

**SEWAGE SLUDGE AND RED GYPSUM
COMPOSITE APPLICABILITY AS
ALTERNATIVE MATERIALS FOR
INTERMEDIATE LANDFILL COVER**

NOR AZALINA BINTI ROSLI

UNIVERSITI SAINS MALAYSIA

2021

**SEWAGE SLUDGE AND RED GYPSUM
COMPOSITE APPLICABILITY AS
ALTERNATIVE MATERIALS FOR
INTERMEDIATE LANDFILL COVER**

by

NOR AZALINA BINTI ROSLI

**Thesis submitted in fulfilment of the requirements
for the degree of
Doctor of Philosophy**

May 2021

ACKNOWLEDGEMENT

In the name of Allah, the Most Beneficent and the Most Merciful. All praises to Allah the Almighty for giving me the strengths, guidance and patience in completing this thesis. First and foremost, I would like to express my deep and sincere gratitude to my research supervisor, Professor Hamidi Abdul Aziz, for allowing me to do research and providing me with his invaluable guidance, insights, advice and encouragement throughout this research. I also would like to thank Professor Razip Selamat and Dr Leonard Lim Lik Pueh for their valuable suggestions, assistance, enthusiasm and for pushing me farther than I thought I could go.

I am extremely grateful to my parents, my husband, my children and my siblings for their endless loves, prayers, sacrifices and understanding throughout the research. Without their supports and motivation, the thesis would not have been possible.

I gratefully thank Mr Nizam, Mr Khairi, and Mr Zaini for their technical guidance and support towards my experimental work in the laboratories at the School of Civil Engineering and School of Materials Engineering. Besides, special acknowledgement goes to research colleague; Mdm Rosmina, Dr Jethro, Mdm Rohaida, Ms Fatimah, Mr Azhar, Dr Anuar and Dr Hafiz for sharing their knowledge, professional advice and guidelines throughout the whole project. Last but not least, I would like to express my deepest gratitude to the Ministry of Higher Education for the scholarship received under SLAB and for the grant awarded under the Fundamental Research Grant Scheme (FRGS) in order to facilitate my research work. Also, to those who have directly and indirectly contributed to the accomplishment of this research, thank you so much.

TABLE OF CONTENTS

ACKNOWLEDGEMENT	1
TABLE OF CONTENTS	2
LIST OF TABLES	7
LIST OF FIGURES	9
LIST OF PLATES	13
LIST OF SYMBOLS	15
LIST OF ABBREVIATIONS	16
LIST OF APPENDICES	18
ABSTRAK	19
ABSTRACT	21
CHAPTER 1 INTRODUCTION	23
1.1 Background of Study.....	23
1.2 Problem statement	24
1.3 Gap of knowledge	26
1.4 Objectives of the study	27
1.5 Scope of work.....	27
1.6 Layout of the thesis	28
CHAPTER 2 LITERATURE REVIEW	30
2.1 Introduction	30
2.2 Landfill cover	30
2.3 Intermediate landfill cover requirement.....	37
2.3.1 Hydraulic conductivity.....	37
2.3.2 Strength	38
2.3.3 Durability	39
2.3.4 Chemical contamination/ Leachability.....	40

2.4	Soil as landfill cover.....	41
2.5	Alternative materials for landfill cover	42
2.6	Sewage sludge	45
2.6.1	Properties of sewage sludge.....	46
2.6.2	Potential application of sewage sludge	49
2.7	Sludge modification	50
2.8	Hydration reaction.....	54
2.9	Red gypsum.....	56
2.9.1	Properties of red gypsum.....	58
2.9.2	Potential application of red gypsum.....	59
2.10	Compaction	62
2.11	Effect of leaching on composite.....	63
2.12	Summary of literature review.....	68
CHAPTER 3 METHODOLOGY.....		70
3.1	Overview	70
3.2	Raw materials and sampling	72
3.2.1	Sewage sludge	72
3.2.2	Red gypsum.....	75
3.2.3	Chemicals and reagents.....	78
3.3	Materials characterization	78
3.3.1	Physical properties	79
3.3.1(a)	Moisture content	79
3.3.1(b)	Particle size distribution	79
3.3.1(c)	Density.....	80
3.3.1(d)	Specific gravity.....	80
3.3.1(e)	Compaction.....	81
3.3.1(f)	Hydraulic conductivity (Falling head method).....	82

