCOD/gTS)	0.6-1.5[1,2]	0.01-5.01[9,10]
pH	4.6-8.4[2,5]	4.5-9.1[9,10,11]
Heat capacity (J/kg.K)	3,200-4,200[6]	707-4,773[9,10]
Thermal conductivity (W/m.K)	0.35-0.6[7]	0.09-0.79[9,10]
Calorific value (MJ/kg)	20-25[7], 15.1-25.1[8]	2-25[9,10]

[1]Rose *et al*., 2015; [2]Penn *et al*., 2017; [3]Wignarajah *et al*., 2006; [4]Levitt and Duane, 1972; [5]Colón *et al*. 2015; [6]Makununika, 2016; [7]Chikava and Velkushanova, 2014; [8]Wierdsma *et al*. 2014; [9]Zuma *et al*., 2015; [10]Velkushanova, 2014; [11]Afolabi and Sohail, 2017.

Table 7.21 Comparison of properties of faecal matter simulants developed by the UKZN PRG (S1 and S2), simulants presented in the literature and described in Table 7.18, and samples of faecal sludge and faeces described in Table 7.19.

Label	Chemical properties		Physical properties					Thermal properties		
	COD total (gCOD/gTS)	pH	Density (kg/m^3)	Total solids (%)	Moisture content (%)	Volatile solids (%)	Ash	Thermal conductivity (W/m.K)	Heat capacity (J/kg.K)	Calorific value (MJ/kg)
S1	1.59	5.9	1,300	19	81	70	30	0.50	2,700	22
S2	1.19	5.3	1,081	29	71	83	17	0.45	3,476	
S3			1,365	19	81	76	24	0.32	2,609	
S4	1.12	5.4	1,070	21	79	88	12			
S5	1.12	5.2	980	21	79	87	12			
S6	1.33	5.3	1,060	18	82	88	12			
FF1	1.24	5.1		24	76	79	21			23
FF2	1.13	5.3		22	78	84	16			20
FF3	1.45	7.0		14	86	89	11			21
FS1	0.69	7.6	1,379	21	79	58	42	0.54	2,530	14
FS2	0.65	7.4	1,350	23	77	49	51	0.60	3,268	14

Physical properties

Overall, based on a comparison of physical properties, simulant S2 demonstrated the closest match to fresh faeces and therefore can be used as a substitute for fresh faeces in applications targeting these physical properties. Simulant S1 was more suited as a substitute for faecal sludge in applications targeting specifically the total solids, moisture content and density. This is outlined in more detail in the following sections and in Table 7.20.

Chemical properties

A comparison of the chemical properties of faecal simulants (S1 and S2) was carried out relative to fresh faecal samples, faecal sludge (from household VIP latrines and CABs) and other simulants found in literature. The pH of simulant S1 (5.92) was higher than, but comparable to that of S2 (5.29). The pH values of both synthetic simulants were comparable to those of fresh faeces (FF1 and FF2) and other synthetic faecal simulants (S4, S5, S6 and S7), but lower than faecal sludge (FS1 and FS2). Nonetheless, the pH of both simulants (S1 and S2) falls within the range for both fresh faeces and faecal sludge as indicated in the literature (Table 7.20). The COD of simulant S1 was higher compared to faecal sludge (FS1 and FS2) and fresh faeces. In contrast, the COD of simulant S2 was comparable to that of fresh faeces (FF1 and FF2) and synthetic simulants (S4 and S6), but it was also higher compared to faecal sludge (FS1 and FS2). It is however, important to note that the COD of both simulants (S1 and S2) fall within the range of fresh faeces and faecal sludge as indicated in literature (Table 7.20). In overall, simulants S1 and S2 demonstrated properties similar to fresh faeces and faecal sludge for applications targeting chemical properties of faecal matter such as COD and pH.

Thermal properties

The thermal conductivity of simulant S1 (0.5 W/m.K) was similar to simulant S2 (0.45 W/m.K and for both synthetic simulants it was comparable to that of faecal sludge samples from dry VIP toilets (FS1) and other faecal simulants S6 and S7. Both simulants (S1 and S2) indicated thermal conductivity properties that fall within the range for both faecal sludge and fresh faeces (Table 7.21). It was also observed that the thermal conductivity of simulant S3 is considerably lower compared to that of S1 and S2; this was attributed to the use of brewer's yeast instead of instant yeast (Deering *et al.,* 2018) though no further tests or analysis were presented by the authors to validate this argument. The heat capacity of simulant S1 (2,700 J/kg.K) is lower as compared to that of S2 (3,476 J/kg.K). However, it can be observed that the heat capacity of simulant S1 is similar to that of faecal sludge from VIP toilets (FS1) whereas that of S2 compares well with that of faecal sludge from community ablution blocks (FS2) which was more diluted. In general, the heat capacity of simulants S1 and S2 fall within the range indicated for both fresh faeces and faecal sludge (Table 7.21). The calorific value of simulant S1 (22 MJ/kg) was comparable to that of fresh faeces (FF1 and FF2), but was considerably higher relative to that of faecal sludge from household VIP latrines and CABs. The calorific value of simulant S2 was not analysed. Overall, simulants S1 and S2 demonstrated properties similar to fresh faeces and faecal sludge for applications targeting thermal properties of faecal matter, namely thermal conductivity and heat capacity.

