DEVELOPMENT OF WALL PUTTY FOR TROPICS USING DRINKING WATER TREATMENT PLANT WASTE ALUM SLUDGE

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Degree of Doctor of Philosophy in Civil Engineering

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DECLARATION OF CANDIDATE AND SUPERVISOR

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ABSTRACT

Water is the main source of life; therefore, a sufficient amount of safe water consumption is essential for public health. It is one of the responsibilities of a country, to ensure the access of its citizens to consume sufficient safe water. In Sri Lanka, the national water supply and drainage board (NWSDB) is the responsible authority for drinking water purification and distribution. NWSDB owned 323 water supply schemes. In drinking water treatment plants, surface water is collected and treated to drinking quality removing impurities dissolved in surface water. In the purification process aluminium sulphate ($Al_2(SO_4)_3$) (Alum) is used as the coagulant and generated alum sludge at the end. The sludge disposal to surface water bodies creates the undesirable formation of mud deposits according to the activation of alum. Direct discharge of sludge into water bodies creates damage to its' creatures and ecosystems. Therefore, direct disposal of alum sludge in open lands and water bodies is prohibited by legislation. Dewatered alum sludge is disposed at landfills and rock blasting wells. However, the increasing daily generation of sludge is creating an urgent necessity for a sustainable solution. The increasing amount of daily alum sludge production has considerable environmental and economic concerns in most countries. Therefore, the world's attention turned to finding a sustainable way to reuse or recycle DWTP alum sludge. This research aimed to address the issues mentioned, by developing a wall putty using waste alum sludge generated in drinking water treatment plants (DWTP) in Sri Lanka. Properties of the DWTP waste sludge differ according to the climatic conditions, geographical conditions, water treatment process and raw water quality. The research was conducted after the identification of the properties of DWTP waste alum sludge of different plants. Laboratory experiments were conducted to study the properties of sludge samples collected from DWTPs in Ambathale, Biyagama and Kandana. Biyagama DWTP was selected to collect sludge for the study due to the low moisture content and high solid content compared to other samples. Waste sludge is discharged at the end of the water treatment process, in semisolid form with high moisture content and it is dewatered through a sludge treatment process in Biyagama DWTP. Dewatered sludge generation of the plant is estimated at $10m^3$ per day. Properties of DWTP waste alum sludge were studied. According to the results, moisture content variation, volumetric shrinkage variation, chemical composition and heavy metal analysis of the sludge was analyzed. In the first phase of the study, experiments were conducted to develop a wall putty mix using wet alum sludge. Test results reveal that volumetric shrinkage can be reduced with physical additives and adhesiveness can be improved with binders, but a wall putty mix cannot be developed with wet sludge by mixing additives and a binder, due to the high moisture content, high shrinkage and alum activation. In the second phase of the study, experiments were conducted to develop a dry powder from wet sludge overcoming the alum activation. To that thermal alterations of DWTP waste alum sludge were studied. Colour and density variations of the burned sludge at different temperatures were studied. Sludge becomes harder when burned, due to the alum activation and none of the processes that exist in the world, to produce dry powder from DWTP alum sludge. Alum activation of the sludge can be overcome by burning sludge with a lubricant. According to the experiments, coconut oil is identified as an effective lubricant. The density of burned sludge with oil is lower than that of burned sludge without oil at each temperature. Finally, a process was developed to produce dry powder from DWTP alum sludge. In the final phase of the study putty properties of the developed dry powder were analyzed and optimized and the performances of the developed wall putty mix were analyzed compared to existing wall finishes. And the real scale performances of the putty were tested. Finally, it was concluded that the developed dry powder is applicable as a wall finisher successfully on both interior and exterior walls. And also new research areas were identified for further studies from this research.

Keywords*: Alum sludge, Drinking water treatment plant, Sludge putty, Tropical climate*

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LIST OF ABBREVIATIONS

Abbreviation	Description
DWTP	Drinking Water Treatment Plant
NWSDB	National Water Supply and Drainage Board
SOF	Scaled Off Factor
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

CHAPTER 01: INTRODUCTION

1.1. General

Water is one of the main requirements of humans and other living creatures. Life cannot be sustained without water, Therefore, ensuring the access of citizens to consume sufficient safe water is one of the responsibilities of a country. A sufficient amount of safe water consumption is essential for public health. A higher portion of the total population of most of the countries in the world has no access to a sufficient amount of safe drinking water; due to the lack of safe natural water resources. Therefore, they provide safe water to the residents after purifying surface water through DWTPs. Most of the residents in Sri Lanka have access to natural water resources; compared to the other countries in the region [1]. The National Water Supply and Drainage Board (NWSDB) is the responsible authority for drinking water purification and distribution. NWSDB has consisted of DWTPs located all over the country and the total drinking water production is estimated at 30 million m^3 per month [1].

DWTP process consists of the steps of coagulation, flocculation, sedimentation, filtration and disinfection [2]. Chemical coagulants are added in the coagulation process to remove suspended soil particles; such as sand, silt, clay and humus, and other contaminants. Alum (Al_2SO_4) is the coagulant used in DWTPs in Sri Lanka. Lime ($Ca(OH)_2$) and chemical polymers are added to the treatment process. Alum sludge is settled in the flocculation and sedimentation processes; it is removed by filtration. Chlorine (Cl) is added to disinfect the treated water in the disinfection process. DWTP is made with organic and suspended matter, coagulant products, microorganisms and chemical elements. Sludge is an unavoidable waste product of DWTPs [3]. The total solid sludge generation of DWTPs in Sri Lanka is estimated at 1,250m^3 per month. Properties of the sludge depend on raw water quality, suspended solids, coagulant type, chemicals added in the process, geographical location and climatic conditions. Direct discharge of DWTP sludge into surface water bodies and open lands creates the risk of contamination of surface and groundwater that affects the quality of the water and aquatic ecosystems. Direct discharge of DWTP sludge is prohibited by Sri Lankan legislation; as DWTP sludge belongs to the non-hazardous industrial waste category [4],[5]. In Sri Lanka sludge is dewatered and sent for land fillings and to fill rock blasting wells. Therefore, DWTPs practice different methods to dewater the sludge; such as sludge lagoons, sludge treatment plants, sedimentation tanks and sludge drying beds.

There is a sludge treatment plant located in Biyagama DWTP. The sludge treatment plant is consisting of two wash water recovery tanks, a sludge balancing tank, a sludge thickener tank, a thickener sludge tank and two sludge decanters. Embedded water in the DWTP sludge is recovered in the sludge treatment process and fed back to the DWTP and the dewatered solid sludge is removed from the plant. The daily dewatered solid sludge production has been quantified as $10m^3$ [6]. The dewatered solid sludge is disposed at landfills and rock blasting wells, but the increase in waste sludge generation now becoming a problem for the DWTP. Incorporation of the DWTP sludge in a material production process or utilization in material production processes will be a workable solution for the waste sludge. DWTP sludge is a fine material that is made with mud. A soil-based wall putty can be developed using water treatment plant sludge as a sustainable solution for the adverse environmental impacts resulting from the direct disposal of DWTP sludge.

Shelter is one of the main requirements of human which provide protection. Present building constructions account for around 40% of the global energy consumption. And also, contributes around 30% of the global CO_2 emissions which results in adverse environmental impacts such as climate change and global warming [7],[8]. Therefore, the present building constructions are focused on sustainable and green concepts; such as replacing conventional construction materials with sustainable materials [9],[10]. Therefore soil based walling materials are becoming the new trend in the present construction industry [11],[12]. Soil-based walling materials were introduced as green materials and acted as a moisture buffer and a thermal insulator to create thermal comfort. And also, soil-based walling materials balance the relative humidity and indoor air quality of the building [13],[14]. Walls constructed with soil-based walling materials required protective coating for both exterior and interior surfaces. The present cement-based wall finishers are inadequate for soil-based walls, as they do not support the exchange of water vapor in the soil-based wall [15]. As the wall finisher does not compatible with the walling material, the finisher detached from the material surface. Cement-based finishers are too stiff and do not adapt to the natural movements of the soil-based wall movements. Therefore, cracks formed on the wall surface allowing moisture to enter and be trapped inside due to the low porosity. A soil-based wall finisher should apply to the soil-based wall to gain the full performance of the soil-based walling materials [16],[17]. Wall putty is a common wall finisher used in the present building sector; therefore, soil-based wall putty developed using a waste product will be a sustainable and a green solution.

Wall putty is a wall plastering material used as a wall finisher and filler. Putty is a powder made with calcium carbonate (whiting) and acid-refined linseed oil. Calcium carbonate is a white mineral (calcite) that is naturally included in chalk, limestone and marbles [18]. Extraction of calcium carbonate contributes to natural resource depletion while degrading the environment. Wall putty production contributes to the environmental impacts directly through volatile organic compounds emission and indirectly through cement production and calcium carbonate extraction [19]. A soil-based wall putty developed with a waste material can eliminate the environmental impacts of raw material extraction for the existing wall putty production process. Therefore, this research was conducted to identify the properties of DWTPs' sludge and to develop wall putty using waste alum sludge while providing a sustainable material to the civil construction industry.

1.2. Research Gap

Direct discharge of waste alum sludge generated in DWTPs to the environment is prohibited by Sri Lankan legislation due to adverse environmental impacts. DWTP sludge generation is increasing with the increasing demand for treated drinking water. And there is no sustainable solution was found for the DWTP waste alum sludge. DWTP sludge is a fine material that is made with mud and there is a potential to develop soil-based wall putty using the sludge.