3.3.2	Mechanical Properties	83
3.3.3	Geotechnical properties.....	84
3.3.4	Chemical properties and microstructural analysis	86
3.3.4(a)	X-ray fluorescence (XRF)	86
3.3.4(b)	X-ray diffraction (XRD).....	86
3.3.4(c)	Scanning electron microscopy (SEM).....	87
3.4	Composite preparation and characterization	88
3.5	Column test	90
3.5.1	Specimens preparation	90
3.5.2	Specimens filling in column.....	91
3.5.3	Synthetic leachate feed solution.....	93
3.5.4	Column leaching	95
3.6	Leachate Sample Analysis	97
3.6.1	pH.....	97
3.6.2	Biochemical oxygen demand (BOD).....	97
3.6.3	Chemical oxygen demand (COD).....	97
3.6.4	Heavy metals	98
3.7	Statistical Analysis	98
CHAPTER 4 RESULTS AND DISCUSSION.....		99
4.1	Overview	99
4.2	Characterization of SS and RG	99
4.2.1	Physical and geotechnical properties of SS and RG	100
4.2.1(a)	Particle size distribution	100
4.2.1(b)	Specific gravity.....	101
4.2.1(c)	Plasticity	103
4.2.1(d)	Optimum moisture content	104
4.2.1(e)	Comparison with soil.....	108

4.2.2	Chemical properties.....	108
	4.2.2(a) Chemical composition	108
	4.2.2(b) Mineral phase.....	110
	4.2.2(c) Surface morphology.....	111
4.2.3	Stress-strain relationship	114
4.3	Optimization of design mix.....	117
4.3.1	Physical and geotechnical performance	118
	4.3.1(a) Particle size distribution	118
	4.3.1(b) Hydraulic conductivity	120
	4.3.1(c) Plasticity	125
	4.3.1(d) Optimum moisture content	125
4.3.2	Compressive strength analysis	127
	4.3.2(a) Effect of moisture content	127
	4.3.2(b) Stress-strain curve and curing age relationship	132
	4.3.2(c) Strength Formation of the Composites.....	134
	4.3.2(d) Role of Ca:Si composition on the strength	136
4.3.3	Optimum design mix.....	142
4.4	Significance of compaction.....	143
4.4.1	Relationship between degree of compaction and porosity.....	144
4.4.2	Consolidation of composites	145
4.4.3	Compressive strength response	147
4.4.4	Hydraulic conductivity behaviour (Distilled water).....	149
	4.4.4(a) First phase.....	150
	4.4.4(b) Second phase	153
	4.4.4(c) Third phase	154
4.4.5	Leaching from Composite.....	155
	4.4.5(a) Leachate Yield.....	155

4.4.5(b)	Leachate quality.....	159
4.5	Response of composite against synthetic leachate.....	163
4.5.1	Hydraulic conductivity.....	163
4.5.2	Leachate yield	166
4.5.3	Leachate quality	167
4.5.3(a)	pH and Heavy metals.....	169
4.5.3(b)	BOD and COD.....	171
4.5.4	Effect of feed solution on the leaching behaviour.....	173
4.5.5	Recommended degree of compaction	176
4.6	Summary of Findings	176
CHAPTER 5 CONCLUSION AND FUTURE RECOMMENDATIONS....		179
5.1	Conclusion.....	179
5.2	Recommendations for Future Research	181
5.2.1	Pre-treatment of raw materials (SS).....	181
5.2.2	Study on the thickness of the composite	181
5.2.3	Application of numerical simulation.....	182
REFERENCES.....		183
APPENDICES		
LIST OF PUBLICATIONS		