Mechanical properties

The set of mechanical properties analysed were rheological properties and particle size distribution. The simulants demonstrated shear thinning (and viscosity reduction) with higher shear rate: behaviour similar to faecal sludge and fresh faeces (Figure 7.11).

A comparison of the viscosity with shear rate of faecal simulants (S1 and S2) relative to fresh faeces samples (FF_3a - FF_3h), faecal sludge from VIP toilets (dFS_3a - dFS_3e) is shown in Figure 7.11. It can be observed that both simulants S1 and S2 demonstrated shear thinning (and viscosity reduction) with higher shear rate: behaviour similar to faecal sludge and fresh faeces, although the results for both S1 and S2 showed behaviour more similar to fresh faeces than faecal sludge. A comparison of the particle size distribution of faecal simulant S1 relative to fresh faeces samples (FF) is shown in Figure 7.12. The size classes for simulant S1 and fresh faeces were similar, but there was a difference in the volume density as indicated by the position of the peaks. More investigations are required to improve on the particle size distribution of simulant S1.

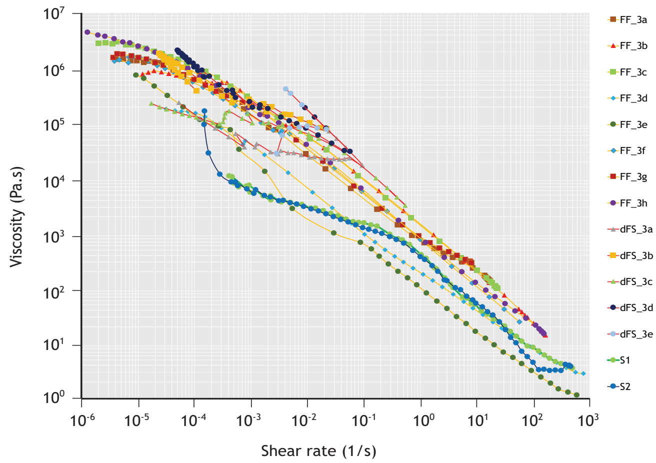

Figure 7.11 A comparison of the relationship between viscosity and shear rate for simulants S1 and S2, fresh faeces (FF) samples and dry faecal sludge (dFS) samples.

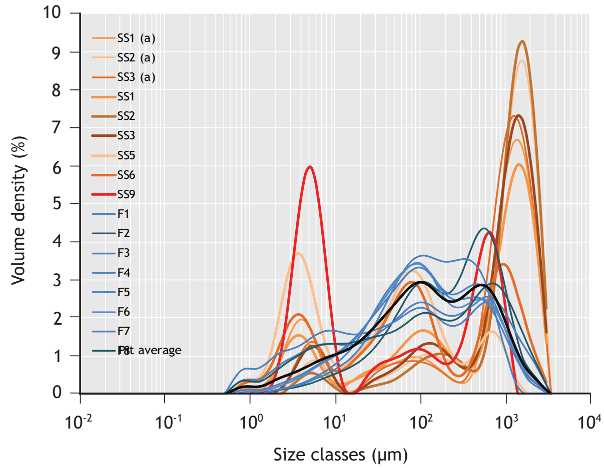

Figure 7.12 A comparison of the particle size distribution of simulant S1 and fresh faeces (FF) samples.

Conclusions and recommendations

Based on the results of the characterisation presented here, it was concluded that simulant S1 most closely mimicked the properties of: (*i*) faecal sludge moisture content, total solids content, density, thermal conductivity and heat capacity; and (*ii*) fresh faeces pH, calorific value, COD_{total} and rheological properties. S2 closely resembled fresh faeces for all the measured properties in this study. In addition, S2 was easier to mix and handle logistically during analysis. There is some degree of overlap with S1 and S2 in their comparison to fresh faeces and faecal sludge in pH, total solids, moisture content and thermal conductivity. Therefore, either S1 or S2 are recommended for usage in applications where the specific parameters are most closely replicated (Table 7.22).

Table 7.22 Simulants S1 and S2's resemblance to fresh faeces and faecal sludge.

Parameter/property	Fresh faeces	Faecal sludge
Total solids	S1, S2	S1
Moisture content	S1, S2	S1
Volatile solids	S2	
Ash	S2	
Density	S2	S1
Calorific value*	S1	
pH	S1, S2	
COD_{total}	S2	
Thermal conductivity	S1, S2	S1, S2
Heat capacity	S2	S1, S2
Viscosity vs shear rate	S1, S2	
Shear stress vs shear rate	S1, S2	

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