As far as science is concerned, it has been identified that climate change and global warming are the issues that have to be addressed in near future; where the building construction sector provides a considerably higher contribution. Existing wall finishing materials and techniques result in environmental impacts. Calcium carbonate extraction results in environmental degradation and natural resources depletion; while putty production contributes to the environmental impacts directly through volatile organic compounds emission and indirectly through cement production and calcium carbonate extraction. Sustainable wall putty is required to avoid the negative impacts of the existing wall putty.

Soil-based walling materials were invented for the construction industry as green materials. But conventional wall finishing materials and techniques are not compatible with those materials. With the application of conventional wall finishers to earth-based walling materials performance will be reduced. Therefore, a soil-based wall finisher is required.

This research seeks to address all those issues mentioned by adding value to the waste alum sludge generated in DWTPs. The proposed wall putty in this research is a sustainable innovation that utilizes waste sludge as the raw material and contributes to sustaining the building construction sector.

1.3. Aim and Objectives

This research was conducted with the main aim of developing wall putty; applicable as a wall finisher replacing both primer and top coat of conventional wall finishes (Figure 1.1), for tropics using DWTP waste alum sludge and with a few objectives including,

1. Analyzing the properties of DWTP waste alum sludge,
2. Analyzing and optimizing putty properties of wet alum sludge,
3. Analyzing possible means to produce dry powdered alum sludge,
4. Analyzing and optimizing putty properties of developed dry powdered alum sludge,

5. Analyzing characteristics of the developed wall putty compared to existing wall finishes, and
6. Analyzing the real-world performance of the developed wall putty.

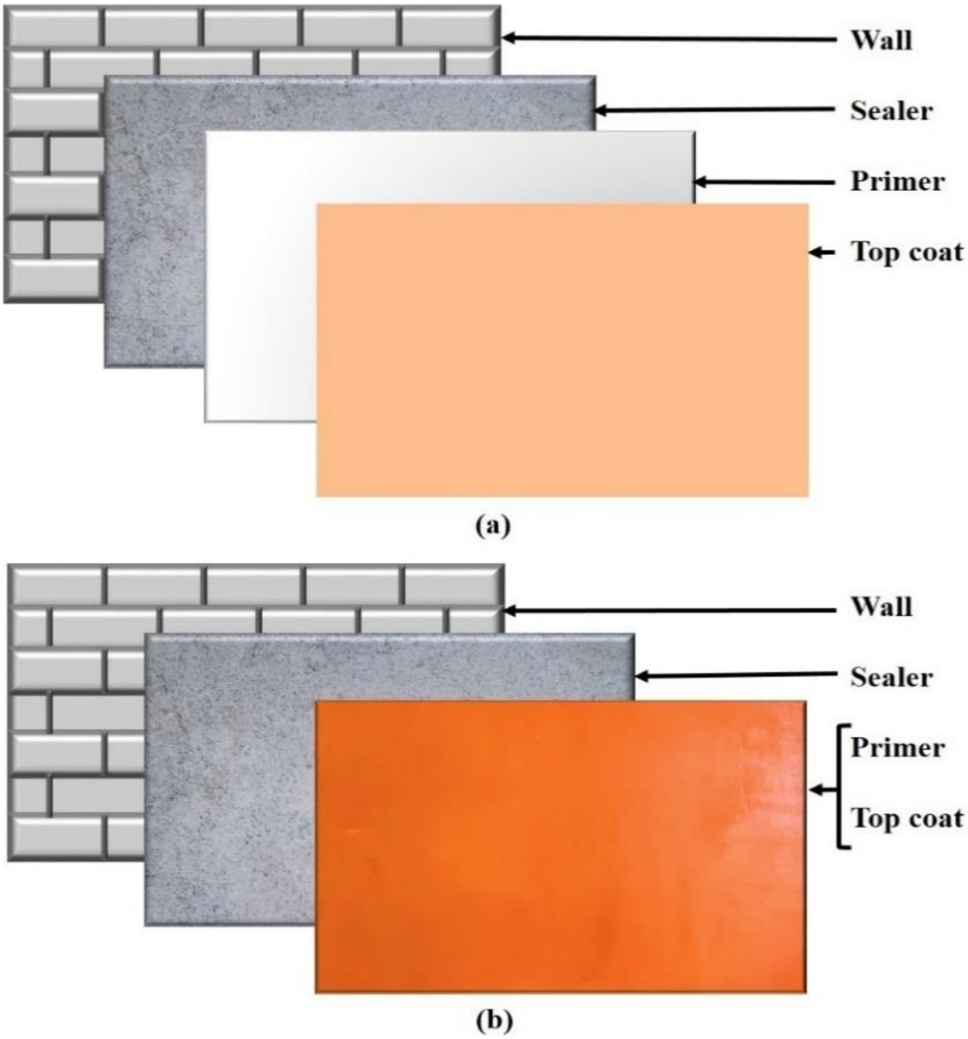


Figure 1.1: Wall finishing system; (a) conventional wall finishes (b) proposed wall finishes

1.4. Methodology

A literature review was conducted as a background study and a methodology was developed for this research study as mentioned below;

1. Collect sludge samples from different DWTPs and conduct a series of experiments to analyze the properties of waste alum sludge.

2. Analyze the putty properties of wet alum sludge and optimize properties by mixing with different additives and binders to develop wall putty using wet alum sludge.

3. Evaluate thermal alterations of waste alum sludge under different temperatures to analyze the thermal properties.

4. Develop a process to produce dry powdered alum sludge with putty properties considering the thermal properties of the sludge.

5. Select a suitable stabilizer for the developed wall putty considering strength and durability.

6. Compare intrinsic properties of the developed wall putty with the existing wall finishes

7. Conduct real scale performances analysis of the developed wall putty to identify the feasibility

1.5. Main Findings

This research was conducted to develop a wall putty for the tropics using DWTP waste alum sludge and the main findings can be concluded as,

1. Dewatered waste alum sludge collected from Biyagama DWTP, has the lowest moisture content and highest solid content compared to raw sludge sample collected from Ambathale DWTP and sludge sample collected from sludge drying beds in Kandana DWTP.

2. Cadmium (Cd) (<0.1ppm), Lead (Pb) (4.3ppm), Mercury (Hg) (<0.1ppm) and Arsenic (As) (0.9ppm) are identified heavy metals includes in DWTP waste alum sludge and available in lower quantities than the maximum permissible level defined for top coatings.

3. DWTP waste alum sludge moisture content varies between the values of 62.31% and 84.72% and volumetric shrinkage varies between the values of 59.82% and

93.62%; humidity is the significant climatic factor effect on shrinkage of the sludge.

4. Physical additives reduce shrinkage of the DWTP waste alum sludge; the optimum sand mixing ratio was identified as 30-60% to obtain optimum wet sludge mix to develop a wall putty mix and banana fiber is the most effective natural fiber type to reduce shrinkage compared to coir and sugarcane fiber.

5. Binders improve the adhesiveness of DWTP waste alum sludge but increase the moisture content of the mix. Drying crack patterns of wet sludge mixture vary with the binder type. Natural binders facilitate surface growth and reduce the durability of the mix.

6. The density of burned alum sludge varies with heat and the lowest density is recorded at 500°C temperature.

7. The density of burned alum sludge with coconut oil is lower than the density of burned sludge at each temperature. The lowest density of burned sludge with coconut oil was recorded at 700°C temperature. Coconut oil is an effective lubricant to use to produce dry powdered alum sludge overcoming alum activation.

8. DWTP wet alum sludge mixed with 8% coconut oil by weight and burning at 700°C temperature are the optimum conditions for the dry powdered sludge production process.

9. Styrene acrylic binder is the most workable stabilizer for the developed sludge putty compared to cement and lime.

10. Sludge dry powder with 300μm fineness is applicable as a wall putty by mixing dry powder 3: binder 1 on a plastered wall surface. And a sealer is applied on the putty surface as a protective coating. The sludge putty can be recommended for both interior walls and exterior walls.

1.6. Organization of the Thesis

This thesis includes eight chapters and the breakdown of the chapters is as follows;

- Chapter 01 discussed general information about the research background, research gap, objectives and methodology. The main findings of this research are also discussed in this chapter.

- Chapter 02 presents a detailed review of the literature conducted to find out the background of the research identifying possible applications of DWTP waste sludge and conditions of existing wall putty technologies.

- Chapter 03 presents the properties of sludge collected from different DWTPs. Findings of the series of experiments conducted with sludge samples and the selection of DWTP to collect sludge for the study are discussed in this chapter.

- Chapter 04 presents the putty properties of DWTP waste alum sludge. Findings of the series of experiments conducted with DWTP waste alum sludge samples are discussed in this chapter; including physical and chemical properties.

- Chapter 05 presents the effectiveness of different admixtures to optimize the putty properties of DWTP wet alum sludge considering the strength and adhesiveness of the mixture.

- Chapter 06 presents the thermal properties of DWTP waste alum sludge. And also, the developed process to produce dry powdered alum sludge considering thermal alterations of the sludge and selection of stabilizer are discussed in this chapter.

- Chapter 07 presents the real-scale behavior of the developed wall putty and properties in comparison with the existing wall finishes.