LIST OF TABLES

		Page
Table 2.1	Different level of sanitary landfill based on the equipped facilities (MHLG, 2004)	32
Table 2.2	Current status of MSW disposal sites in Malaysia (JPSPN, 2019)....	33
Table 2.3	Comparison of types of cover systems according to its application and functionality (EPA, 2009; NSWEP, 2015).....	36
Table 2.4	Soil expansion prediction by plasticity index	40
Table 2.5	Basic properties of natural soil.....	42
Table 2.6	Waste materials as alternative landfill cover material	44
Table 2.7	Variation of the chemical composition of sewage sludge from various countries	46
Table 2.8	Basic properties of sewage sludge	48
Table 2.9	Heavy metals concentration in sewage sludge.....	49
Table 2.10	Previous literature on sewage sludge modifications	52
Table 2.11	Chemical composition of red gypsum.....	57
Table 2.12	Basic properties of red gypsum.....	58
Table 2.13	Potential application of RG when mixing with other materials.....	61
Table 2.14	Typical characteristics of MSW landfill leachate in Malaysia	66
Table 3.1	List of chemical and reagents.....	78
Table 3.2	Degree of compaction and dry density.....	91
Table 3.3	Designed and measured solution of synthetic leachate.....	94
Table 4.1	Comparison of physical and geotechnical properties of SS and RG between this study and selected literature.....	102
Table 4.2	Comparison of the chemical composition of SS and RG by mass (%) between this study and selected literature.....	110

Table 4.3	Geotechnical properties of composite improved as the amount of sewage sludge reduced.....	123
Table 4.4	Comparison of composites strength gain (%) between this study and selected literature.....	136
Table 4.5	Design mix composition and the Ca, Si and Fe composition	137
Table 4.6	Composite performance in comparison with SS modified with other modifier agent	143
Table 4.7	Comparison of leachate quality from the various compacted sample after 180 days with feed solution and typical raw leachate .	168
Table 4.8	Equivalent rainfall of 75 % compaction feed with distilled water and synthetic leachate from leachate yield.....	176

LIST OF FIGURES

	Page
Figure 2.1	Diagram of an open dumpsite (WHO, 2006 in Jegede et al., 2010) ..31
Figure 2.2	Cross-section of an engineered landfill, which is designed with a level 4 sanitary system (Artiola, 2019)34
Figure 2.3	Three types of landfill cover and their properties.....35
Figure 2.4	Scanning electron microscopy images of sewage sludge (a) Ahsaine et al. (2017) (b) Boutchich et al. (2015).....47
Figure 2.2	Needle-like crystal and honeycomb structure of CSH and platelet CH (Na, 2015).....55
Figure 2.6	Occurrence type of Fe in soil microstructure (a) bridge form (b) cladding form (c) individual crystalline particle (Zhang et al., 2016)56
Figure 2.7	SEM of red gypsum (a) Azdarpour et al. (2018) (b) Gazquez et al. (2009)59
Figure 2.8	Phase of waste decomposition in landfill (Abdallah, 2011)64
Figure 3.1	Flowchart of the experimental activities71
Figure 3.2	(a) Sewage treatment process flow (b) Layout of Kuching centralized wastewater treatment plant73
Figure 3.3	Flow diagram of the sludge treatment facility in the sludge handling building74
Figure 3.4	Fresh dewatered SS consist of moist and loose agglomeration of fine granules75
Figure 3.5	Process Flow of the Production of TiO ₂ (vertical process flow) and treatment of waste acid prior to discharge which produces red gypsum as a by-product (horizontal process flow)76
Figure 3.6	RG consist of dry lump and fine particles.....77

Figure 3.7	Schematic diagram of a falling head hydraulic conductivity.....	83
Figure 3.8	Series of column preparation and the inset shows the closed-up view of packing of the sample's detail in column.....	92
Figure 4.1	Particle size distribution for red gypsum (dry sieve) and dewatered sewage sludge (wet sieve).....	101
Figure 4.2	The compaction curve of SS and RG.....	105
Figure 4.3	XRD for identification of mineral in (a) SS (b) RG in accordance with the American Mineralogist Crystal Structure	111
Figure 4.4	SEM images of SS at 3000x magnification	112
Figure 4.5	SEM images of RG at 3000x magnification	113
Figure 4.6	EDX spectra for the detection of major elements in (a) SS (b) RG.	114
Figure 4.7	Stress-strain curved of SS and RG samples at day 0 in optimum moisture condition.....	116
Figure 4.8	Particle size distribution curve of the various composites (dry sieve)	119
Figure 4.9	The hydraulic conductivity for all mix is consistent in the order of 10^{-5} cm/s.....	121
Figure 4.10	Optimum moisture content shifted to the right, and the maximum dry density decreased as the ratio of SS increased.....	127
Figure 4.11	Effect of moisture content (MC) on stress-strain curve for composite (a) 4SS:0RG (b) 3SS:1RG (c) 1SS:1RG (d) 1SS:3RG (e) 0SS:4RG	130
Figure 4.12	Stress-strain curve of the composites (a) 4SS:0RG (b) 3SS:1RG (c) 1SS:1RG (d) 1SS:3RG (e) 0SS:4RG	133
Figure 4.13	Strength development of different design mixes over curing days..	135
Figure 4.14	Variation of unconfined compressive strength on day 28 at different design mix	137
Figure 4.15	X-ray Diffraction (XRD) for identification of hydrated and unhydrated products in various design mixes in accordance to the	

	American Mineralogist Crystal Structure Database (Schmidt et al., 2011; Hawthorne and Ferguson, 1975; Schofield et al., 1996).....	139
Figure 4.16	EDX spectra for the detection of the major element in various composites.....	140
Figure 4.17	Inverse linear correlation between the degree of compaction and initial porosity	145
Figure 4.18	Variation of thickness level of compacted composites after continuous percolation with distilled water for six months	146
Figure 4.19	Inverse linear correlation between the consolidation ratio (after 180 days submergence with distilled water) and degree of compaction	147
Figure 4.20	Stress-strain curve of the samples under a various degree of compaction	148
Figure 4.21	Correlation between compaction degree and compressive strength where at least 80 % compaction is required to achieve minimum strength of 345 kPa	149
Figure 4.22	The hydraulic conductivity for samples at various degree of compaction decreased with the continuous flow but stabilized after 75 days, except for sample compacted at 80 %	150
Figure 4.23	Linear correlation between initial hydraulic conductivity (day 1) and initial porosity (with the corresponding degree of compaction)	151
Figure 4.24	Formation of CSH was observed in the sample extracted from the column under SEM images (3000x magnification)	152
Figure 4.25	Detection of Ca and Si as the major element in the hydrated product via EDX spectra	153
Figure 4.26	Leaching of fine particles was observed in the discharging tube.....	154
Figure 4.27	Effect of degree of compaction on the cumulative leachate yield ...	155
Figure 4.28	Cumulative leachate yield for day 1 dan 3 is decreasing with increasing degree of compaction.....	158

Figure 4.29	Linear correlation between initial leachate yield (day 1) of various degree of compaction and initial porosity.....	158
Figure 4.30	No correlation between final leachate yield and degree of compaction after day 3	159
Figure 4.31	pH concentrations in the leachate at various degree of compaction	160
Figure 4.32	Decreased of (a) Ca (b) Cu (c) Fe (d) Zn and (e) COD concentrations in leachate from samples at various degree of compaction	161
Figure 4.33	Hydraulic conductivity of samples at various degree of compaction decreased with the continuous flow of synthetic leachate	164
Figure 4.34	Sample extracted from (a) 75 % compaction consist of dry lump, which size ranging between 25 to 30 mm (b) 70 % compaction is moist and in an agglomeration of granule form, size ranging between 5.0 to 10 mm	166
Figure 4.35	Effect of degree of compaction on leachate yield, where leachate yield reduced by 95 % at 75 % compaction.....	167
Figure 4.36	Variation of (a) pH (b) Cu (c) Fe and (d) Zn concentration in leachate.....	170
Figure 4.37	Reduction of (a) BOD and (b) COD concentrations from samples at various degree of compaction	172
Figure 4.38	Reduction of hydraulic conductivity is faster when synthetic leachate is flowing through the composite.....	174
Figure 4.39	Formation of lump (a) sample feed with synthetic leachate, size of lump ranged between 25 to 30 mm (b) sample feed with distilled water, size of lump ranged between 5 to 15 mm	174
Figure 4.40	Cumulative leachate yield reduced by 50% when synthetic leachate is flowing through the composite.....	175