- Chapter 08 of this thesis presents conclusions, recommendations and future research related to this research.

CHAPTER 02: LITERATURE REVIEW

2.1. General

This research was conducted with the main aim of the development of wall putty for the tropics using DWTP waste alum sludge. As the first step, a detailed review of the literature was conducted to find out the background of the research identifying possible applications of DWTP waste sludge and conditions of existing wall putty technologies. The findings of the literature review were used to plan and advance this research study. Therefore, the literature review was conducted under the main topics as follows;

- Drinking water treatment
- DWTP waste sludge
- Sustainable building construction and materials
- Wall finishes and technologies
- Durability of wall finishes

2.2. Drinking Water Treatment

Water is one of the main requirements of humans and all living creatures. A human can survive only for three days without drinking water; and the average water requirement of a human depends on biological factors (age, gender and weight) and climatic factors [20]. Average per capita water consumption is high in hot climatic zones compared to temperate climatic zone. The average drinking water requirement of Sri Lanka is high due to tropical climatic conditions. Daily consumption of safe drinking water in sufficient amounts, is essential for better human physiology and psychology as water is important for metabolic activities [21]. Therefore, ensuring the access of citizens to consume sufficient safe water is one of the responsibilities of a country; as a sufficient amount of safe water consumption is essential for public health [22],[23]. A higher portion of the total population of most of the countries in the world has no access to a sufficient amount of safe drinking water (Figure 2.1); due to the lack of safe natural water resources. Therefore, they provide safe water to the residents after purifying surface water through DWTPs. Most of the residents in Sri Lanka have access to natural water resources more than the population of other countries in the region (Figure 2.1) [1].

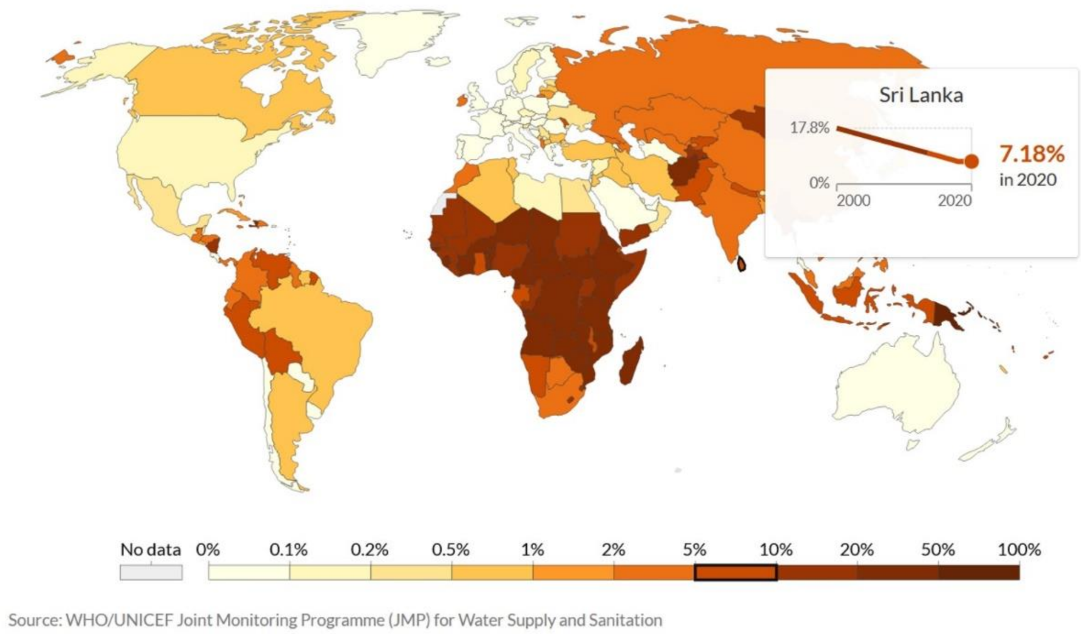


Figure 2.1: Population without access to an improved water source, 2020

2.2.1. Drinking water treatment process

There are different water treatment processes and technologies available in the world. Aquatic systems, mechanical systems and terrestrial systems are the available conventional and non-conventional wastewater treatment technologies. Most drinking water treatment plants purify surface water up to drinking water quality and there are two common treatment processes; conventional treatment technologies and advanced treatment technologies [24]. Conventional treatment technologies include processes of clarification, filtration, coagulation, flocculation, adsorption and disinfection. Advanced treatment processes consists with ultrafiltration technologies [25],[26]. Surface water dissolved with soil particles; sand, silt, clay and humus, and other contaminants deposited from surface runoff and effluent dispose in urban areas and industries. Surface water quality is considered when selecting a water treatment process. Water purification costs also vary with the type of water treatment process [2]. Sludge is an unavoidable waste product of DWTPs and the sludge generating rate of the water treatment plant was estimated as 1%-3% of purified total raw water amount [27].

DWTP sludge is an unavoidable waste product, generated in water treatment and categorized under industrial waste with no harm [27]. But the composition of the DWTS differed with the geographical location, climatic conditions and raw water quality. Therefore DWTP sludge generated in DWTPs located in different countries contain heavy metals and other contaminants exceeding maximum permissible limits; which has the potential to create adverse impacts on eco-systems and human health [28],[29],[30]. Direct discharge of DWTP sludge into water bodies and land is prohibited by the legislation of most countries considering the potential adverse impacts. Therefore, the DWTP sludge should be treated before disposal. With the increasing demand for drinking water, the estimated sludge generation is increasing and the cost for sludge treatment and disposal increasing as shown in Figure 2.2 [31],[32].

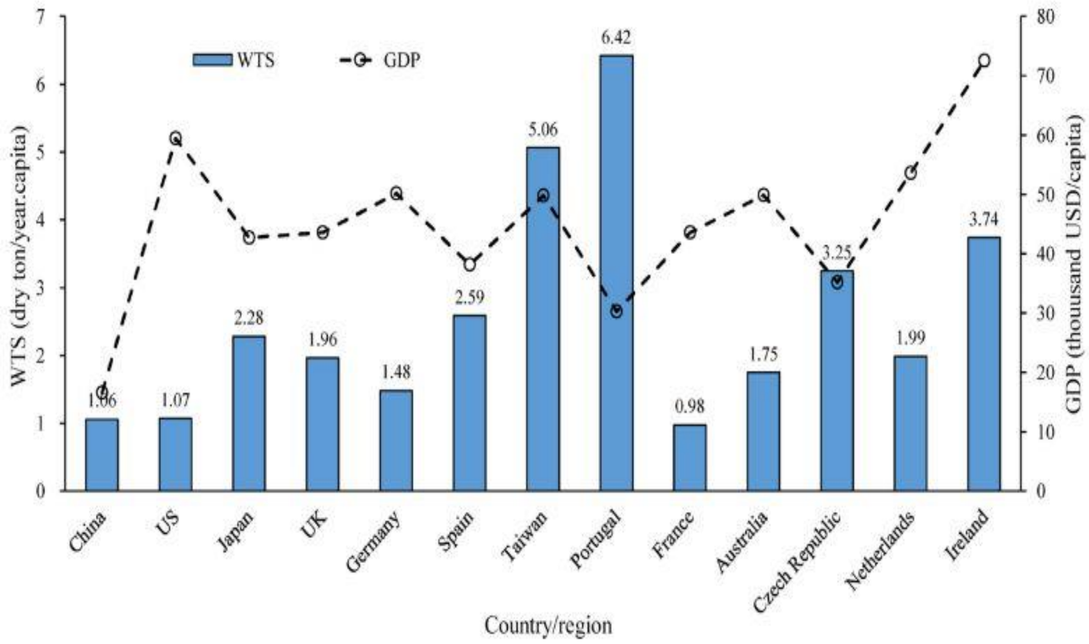


Figure 2.2: Estimated quantities of DWTP sludge in different countries and estimated cost of sludge treatment and disposal [31]

2.2.2. Drinking water treatment in Sri Lanka

Sri Lanka has so many natural resources; natural water resources are one of the valuable resources. And there was access to safe water for a higher portion of the Sri Lankan population. Urbanization and industrialization restricted the accessibility of the urban population to safe water compared to rural areas. Therefore, the government of Sri Lanka has the responsibility to distribute safe drinking water in sufficient quantities to urban areas; and NWSDB is the responsible authority for water purification and distribution [1]. NWSDB operates with 323 major, medium and small-scale water supply schemes, located all over the country as shown in Figure 2.3 [33]. Raw water from surface water bodies was collected in DWTPs and treated to drinking quality before distribution. Because surface water is dissolved with impurities such as sand, silt, clay, humic particles and other contaminants; as a result of surface runoff and waste disposal from urban areas and industries [2].