LIST OF PLATES

		Page
Plate 3.1	Pycnometer method for specific gravity test (a) red gypsum using distilled water (b) sewage sludge using kerosene	81
Plate 3.2	(a) Cylindrical mould and hammer used to prepare specimens for UCS test (b) The ELE Digital Tritest 50 UCS machine for UCS test	84
Plate 3.3	(a) ELE 24-0540 cone penetrometer used in LL test (b) RG sample thread crumble at a diameter of 3.2 mm for PL test (c) The displacement and cracking in SL test.....	85
Plate 3.4	(a) RG specimens extruded from the UCS cylindrical mould (b) Failure form of the cured sample tested under UCS machine	89
Plate 3.5	Synthetic leachate (a) before filter, brownish colour (b) after the filter, greenish colour	94
Plate 3.6	Experimental set-up of column test (a) schematic diagram (b) real model in the laboratory	96
Plate 4.1	(a) Brittle failure of SS in the plastic limit test, where the thread crumble before 3.2 mm (b) SS form a thread of 6 mm with further addition of water and (c) 3.2 mm thread formation of red gypsum. .	104
Plate 4.2	SS condition after (a) 20 % (b) 40 % (c) 60 % (d) 80 % (e) 100 % addition of water	106
Plate 4.3	RG condition after (a) 20 % (b) 40 % (c) 60 % addition of water... .	107
Plate 4.4	Failure form of (a) SS and (b) RG under UCS test.....	116
Plate 4.5	Composite (a) 4RG:0SS (b) 3RG:1SS (c) 1RG:1SS (d) 1RG:3SS (e) 0RG:4SS	119
Plate 4.6	Formation of crystal and surface morphology at 3000x magnification: (a) 0SS:4RG, \bar{x} : 3.3 μm , n: 18, s: 0.7 , (b) 1SS:3RG, \bar{x} : 4.3 μm and 9.4 μm , n: 7 each, s: 0.89 and 1.42, respectively; (c)	

	1SS:1RG, \bar{x} : 4.3 μm , n: 15, s: 1.17 (d) 3SS:1RG, \bar{x} : 8.8 μm n: 6, s: 0.46 and (e) 4SS:0RG, \bar{x} : 17 μm , n: 7, s: 0.61	122
Plate 4.7	Composite of (a) 0SS:4RG at 30 % moisture content (b) 1SS:1RG at 35% moisture content (c) 3SS:1RG at 55 % moisture content (d) 4SS:0RG at 55 % moisture content.....	128
Plate 4.8	(a) Size distribution of the composite is less than 2 mm (b) Small lump, 5 to 15 mm in size is observed in the sample extracted from the column.....	152
Plate 4.9	(a) Some of the samples were pressed against the wall using a glass rod to minimize the air bubble (b) the samples were pressed/compacted using a caulk gun (c) picture of a real caulk gun	156
Plate 4.10	(a) Air bubbles were detected between the samples and the wall (b) the fluid movement in both lateral and horizontal direction	157

LIST OF SYMBOLS

		Unit
a	Cross-sectional area of standpipe	cm ²
A	Cross-sectional area o sample	cm ²
C _u	Uniformity coefficient	-
C _c	Curvature coefficient	-
d	Spacing between the planes for XRD	-
D _c	Degree of compaction	-
DO _{Bf}	Final Dissolved oxygen of blank	mg/L
DO _{Bi}	Initial Dissolved oxygen of blank	mg/L
DO _{Sf}	Final Dissolved oxygen of sample	mg/L
DO _{Si}	Initial Dissolved oxygen of sample	mg/L
h	Head difference	mL
h ₀	The water level at t is zero	mL
h _t	The water level at the time, t	mL
λ	Wavelength of Xray	-
k	Coefficient of hydraulic conductivity	cm/s
L	Length of sample	cm
L ₀	Length of the sample before drying	cm
L _D	Length of the sample after drying	cm
m	Mass	g
n	Order of diffraction	-
n	Number of pores	-
η	Porosity	%
P	Dilution factor	-
ρ	Density	g/cm ³
ρ _d	Dry density	g/cm ³
ρ _{dmax}	Maximum dry density	g/cm ³
ρ _{ds}	Density of particles	g/cm ³
S	Standard deviation	-
S _w	Weight of sample before drying	g
S _D	Weight of sample after drying	g
t	Time interval	s
V	Volume	m ³
x	Pore size	mm
\bar{x}	Average pore size	mm
γ _{dmax}	Maximum dry weight	g/cm ³