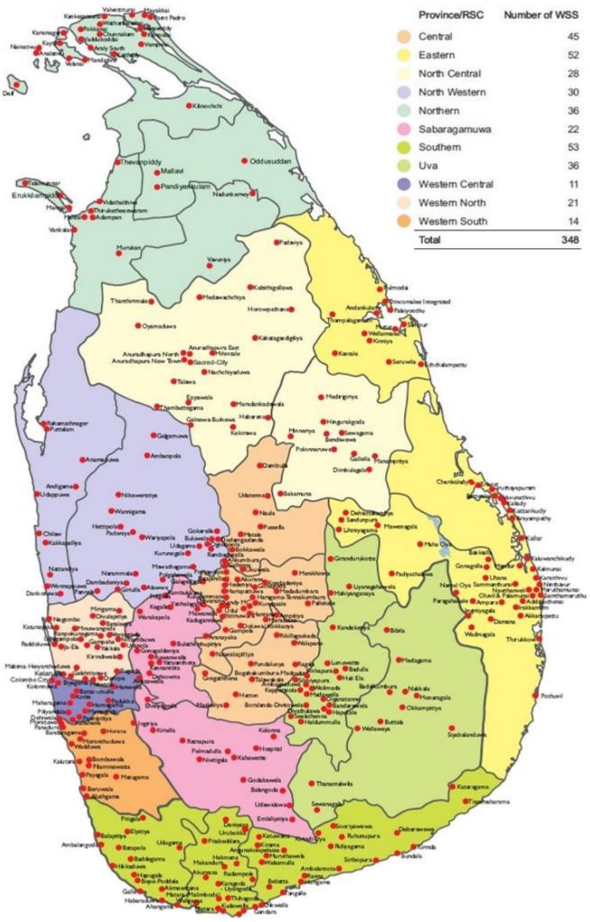


Figure 2.3: Existing water supply schemes of NWSDB Sri Lanka [33]

DWTPs in Sri Lanka practice conventional water treatment technologies as the surface water contamination is at a lower level in the country than in other countries in the world. Therefore the water purification process in DWTPs in Sri Lanka includes coagulation, flocculation, sedimentation, filtration and disinfection processes [2]. Chemical coagulants are added in the coagulation process to remove suspended impurities such as sand, silt, clay and humic particles. Lime ($Ca(OH)_2$) and chemical polymers are added to the treatment process. Alum sludge is settled in the flocculation and sedimentation processes; it is removed in by filtration. Chlorine (Cl) is added to disinfect the treated water in the disinfection process. Alum-based waste sludge is generated in DWTPs in Sri Lanka and removed after dewatering [3]. There are different technologies used for sludge dewatering, such as sludge treatment plants, sludge drying beds, sludge lagoons and constructed wetlands.

Biyagama DWTP is located at Kelani River right bank. The plant is designed with a conventional physic-chemical water treatment process to consist of two intake structures, a raw water regulation tank, a mixing chamber, six flocculation/clarifiers, eight filters and a clear water/contact tank [34]. Raw water is collected from the Kelaniya River; and daily release 180,000m^3 of treated drinking water from the plant. Biyagama DWTP fulfil drinking water requirement of one million of population at divisional secretariats of Biyagama, Kelaniya, Mahara, Wattala, Ja-ela and Dompe. There is a sludge treatment plant located in Biyagama DWTP. The sludge treatment plant is consisting of two wash water recovery tanks, a sludge balancing tank, a sludge thickener tank, a thickener sludge tank and two sludge decanters. Embedded water in the DWTP sludge is recovered in the sludge treatment process and fed back to the DWTP; the dewatered solid sludge is removed from the plant. The daily dewatered solid sludge production has been quantified as 10m^3 [6].

2.3. DWTP Waste Sludge

There are different types of sludge with specific properties. Properties of the sludge differ on different factors; such as the geographical location of the plant, climatic conditions, raw water quality, treated water quality and water treatment process [29],[31]. The water treatment process includes physical processes and chemical treatments. In the treatment process coagulants, polymers, lime, chlorine and other chemicals were added. Coagulants are added to remove suspended particles in raw water which do not settle under gravity due to the light weight. Aluminium salts ($Al_2(SO_4)_3.18H_2O$), ferric ion salts ($FeCl_3.6H_2O$), and ferrous iron salts ($FeCl_2$, $FeSO_4.7H_2O$) are the coagulants used in DWTPs [35],[36]. DWTP sludge removed from each plant consists of coagulant products added in the treatment process. Concentrations of the coagulants and other chemicals added in the treatment plant depend on the raw water quality and the treated water quality. Therefore, the sludge from different DWTPs consists of different quantities of coagulant products and other chemicals. Three types of DWTP sludge can be identified according to the coagulant type and the chemical composition; 'Alum sludge', 'Ferric sludge' and 'Lime sludge' [31]. Each type of DWTP sludge has unique properties due to the behavior of different chemicals and coagulant products (Table 2.1).

Table 2.1: Properties of DWTP sludge types

Sludge Type	Moisture content (%)	Density (gcm^{-3})	Soil classification (USCS)	Loss on ignition (%)	References
Alum sludge	80-550	1.86-2.33	High-plasticity clay	15-57	[31],[37],[38],[39]
Ferric sludge	108	2.26-2.72	High-plasticity clay	24-50	
Lime sludge	38-72	2.57-2.62	Low-plasticity silt	35-40	

2.3.1. DWTP sludge disposal methods

All the DWTPs in the world released the waste sludge to nearby water bodies and open lands at the beginning. After that DWTP sludge is categorized as a non-hazardous industrial waste [32],[40]. However, it is non-hazardous, disposal of water bodies and open land is prohibited by legislation. Dispose of sludge creates potential disturbances to the natural water reservoirs and aquatic ecosystems due to the unwanted mud deposits [4]. The increasing generation of sludge is becoming a huge problem for most countries; as shown in Table 2.2, due to the high cost engage in sludge treatment, transportation and disposal processes. Dewatered DWTP solid sludge dispose of at landfill sites after treatments by many countries; but some developing countries still release it to water bodies and nearby drains due to the high cost of sludge treatment and disposal practices [2],[41]. According to the literature very few DWTPs reuse or recycle their waste sludge.

Table 2.2: Increasing waste sludge generation in other countries

Source	DWTP	Country	Sludge Generation	Disposal Method
[2]	Ghaziabad	India	29,700 tons/yr.	Discharged to a nearby drain
[30]	Santa Maria	Brazil	2,100m^3/day	Discharged to rivers and sea
[42]	From all DWTPs of the country	South Korea	1,159.1 tons/day (2016) 982.7 tons/day (2011)	Disposed in landfills
[43][44]	Metropolitan Waterworks Authority	Thailand	300 tons/day in the dry season 700 tons/day in the wet season	Disposed in landfills
[45]	From all DWTPs of the country	Italy	Dewatered sludge 750,000 tons/yr.	Disposed in landfills
[46]	Fong-Yuan DWTP	Taiwan	6,000 tons/yr.	Disposed in sanitary landfills
[47]	From 29 DWTPs	Taiwan	160,000 tons/yr.	Disposed in landfills
[48]	From 5 DWTPs	Taipei - Taiwan	70,200 tons/yr.	Disposed in landfills
[49]	From 384 DWTPs	France	63,800 tons/yr.	Disposed in landfills
	From 307 DWTPs	Mexico	2.8x10^9 m^3/yr.	Disposed in landfills
	From 215 DWTPs	Spain	120,000 tons/yr.	Disposed in landfills
[50]	Sent Joan Despí DWTP, Barcelona	Spain	17,000 m^3/day	Mixed with raw materials in cement production after spray drying.

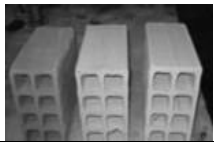
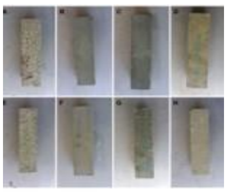
Dewatered sludge generated in Biyagama DWTP is also disposed at landfills and rock blasting wells, but the increase in waste sludge generation now becoming a problem for the DWTP. Incorporation of the DWTP sludge in a material production process or utilization as a raw material in a material production process will be a sustainable solution for the waste sludge; to eliminate the results of the environmental impact when disposing of DWTP sludge [51].

2.3.2. DWTP sludge applications

Direct discharge of water bodies, open lands and nearby drains was the common DWTP sludge disposal method practiced in the world until the direct discharge of sludge was prohibited by legislation. Therefore, all the countries started looking for a sustainable solution to discharge or recycle DWTP sludge. Some research studies were conducted to improve the efficiency of DWTP processes to reduce the sludge production rate of the plant. But the sludge production was unable to eliminate; as it is an unavoidable waste product of the DWTP process. Therefore, treated DWTP sludge was disposed in landfills. But the high sludge treatment cost and transport cost to dispose in landfills led to fond processes to recycle DWTP sludge.

DWTP sludge is a fine material similar to mud and clay in texture. The sludge is made with coagulant products and chemical elements, organic and suspended matter and microorganisms [13],[15]. Mud and clay are versatile materials used in the construction industry from prehistoric times [52],[53]. Therefore, most of the research was conducted to identify the possible uses of DWTP sludge as an alternative to mud and clay. And also, research studies were conducted to analyze the possibility of DWTP sludge to incorporate into construction material production processes without affecting the properties and performances of the products (Table 2.3).

Table 2.3: Experiments conducted to incorporate DWTP sludge in material productions

Source	Year	Country	Product	Findings
[54]	2017	Brazil	Concrete 	The addition of DWTP sludge in wet form reduces the strength of concrete. The ideal incorporation level was identified as up to 5%; which effective limit for non-structural concrete.
[44]	2015	Thailand	Brick	DWTP sludge–fly ash geo-polymer bricks have a longer service life compared to clay–cement bricks, which are used commonly in wall constructions in many countries.
[55]	2016	India	Brick 	Bricks can be produced by incorporating the DWTP sludge with clay materials. Ferric sludge has better mechanical properties than alum sludge.
[32]	2005	Taiwan	Brick 	Adding DWTP sludge increase the sintering temperature requirement. Under the common brick-making condition, DWTP sludge can be incorporated up to 15% with clay to produce first-grade bricks.
[56]	2017	Egypt	Refractory brick 	DWTP sludge can incorporate successfully with rice husk ash to produce high-quality insulating refractory bricks for various thermal insulating applications.
[57]	2015	Brazil	Ceramic brick 	Ceramic bricks can be produced by incorporating DWTP sludge up to 13.9%.
[58]	2017	Morocco	Portland cement 	Incorporation of DWTP sludge with clay in the synthesis of Portland clinker complementarily can reduce the energy demand of Portland cement production.
[59]	2011	Jordan	Tile	Tiles produced by mixing DWTP sludge replacing 50% of cement, comply with the breaking strength of 2.8MPa required for external use tiles.

According to the previous research studies the main findings can be concluded as below;

- WTP sludge has some unique characteristics to enable its incorporation in construction materials such as bricks, ceramics, cement and geopolymers.
- The main challenges in the application of WTP sludge in construction materials are derived from its high variation in physicochemical properties and relatively high content of organic matter, which will increase the porosity and water absorption therefore potentially adversely affecting products' structural integrity and performance.
- The majority of studies with ceramic bricks showed that the incorporation of alum sludge up to 10% is satisfactory in maintaining the structure performance. For iron-based sludge, an increase in mechanical strength was observed when more significant proportions were added. A similar effect was observed in studies with lightweight aggregates, where Fe content in the sludge had a high impact on water absorption and compressive strength.
- Regarding the production of cement and concrete with the partial addition of DWTP sludge, it is potentially feasible, especially as a pozzolanic addition and replacement of sand in concrete up to 5%.
- The effect of sintering temperature and the ratio of oxides had a great influence on heavy metals leaching from WTP sludge amended products. Sintering above 1000°C is recommended to ensure the full immobilization of heavy metals such as Cd, Cr, Cu and Pb hence preventing further environmental pollution.
- Used as a substitution, WTP sludge can make saving for raw materials and energy, replace landfill as solid waste management, and contribute to sustainable construction materials production.

2.4. Sustainable Building Construction and Materials

The shelter is a main requirement of humans; from prehistoric times shelters were used as a protective structure to protect from extreme environmental conditions. Extreme conditions can be identified as heavy rain, extreme wind, harmful radiation and protection from animal attacks. In the beginning, primitive structures were used as shelters and with civilization building constructions were developed and improved with the technology development. In prehistoric times shelter was a protective structure but present structured buildings are designed with wide verities of activities including living, entertaining and manufacturing [60]. Different building materials used in building constructions can be identified as walling materials, floor finishes, roofing materials, paving materials, wall finishers, etc [61],[62]. Walls and roofs are important building components in the concern of protection; as they are directly exposed to the external environment and protect building occupants from external heat gain, extreme weather conditions and other external effects [61].

More than 400 million tons of materials are annually consumed by the building construction sector; according to the estimations of the Green Building Council of the United Kingdom. Raw material extraction for construction material productions creates adverse environmental impacts; resulting in natural resource depletion, damaging natural ecosystems and affecting natural cycles. And also, the material extraction processes create adverse environmental issues through fuel consumption, chemicals, dust and heat emissions and noise pollution. The construction industry contributes to the high amount of global waste generation and global resource consumption. Building constructions contribute to the consumption of 70% of electricity, 50% of energy and 15% of natural water; while contributing to emissions of 40% of CO_2 and 30% of waste. And the estimated values depend on the country, economic level and lifestyles of the residents [63],[64].

Environmental issues of building constructions run throughout the whole lifecycle of development. Those impacts occur from the beginning of initial works, during the construction period, in the operational stage and up to the final demolition stage [63]. Land clearing and preparation for building constructions change natural land use patterns resulting destruction of natural habitats and destroying wildlife. The building construction process contributes to global warming, greenhouse gas emissions, air pollution and water pollution; through the processes of material extraction, manufacturing and transportation [65]. After considering all those adverse issues of conventional building construction practices, it was necessary to resort to a sustainable construction process [66]. At the present, all the development practices are compiled with the Sustainable Development Goals (SDGs) adopted by the United Nation in 2015. Therefore building constructions move from conventional building practices toward sustainable building constructions [67],[68].

2.4.1. Sustainable building constructions

Sustainability can be defined as, the fulfillment of the present requirements without compromising the ability to fulfillment of future requirements. Sustainable design refers to sustainable practices in the construction industry; including building designs and constructions. Buildings designed with sustainable concepts; also define as green buildings, have many advantages in the areas of resource efficiency, environmental impacts, and social and economic impacts. The green building concept has been developed to mitigate adverse impacts of conventional construction practices to meet the design intentions of the present while considering effects in the future. The whole lifecycle of the building is considered in the green building concept. It is a continuous process applicable from the site selection stage, material selection step, throughout the construction process, in the operation stage and up to the demolition stage; considering all the adverse impacts of each step [69].

There are different green building rating systems in the world to assess sustainable building constructions; such as LEED, USGBC, GBCSL, BREAM, etc. [70]. Those rating systems have been developed by allocating credits for several categories, including sustainable site, sustainable design elements, location and transportation, material and resource, building product disclosure and optimization, energy and atmosphere and indoor environmental quality [71]. In those rating tools, a considerable number of points were allocated under sustainable building construction methods. Building construction methods that reduce resource consumption and improve the usage of locally available sustainable materials were encouraged in sustainable building design and construction.

There are important benefits of sustainable building constructions over conventional constructions; such as upgrading building occupants' health, indoor comfortability, building life cycle cost reduction, reduction of waste generation, energy and water saving, increasing building lifetime and combination renewable energy sources [72],[69]. Green buildings can reduce solid waste generation by 70% and carbon emissions by 35%; while reducing energy usage by 50% and water usage by 40% compared to conventional buildings [73]. The initial cost of green buildings is much higher as concluded in many research findings. Initial cost engaged in green building constructions and green concepts implementation; however, research studies were clearly showing the operational cost reduction and financial benefits which can be achieved considering the life cycle approach of green buildings compared to conventional buildings [74]. Therefore, research studies are conducting to develop low-cost construction materials for sustainable constructions and to develop green features with high efficiency and low cost; in order to reduce the initial cost of green buildings.

2.4.2. Sustainable construction materials

The rapid population growth of the world increases the demand for buildings; and creates a high demand for construction materials [75]. The building material production processes use natural resources, such as clay, sand, stones and lime in large quantities, in developing countries. There is a high demand for clay bricks and clay tiles; produced with clay, concrete blocks; produced with cement and sand, concrete; prepared by mixing aggregates of stones, and cement; made with lime. A considerable amount of energy is consumed in the mining, transportation and burning processes of these raw materials in construction material production processes. And also the production processes result in adverse environmental impacts; such as deforestation due to wood consumption, saltwater intrusion into rivers and loss of soil fertility [76]. Therefore, it is important to replace conventional raw materials in the construction material production process with alternatives to reduce the burden on natural resources.

There is a considerable high number of points allocated for construction material selection by most of the building sustainability assessment tools in the world. Resource efficiency is considered in the material and resource category of all assessment tools [10]. In LEEDv4, 13 points were allocated for the material and resource category and which is 11.81% of the total point allocation; and in the GREENSL rating tool, 14 points were allocated and it is 14% of the total point allocation [63]. Resource efficiency in building constructions includes the efficient use of energy, natural resources, and materials; and encourages to use of sustainable materials, reuse of materials and use of alternative materials with low environmental impacts [7],[61]. Building constructions contribute to high consumption of energy and material; 50% of the raw materials and 42% of energy are used for building constructions annually in European Union according to the estimations [7].

Cement is one of the common construction materials used in the construction industry around the world; it is estimated that the annual cement production in the world is over 2 billion tons [77]. It was predicted that concrete use reach four times, the use in the year 1990, By 2050, if not found an alternative mixture [77],[78]. It was estimated that 1 ton of cement production results in 1 ton of CO_2 emission; and cement production is responsible for 5% of the annual global CO_2 emissions [79],[80]. Most developed countries use waste products as alternatives to natural resources use for construction material production and there are sustainable construction materials developed from waste products [66],[76].

2.4.3. Walling materials

Building wall is the most important building component. The cost of wall construction contributes to 35% of the total building construction cost in Sri Lanka; while walling materials account for more than 15% of the total building construction cost [61],[53],[81]. There are two types of walling materials in the world; solid walling materials and lightweight walling materials. Solid walling materials are used in tropical countries and it is the most common walling material type used in Sri Lankan building constructions [80]. There are different solid walling materials used in Sri Lankan buildings; such as burnt clay bricks, concrete blocks, Cabook blocks, cement stabilized earth blocks (CSEB), mud concrete blocks (MCB) and geo-polymerized earth blocks [61]. Durability and structural performance of walling materials is very important as they are directly exposed to outdoor extrema environmental conditions.