LIST OF ABBREVIATIONS

ASR	Activated Sludge Reactor
Al	Aluminium
B	Bentonite
BOD	Biochemical Oxygen Demand
C	Cement
CH	Portlandite
CH ₄	Methane
C ₂ S	Belite
C ₃ S	Alite
CSH	Calcium Silicate Hydrate
COD	Chemical Oxygen Demand
CO ₂	Carbon Dioxide
CP	Coir Pith
CS	Construction Sludge
Ca	Calcium
Cu	Copper
DW	Distilled Water
FA	Fly Ash
FAS	Ferrous Ammonium Sulphate
Fe	Iron
HC	Hydraulic Conductivity
HL	Hydrated Lime
IO	Inorganic
ICP	Inductively Couple Plasma
L	Lime
LL	Liquid Limit
LOI	Loss on Ignition
MDD	Maximum Dry Density
N	Nitrogen
NH ₃ -N	Ammoniacal Nitrogen
NSWD	Natural Solid Waste Department
OMC	Optimum Moisture Content

P	Phosphorus
PI	Plasticity Index
PL	Plastic Limit
PMS	Paper Mill Sludge
Pb	Lead
QL	Quicklime
RG	Red Gypsum
RAS	Return Activated Sludge
S	Sulphur
SAC	Sulphoaluminate Cement
SEM	Scanning Electron Microscopy
Si	Silica
SL	Synthetic Leachate
SMW	Stone Material Waste
SS	Sewage Sludge
SSA	Sewage Sludge Ash
TC	Tire Chips
TDA	Tire Derived Aggregate
UCS	Unconfined Compressive Strength
VOA	Volatile Organic Acid
WAS	Waste Activated Sludge
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence
Zn	Zinc

LIST OF APPENDICES

Appendix A	SEM Images for Silt And Clay
Appendix B	Regression analysis: compressive strength versus degree of compaction
Appendix C	Table of hydraulic conductivity using distilled water
Appendix D	Effect of Compaction on Hydraulic Conductivity (Distilled Water) Using Tukey Method (Grouping Information)
Appendix E	Table of leachate yield using distilled water
Appendix F	Regression Analysis: Degree of Compaction Versus Leachate Yield For Day 1, 3, 7, 28 And 180 Days
Appendix G	Table of Leachate Concentration (Percolate Using Distilled Water)
Appendix H	Effect Of Compaction On Hydraulic Conductivity (Synthetic Leachate) Using Tukey Method (Grouping Information)
Appendix I	Table of hydraulic conductivity using synthetic leachate
Appendix J	Table of leachate yield using synthetic leachate
Appendix K	Table of leachate concentration (percolate using synthetic leachate)

**KEBOLEHLAKSANAAN KOMPOSIT SISA KUMBAHAN DAN
GIPSUM MERAH SEBAGAI BAHAN ALTERNATIF UNTUK PENUTUP
PERANTARA TAPAK KAMBUS TANAH**

ABSTRAK

Penggunaan tanah sebagai penutup kambus tanah adalah tidak mampan dari segi ekonomi dan tidak lestari kepada persekitaran. Tambahan, tanah tersebut boleh digunapakai untuk tujuan lain seperti pertanian dan pembinaan. Kajian terdahulu telah menggunakan sisa kumbahan dan abu terbang untuk menggantikan tanah sebagai penutup kambus tanah, tetapi kebanyakannya adalah untuk kawasan yang menerima hujan sederhana. Kajian ini cuba untuk menggunakan sisa kumbahan (SS) dan gipsum merah (RG) sebagai bahan komposit penutup kambus tanah, berbanding pelupusan di tapak kambus tanah terkawal sebagai amalan semasa di Malaysia ketika ini. Kajian ini melibatkan penyiasatan rekabentuk campuran yang optimum berdasarkan kekonduksian hidraulik (k), kekuatan mampatan tidak terkurung (UCS) dan indeks keplastikan (PI), termasuk juga meneliti peranan SS dan RG dalam komposit. Kajian ini juga menyiasat kesan pepadatan ke atas komposit dari segi k, UCS dan tingkah laku lesapan. Sisihan piawai dan bar ralat dibuat pada setiap bacaan serta analisis regresi dilakukan untuk mengkaji perkaitan antara parameter menggunakan perisian Minitab 17. Ujian turus menggunakan kaedah turus tetap telah dilakukan dengan mengalirkan air suling (DW) atau cecair sintetik larut lesap (SL) melalui komposit yang telah dipadatkan kepada 60, 70, 75, 80 dan 85 % secara berat. Kualiti cecair larut lesap dari segi pH, BOD, COD, Cu, Fe dan Zn telah dipantau pada hari yang telah ditentukan terlebih dahulu. Komposit SS:RG bernisbah 1:1, yang juga merujuk kepada Ca:Si bernisbah 2.5:1, adalah nisbah yang paling ideal untuk pembentukan kalsium

silika terhidrat (CSH), dengan merekodkan UCS sebanyak 520 kPa, k pada 10^{-5} cm/s dan PI pada 28.5 %, dan sesuai untuk digunakan sebagai penutup kambus tanah. Ciri-ciri keplastikan adalah disebabkan pengaruh penggumpalan oleh ferum (Fe) dalam RG yang membolehkan pembentukan agregat mikro. Tahap pemadatan adalah berkadaran terus dengan keliangan awal, tetapi, tidak mempengaruhi k bagi DW. Walau bagaimanapun, k menunjukkan perbezaan pada 75 % pemadatan apabila SL melalui komposit. k menunjukkan penurunan dalam tiga peringkat; dua peringkat pertama adalah didominasi oleh penyusunan semula partikel dan penghidratan oleh CSH, diikuti oleh pengstabilan k di peringkat ketiga. Penurunan k adalah satu magnitud lebih pantas apabila dilalukan dengan SL, disebabkan oleh pemerangkapan mendakan logam berat di antara matrik CSH. Komposit tidak menunjukkan sebarang potensi untuk mencemarkan alam sekitar dan pemadatan pada tahap 75 % dapat mengurangkan kepekatan larut lesap sebelum memasuki sistem rawatan larut lesap. Pemadatan minimum 80 % adalah disyorkan untuk operasi di tapak kambus tanah. Hasil penemuan dari kajian ini sangat berguna sebagai rujukan untuk penghasilan komposit alternatif untuk penutup tapak kambus tanah di kawasan tropikal seperti Malaysia.

**SEWAGE SLUDGE AND RED GYPSUM COMPOSITE
APPLICABILITY AS AN ALTERNATIVE MATERIALS FOR
INTERMEDIATE LANDFILL COVER**

ABSTRACT

Application of soil as landfill cover is not economical nor environmentally sustainable; instead, soil can be more beneficial in agricultural and construction sectors. Past studies replaced soil as landfill cover with waste such as sewage sludge and fly ash, primarily for application in a temperate climate. This study attempts to apply sewage sludge (SS) and red gypsum (RG) as a composite for landfill cover, which is currently disposed of as scheduled waste in secured landfills in Malaysia. The study investigated the optimum design mix based on the characterization of hydraulic conductivity (k), unconfined compressive strength (UCS) and plasticity index (PI), as well as scrutinizing the role of SS and RG in the composite. The study also examined the effect of compaction on the characteristics of composite in terms of k , UCS and leaching behaviour. The standard deviation and error bar was reported for the measurement, and regression analysis was conducted to study the correlation between parameters using Minitab 17 software. A series of column test using the constant head method was carried out by percolating distilled water (DW) or synthetic leachate (SL) through composites compacted to 60, 70, 75, 80 and 85 % by weight. The leachate quality was monitored at pre-determined days for pH, BOD, COD, Cu, Fe and Zn. The SS:RG composite of 1:1 corresponds to Ca:Si ratio of 2.5:1 was found ideal for calcium silicate hydrate (CSH) formation, recorded a UCS of 520 kPa, k of 10^{-5} cm/s, and PI of 28.5 %, favourable for application as landfill cover. The plastic behaviour was attributed to the coagulating performance of iron (Fe) in RG, contributing to the