The tropical climate zone included countries located near the equator which consists of tropical climatic conditions. Sri Lanka belongs to the tropical wet climatic zone; with the climatic conditions of high daily temperatures vary in between 20^0C–30^0C, year-round uniform high precipitation, over 2000mm total rainfall and humidity vary in between 60%-95% [82]. Therefore, the walling materials of buildings in the tropical zone are exposed to tropical climatic conditions consisting of high humidity, rainfall and temperature [80]. Durability of walling materials is directly affected by the tropical climate conditions. Continuous exposure of walling materials to tropical climate; which consists of high solar radiation, rain, wind and temperature results in the deterioration of walling materials. Climatic conditions consist of high humidity and moisture, which accelerate the biological growth of walling materials. Surface growths of fungus, algae, lichen and moss can be identified in the tropical climate. Surface growth damages the appearance of the building while reducing the walling materials' strength and durability. And also surface growth adversely affects indoor air quality and occupants' health [83].

At the present, different walling materials are used for construction. Walling materials have different intrinsic properties; and have different surface roughness values [80],[61]. According to previous studies it has been identified as walling materials with low surface roughness values are more durable and resistant to mould and moss growth [62],[84]. Wall finishes are applied to smooth wall surfaces against the rough surface of the wall. Smooth building walls improve indoor air quality; reduce dust level, increase the interior light level and evade fungus and moss growth [85].

2.5. Wall Finishes and Technologies

Walling materials have different surface roughness values. With the increase in surface roughness durability of walling materials is reduced. To overcome these issues and to increase the durability wall paster is applied on walling material [62],[86]. wall plaster provides a smooth and finished surface while providing a protective coating acting as a moisture barrier for walling material. And also wall plaster added a little extra strength support to walling material. Wall plaster increases the appearance of the building while creating occupant comfort in the building [85],[87].

The most common wall plaster type is cement plaster; where the main ingredient is cement. Rough cement plaster is prepared by mixing cement and sand. And also there are gypsum plasters; where gypsum is the main ingredient [88]. In Sri Lankan buildings, cement and rough cement plaster are widely used. There is a high demand for cement and sand in the building construction sector in Sri Lanka. Cement production and application result in some adverse environmental issues; such as environmental pollution, GHG emissions, natural resource depletion and dust emission [89],[90]. Similarly, cement production creates health problems including respiratory problems [91]. The demand for sand also increases as sand is the main ingredient of rough cement plaster. River sand mining creates many adverse environmental issues in Sri Lanka. And also the high price of sand contributes significantly to increasing the building construction cost [92],[62]. Green building concept encourages to reduction of cement and sand usage considering adverse environmental impacts of both materials. And research studies are conducted to find out environmentally friendly alternatives for sand and sustainable processes to reduce the environmental impacts of cement production and usage.

2.5.1. Historical evidence of earthen wall finishes in the world

From prehistoric times wall finishing techniques were practiced in decorative and communication perspectives [93]. The prehistoric man used smooth surfaces for cave paintings which were used for decoration and communication [93]. When considering historical evidence, can be seen that materials and techniques used for wall smoothing and finishing have changed with time. In prehistoric times man used plasters to make the base for their cave paintings. For those plasters, they used soil as the main ingredient and added animal fat, plant saps, balsams, milk or blood as the binding medium [94]. There is so much evidence of historical earth-based constructions constructed thousands of years back, which can be found all over the world including Sri Lanka.

Bhaja Caves – India: A durable earthen plaster used for exterior and interior plastering is found in Bhaja caves in India and dated back from the 1st century BC to the 3rd century AD (Figure 2.4 (a)). The plaster was made with clay, mixed with raw soil, slaked lime, rice husk and proteinaceous adhesive; to give strength and stop cracking during the drying [95].

Tomb paintings – Egypt and Minoan wall paintings: Paintings were painted on properly prepared plasters in the tomb in Egypt and Minoan walls which dated back to the 4th and 5th century BC (Figure 2.4 (b) & (c)). They used sand and lime plaster with different thicknesses in different places [94].

Mud plasters – Mali: In Mali, wet mud fermented with rice husks was used as wall plaster (Figure 2.4 (d)) and some African countries used proteins to have enzyme reactions, therefore, they mixed milk and sometimes animal blood into the plaster mixture [96].

Tung-oil-lime putty – China: Tung-oil–lime putty is a special organic-inorganic binding material that was widely used in ancient China. It is mainly composed of boiled tung oil and lime. To reinforce its cracking resistance and save raw materials, plant fibers were also added. Due to its good water-resistivity, adhesive property, mothproofing and stability, it was used in numerous fields. According to ancient records and archaeological discoveries, the application of putty dated from about AD 581–AD 907 (Figure 2.4 (e)) [97],[98].

Blood lime plaster – Mexico: Blood lime plaster is used in ancient Europe, China and Mexico (Figure 2.4 (f)). These traditional oriental blood lime plasters have high bonding strength, water resistance, weather resistance and smoothness than the other historical plasters [99]. The blood proteins affect the crystal formation of the plaster and develop a compact layer that improves the surface properties of the plaster [100].

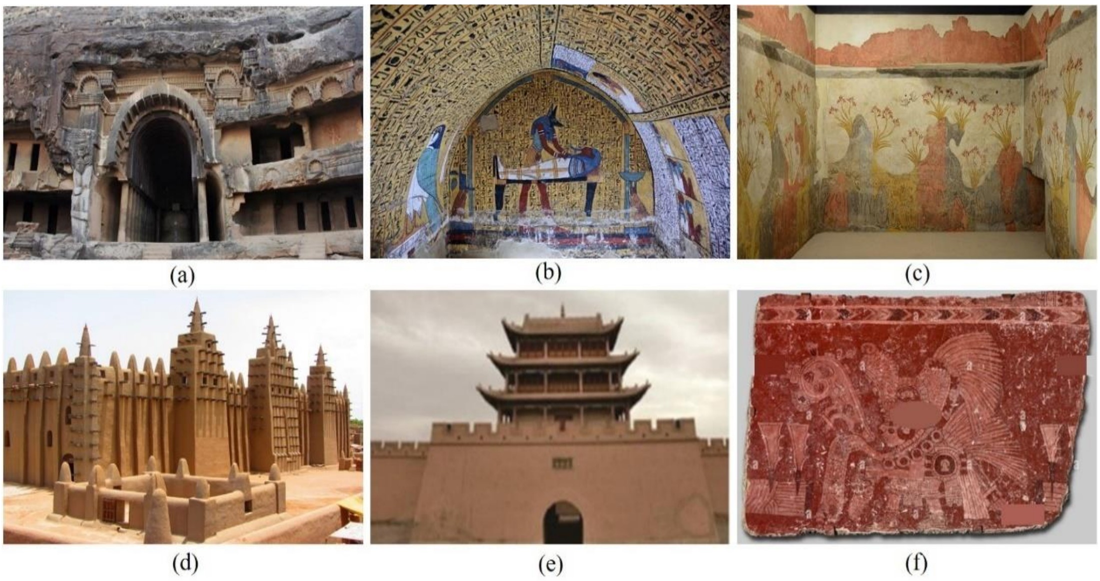


Figure 2.4: Historical earthen plasters in the world; (a)Bhaja caves – India; (b)Tomb paintings – Egypt; (c)Minoan wall paintings; (d)Mud plasters – Mali; (e)Tung-oil-lime putty – China; (f)Blood lime plaster - Mexico

2.5.2. Historical evidence of earthen wall finishes in Sri Lanka

Sri Lanka has a great written history with shreds of evidence compared to other countries in the world. Historical monumental constructions lasting for thousands of years can be found all over the country. Sigiriya is one of the UNESCO world heritages located in Sri Lanka; constructed by King Kashyapa in the 5^{th} century AD (more than 1500 years old). The Sigiriya is popular all over the world because of its mirror wall and the fresco (Figure 2.5). The mirror wall is created with highly polished soil-based plaster on the internal surface of the parapet wall [101]. The world-famous fresco of Sigiriya is painted on a soil-based plaster which is made with few layers. The reddish-brown color ground layer of the plaster (half an inch in thickness) was made with tempered earth and kaolin and coated with at least two layers of white chunam (one-fourth to half an inch thickness). The clay base of the plaster was strengthened by the admixture of paddy husk and shreds of coconut fiber [102].

Figure 2.5: Soil-based plasters in Sigiriya Sri Lanka; (a) Mirror wall (b) Sigiriya fresco

Sri Lanka has a great proven history of earth-based constructions. Stupas are monumental structures built to Honour Lord Buddha; they are architecturally important Buddhist structures. The very first stupa constructed in Sri Lanka is Thuparama (Figure 2.6 (a)); which was built by King Devanampiyatissa (250-210 BC) in the capital city of Anuradhapura. Jetavana is the largest structure made of brick in the world [103] (Figure 2.6 (b)). Stupas are solid structures, built with burnt clay bricks and un-burnt sun-dried clay bricks. The bricks were laid with a thin mortar; made with clay slurry, called ‘butter clay’, and the outer surface was protected with a thick plaster mixed with plant-based adhesives. Ingredients used to prepare mortar in stupas were identified as finely crushed dolomitic lime, sand and clay; after studying the plaster samples of Abhayagiri (Figure 2.6 (c)) (constructed in the first century BC) and Jetavana (constructed in the third century AD) stupas. This evidence are proving that lime mortar technology had developed throughout the centuries [103].