micro-aggregation in the composite. The degree of compaction was linearly correlated with initial porosity but did not affect k in the case of DW. However, k changed at 75 % when SL percolated through the composite. The k decreased in three stages; the first two stages were predominated by the rearrangement of particles and hydration of CSH, followed by stabilization of k in the third stage. The faster reduction of k by about one magnitude order in the case of SL was attributed to the entrapment of heavy metal precipitated within the matrices of CSH gel. The composite did not exhibit potential environmental pollution, and compaction at 75 % reduced the strength of leachate for the receiving leachate treatment system. This study recommended a minimum of 80 % compaction for a landfill operation. These findings will be a useful reference for developing alternative composite for landfill cover in tropical climates, such as Malaysia.

CHAPTER 1 INTRODUCTION

1.1 Background of Study

Landfilling remains the main method of waste disposal to date in Malaysia. Based on National Solid Waste Department (NSWD), there are 146 of 296 landfills in Malaysia active as of 2019. A significant amount of earthen materials is being used as landfill covers to control odours, vectors, fires, litter and scavenging and to minimize the emissions of landfill gas into the atmosphere and vertical infiltration of water into waste, which subsequently control the leachate yield (Vinitha et al., 2019; Aziz et al., 2016; Travar et al., 2015). Generally, there are three types of landfill cover, namely daily cover, intermediate cover and final cover. Each type of cover have different function and required different thickness of soil.

Malaysia is generating about 10 million tonnes of sewage sludge per year (Zakaria et al., 2015) from the existing 3 million wastewater treatment facilities that are in operation (SPAN, 2019). Besides that, the sludge is also generated from the existing communal septic tank, which requires desludging every 2 to 5 years. The facilities to treat and dispose of this sludge are limited, and currently, sewage treatment plants with excess capacity are being used to treat septic tank sludge as temporary means. Most of the sludges are dumped at secured landfills because it is still considered the cheapest option being practised by most of the existing wastewater treatment plant operators (Roslan et al., 2013). Modern sludge treatment facilities are only available at the recent plant; nevertheless, the dried sludge is still sent to landfills as a final disposal route.

1.2 Problem statement

Every landfill cover layer typically consists 6 to 12 inches of earthen materials (Vallero and Blight, 2019; NSW EPA, 2015), which makes up about 25 % of total landfill volume (Ng and Lo, 2007). The majority of landfill sites in Malaysia have inadequate soil cover, which makes the sanitary condition of the landfill inferior (MHLG, 2004). For landfills where suitable soil is insufficient, there is a need to transport suitable soil from an off-site source which increases the price of the soil and the risk of erosion at the off-site source. This practice is not economically and environmentally sustainable, and therefore motivated the study for alternative landfill cover materials to conserve the natural resources.

There have been many studies conducted to find alternative materials for landfill cover, in which sewage sludge is one of the common waste materials used (Fan et al., 2019a; Balkaya, 2019; Fan et al., 2019b; Vinitha et al., 2019; He et al., 2015a; Na, 2015; Li et al., 2014). Sewage sludge is classified as scheduled waste, SW204 under Schedule 1, in the EQA 1974 (ILBS, 2019) because it contains one or several metals, including copper, zinc, chromium, nickel, lead, cadmium, aluminium and tin. Therefore, it is required to be incinerated and disposed to secured landfills (Roslan et al., 2013; Bradley and Dhanagunan, 2004). This method is not economically and environmentally sustainable, considering Malaysia is producing an estimated 10 million tonnes of sewage sludge in 2020 (Zakaria et al., 2015). Therefore, it is worth considering sewage sludge as an alternative material for landfill cover as it will address issues of soil scarcity and optimize the filling of the landfill, as well as a potential financial offset for premises to the sewage sludge disposal. The government is now aiming to reclassify sludge as non-scheduled waste. It is anticipated that Malaysia