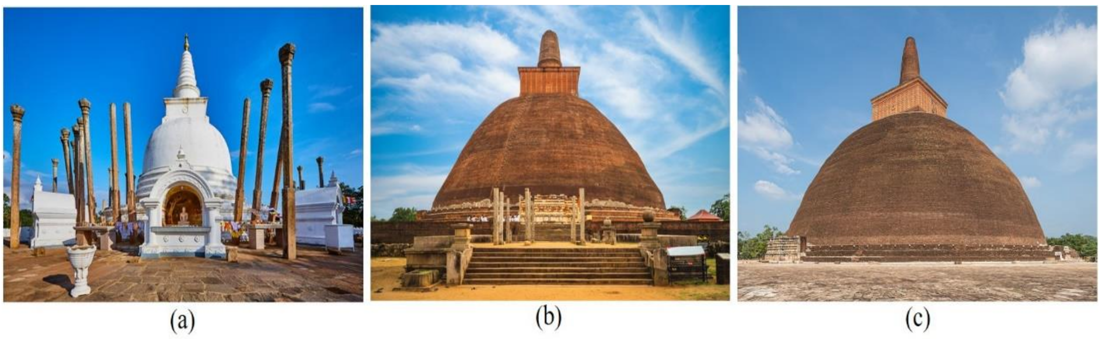


Figure 2.6: Stupa – earth-based historical constructions in Sri Lanka; (a)Thuparamaya; (b)Jethawanaramaya; (c)Abhayagiriya

2.5.3. Present wall finishes and technologies

Present building constructions use different wall finishing materials; such as cement, wall care putty, lime slurry, etc, and different techniques; such as plastering and cladding are used to smooth and finish wall surfaces [104],[105]. But Cement and sand are the main ingredients of the wall plaster. Cement production contributes to 5% of global annual CO_2 emission [78],[77], and sand mining results in adverse environmental impacts such as environmental degradation. And also sand price is increasing gradually at present while increasing the construction cost of buildings [106],[107]. Cement and sand usage in the building construction industry can be reduced by avoiding cement plasters used as wall finishes. The reduction of cement and sand usage can reduce building construction costs and the global annual CO_2 emission. Wall care putty is a thick mixture of finely powdered calcium carbonate (whiting) and acid-refined linseed oil [18]. Calcium carbonate extraction results in environmental degradation and natural resource depletion. Wall putty production contributes to the environmental impacts directly through volatile organic compounds emission and indirectly through cement production and calcium carbonate extraction [19]. On the other hand, these conventional wall finishing materials and techniques are not compatible with soil-based walling materials.

2.5.4. Wall care putty

With the increase in building construction, the demand for wall finishes is increasing. Wall care putty is the most commonly applied material as the primer layer for both interior and exterior wall surfaces. Wall care putty is applied as a leveling material on the wall plaster and acts as a protective layer for the wall plaster while providing a strong and durable base for the top coat. And also the putty materials are developed with the ability to fill dents, and hair cracks to level the rough surface of the plaster [108]. Wall putty materials are developed with the characteristics of;

- High bonding strength
- Moisture barrier
- High durability
- Low bio-receptivity

There are different types of wall putty products available in the market; such as lime, white cement putty, acrylic putty and Plaster of Paris (POP).

Lime putty: this is a conventional wall putty product applied in traditional constructions. And also, it was the widely applied wall putty in past constructions. Lime putty developed with calcium carbonate extracted from lime depositions; such as limestones, chalk, corals and marbles.

White cement wall putty: is a putty product commercially available in powder form; and it is developed with a mineral, white cement and polymer. The powder is applied after mixing with water. There are different white cement-based wall putty products are available in the market from different commercial brands. Each brand has different properties.

Acrylic wall putty: is a ready-use putty mix, developed with acrylic polymers and other chemicals. POP is a powder material developed with gypsum and the putty mix is prepared by mixing the powder with water [109]. Talcum, quartz, gypsum and cement are the main raw materials for most commercial acrylic wall putty materials and the material should consist of the engineering properties of high bonding strength, crack resistance, resistance to water, low shrinkage and enough flexibility [108].

Most common wall care putty products in the market are white. Wall putty is applied as the primer layer of the wall providing a uniform base for the top coating. Paint is applied as the top coat and to avoid impact on the selected color of the paint wall putty is applied in white color. Therefore, there is high demand for white color wall putty products; but in the present market colored wall putty products are available. Colored putty products are developed by adding color pigments to conventional white commercial wall putty products. Colored wall care putty products are applied as the primer layer with a protective top coat eliminating the application of a paint layer on walls. According to architectural purposes and client requirements, colored wall putty products are applied in buildings. However, the increasing consumption of natural resources has led to a strong depreciation alarming the need for sustainable alternatives for existing wall care putty materials.

2.6. Soil-based Wall Finishes

Soil-based walling materials are becoming the new trend of the present construction industry as an eco-sustainability material; such as mud concrete blocks, cement stabilized earth blocks and rammed earth walls [13],[15],[110]. Soil-based walling materials perform as a moisture buffer; to control the humidity of the indoor environment; a thermal insulator; provide thermal comfort, and improve the indoor air quality of buildings [15],[17]. Walls constructed with soil-based walling materials require protective coating for both exterior and interior surfaces. Cement-based plasters are not compatible with soil-based walling materials. Cement-based plasters are highly rigid materials and do not facilitate moisture transmission and natural wall movements of soil-based building walls. As result, the detachment of cement-based plaster from the building wall reduces the optimum performance of soil-based walling materials [13]. Cement-based pastes are not suitable for repairs of soil-based walls; soil-based walls repaired with cement-based mixtures were cracked easily and allowed trapped rainwater inside the wall. A soil-based wall finisher and a mixture; for repairs of soil-based building walls, are required to obtain optimum performances of soil-based constructions [15],[111].

Mud and clay are versatile natural materials used in the construction industry. There are available walling materials, mortars, plasters, roofing materials and flooring materials made with mud and clay. Mud and clay-based materials are universally accepted as environment-friendly and user-friendly materials for building constructions [16]. There is a very long history of mud and clay-based plasters and renders; historical evidence is available in all regions of the world. Mud and clay-based finishes are optimum and ideal for soil-based building walls, but the most important fact is that soil-based wall finishes are compatible with building walls constructed with any walling material [112].

2.6.1. Research conducted on soil-based wall finishes

With the adaptation to sustainable building construction practices, demand for sustainable materials were increasing at present. Most countries in the world conducting research studies to develop sustainable building construction methods and introduce sustainable construction materials. To that soil-based walling materials and wall construction methods were introduced to the present construction industry. Although soil-based walling materials and construction methods were used from ancient times in most countries; present research studies were conducted to develop the ancient soil-based technologies to make them compatible with present building construction technologies. Research studies were conducted to develop soil-based wall finishes using mud and clay with the aims of;

- To use for repairs of ancient soil-based structures and constructions,
- To develop a wall finishing material compatible with present soil-based construction technologies
- To develop eco-sustainable construction material

Advantages of the soil-based wall finish [113],[114] compared to conventional wall finishes were identified as;

- Soil-based wall finishes are successfully applied to different building wall types; such as, rammed earth walls, adobe walls, concrete walls, wood walls, brick walls and straw bale walls.
- Soil base wall finishes perform as an insulator for heat, moisture, sound, odor and noise.
- Soil-based wall finishes create thermal comfort for occupants against the temperature variation of the outdoor environment while maintaining optimum indoor humidity.
- Soil-based wall finishes contribute to improving indoor air quality compared to conventional wall finishes.

Soil-based wall plasters were developed by mixing different clay types with different admixtures. Research studies were conducted to develop ready-mixed clay plasters by mixing clay sand in different ratios; also clay plasters were developed by mixing different clay types with different binders and additives; as shown in Table 2.4. in the studies mixtures were prepared by mixing using a hand mixer or a mechanical mixer until a proper consistency was observed [113],[114].

Table 2.4: Materials and tests conducted in research studies to develop soil-based wall finishes

Source	Year	Product	Materials	Tests conducted
[113]	2015	Ready-mixed clay plasters	Red clay Yellow clay Sand	• Volumetric shrinkage • Observational shrinkage • Ball drop test • Compressive strength • Moisture content • XRF analysis • XRD analysis
[114]	2014	Ready-mixed clay plaster	Clayey soil Siliceous aggregates (0/4 mm sand) Cement Lime	• Linear shrinkage • Compressive strength • Flexural strength • Adhesive strength • Density • XRD analysis
[115]	2017	Eco-efficient earth-based plaster	Clayish earth Siliceous sand (0-2mm) Cut out fibers (1-2cm long)	• Particle size distribution • Density • Biological susceptibility • XRD analysis

According to those research studies the main findings can be concluded as below;

- Different clay types have different physical and chemical properties and the effectiveness of clay plaster depends on the clay type.
- Shrinkage and bonding strength are the main properties of the clay that should consider when developing clay plaster or putty.
- Shrinkage of clay plasters can be measured by conducting a volumetric shrinkage test and observational shrinkage test (Figure 2.7). Shrinkage of clay plaster can be reduced by adding fibers.
- Surface crack formation of clay plasters increases, with the increased moisture content of the mix; and the optimum water mixing ratio was identified as 30%-40%.
- Bonding strength decreases, with the increased clay content of the mix while increasing drying cracks according to the observational shrinkage test.
- Bonding strength can be improved by adding binders and the standard bonding strength of wall putty products is ≥0.6Mpa. The nature of the bond can be analyzed

after observing the bond-breaking pattern of the sample according to the ASTM D5868-014 test standards (Figure 2.8) [116].

- The standard density of the soil to develop effective soil-based plasters was identified as 2.6-2.7gcm^{-3} and the standard particle size distribution was identified as 18%-22% of clay, 40%-42% of silt and 30%-40% of sand according to IS:13077-1991 standards.
- Plaster properties of the clay mix can be improved by mixing sand and the optimum clay sand mixing ratio can be identified by conducting a ball drop test (Figure 2.9).

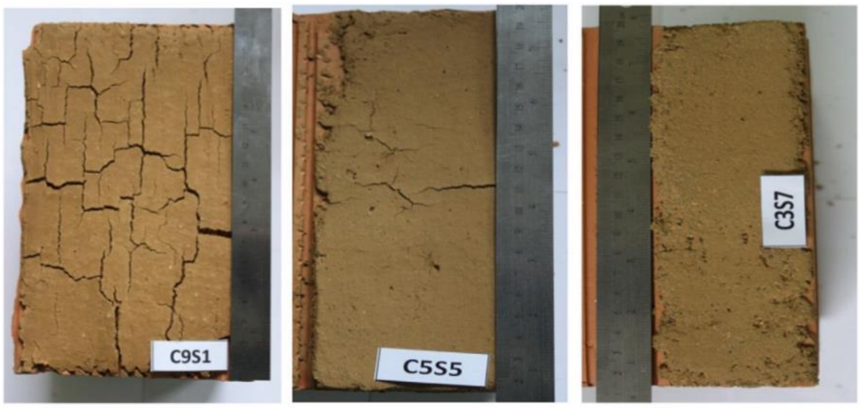
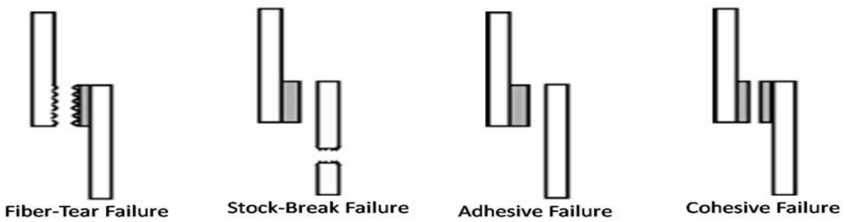


Figure 2.7: Observational shrinkage test for clay plaster



Result	Nature of the bond
Fibre-Tear Failure	Bond strength of putty < Bond strength of plaster material
Stock-Break Failure	Bond strength of putty > Bond strength of plaster material
Adhesive Failure	Low bond strength between putty and plaster material
Cohesive Failure	High bond strength between putty and plaster material

Figure 2.8: Possible crack patterns in bonding strength test and analysis of nature of the bond

(a) High clay content (b) Poor clay content (c) Optimum clay content

Figure 2.9: Possible observations in a ball drop test

2.6.2. Test standards for soil-based wall finishes

According to the literature, there is no developed standard for the characterization of soil-based wall finishes [113]. Therefore, standards developed for commercial wall putty products, cement and lime-based plasters, soil-based block productions, and mud mortar, were followed in relevant research studies; as shown in Table 2.5.

Table 2.5: Test standards used in previous research studies

Source	Product	Test	Standard	Standard value
[117]	Mud plaster	Particle size distribution	IS:13077-1991	18%-22% of clay 40%-42% of silt 30%-40% of sand
		Density	EN 1097-3	2.6-2.7gcm^{-3}
[115]	Eco-efficient earth-based plasters	Density	EN 1097-3	2.6-2.7gcm^{-3}
		XRD analysis for mineralogical analysis	DIN 18947,2013	-
		Fungus growth test	ASTM D 5590-00	0%
[108]	New exterior wall putty	Bond strength	ASTM D5868-014	≥0.6Mpa
		Sanding property	JGT-157-2009 GB/T9278	Easy
[113]	Ready-mixed clay plaster developed with clay and sand	XRF analysis to determine the chemical composition	DIN 18947,2013 (German Standard)	-
		XRD analysis for mineralogical analysis		-
		Ball drop test		Optimum clay/sand proportions are semi-shiny and exhibit only a small number of surface cracks, with no shattering
		Volumetric shrinkage		<10%

2.7. Characteristics of Wall Care Putty Products

Wall care putty is applied as a leveling material on the wall plaster and acts as a protective layer for the wall plaster while providing a strong and durable base for the top coat. And also the putty materials are developed with the ability to fill dents, and hair cracks to level the rough surface of the plaster [108]. Wall putty materials are developed with the characteristics of;

- High durability
- Low bio-receptivity
- High bonding strength
- Moisture barrier

2.7.1. Durability of wall finishes

Building components such as building walls and roofs are constantly being designed and manufactured to satisfy the ever-growing needs of society. Many of these walls and roofs will be subjected to adversative conditions over their life and these conditions will affect their intended performance. Durability measures that building component will perform their functions under the expected conditions. The durability of building components can be defined as, the safe performance of a structure or a portion of a structure for its expected design life, according to the ASTM E241 standard. Therefore selected materials should be durable enough to perform optimum conditions throughout the whole lifecycle of the building [118].

Building walls are directly exposed to the external environment; therefore, the durability of the wall finishers under humid tropical climates should be concerned. Whole life cycle cost includes component replacement interval, maintenance activities and frequency; therefore, life cycle cost is influenced by durability. There are different stress factors effected on the durability of wall finishes; such as mechanical, thermal, environmental and biological factors. High solar radiation, heavy monsoonal rains and high wind conditions can occur in tropical climatic zones; and surface erosion, mass loss, pitting, cracking and surface growth can result when exposed to tropical climatic conditions for a longer time duration [118]. The ability of a wall finisher to resist when exposed to heavy rain conditions should be measured. Exposure to stress factors results in strength loss of buildings and adversely affect the appearance of the building; therefore, measuring the durability of a wall finisher is important when selecting or developing a wall finisher to apply in the tropical climatic zone [62],[119]. Commercial wall putty products available in the market are subjected to scale-off, fungus growth, color deterioration and water leakages after long-term exposure to tropical climatic conditions [84],[86],[120].

2.7.2. Tropical climate and rain surface erosion

There are different climatic zones in the world; the tropical climatic zone is one of the major climatic zones with a wide spread. The tropical climatic zone consists of countries located near the equator. Sri Lanka belongs to the tropical wet climatic zone and the climatic zone consists of high daily temperature; vary in between 20^0C–30^0C, year-round uniform precipitation, over 2000mm total rainfall and humidity between 60% - 95% [82]. When designing a building, it is important to consider the climatic conditions of the climatic zone where the building is located. Because the durability of the building directly depends on the exposed climatic conditions. Buildings in the tropical zone must be designed considering the tropical climatic conditions. But at present, building designers use European and American construction concepts for buildings in the tropical zone. Building designed without considering the climatic zone can result in thermal discomfort; which contributes to increased demand for artificial heating, cooling and ventilation and increases building energy demand [121].

Building walls and roofs are directly exposed to tropical climatic conditions [122],[123]. However, tropical climatic conditions are the nastiest climatic conditions for building materials; due to the high heating and continuous wetting conditions. These adverse climatic conditions accelerate weather degradation, scaling off, natural decay, mould and moss growth on building walls. Sri Lanka is an equatorial country with a tropical climate; consisting of high humid and moist conditions throughout the year [84]. These climatic conditions accelerate the mould and moss growth on building walls while reducing the aesthetic value of the building. Similarly, it affects the durability and strength of the building structure [62],[124].

2.7.3. Bio-receptivity of wall finishes

The ability of a material to be colonized by a living organism is defined as the 'Bio-receptivity' [125]. Bio-receptivity of the walling material depends on the intrinsic properties of the material [126],[127]. High humid and moist conditions facilitate the bio-receptivity of building walls. Water is the main requirement of organisms' metabolic activities; walling materials absorb water during rain or when exposed to flood conditions or high humidity environments. Building walls get wet when expose to heavy rain conditions under tropical climatic conditions; and wetted wall finishing materials increase the material bio-receptivity [128],[129]. Fungus growth on wall putty under wet conditions can be identified as the most common effect when exposed to highly humid environments and rain.

A fungus is a microscopic level living creature that is not visible to the human eye. But the fungus is visible to human eyes, only when they are colonized. Fungus belongs to the kingdom of fungi. They obtain nutrients from the attached surface degrading the material [130],[131]. The fungus can colonize most of the habitats in the world; including land, underground, soil, surface waters and oceans. Fungus growth is accelerated by high humid and moist conditions [131],[130]. Therefore, the fungus can successfully colonize building surfaces under highly humid and moist conditions.

2.7.4. Fungus growth on building walls

There are a few factors affecting fungus growth; such as the nature of the surface, exposure time, environmental temperature, moisture, humidity and fungus species. Tropical climatic conditions, including high humidity and moisture, are favorable for fungus growth. Therefore, the buildings in the tropical zone are more vulnerable to fungus growth [128],[132]. *Aspergillus niger* and other *Aspergillus spp* are the identified fungus species on building walls [128]. Fungus growth damages walling materials and results in health problems for the building occupants. Deterioration of the wall finishes due to fungus results in aging, strength reduction and discoloration; which reduce the aesthetic value of the building. And also, fungus growth adversely affects indoor air quality. The fungus produces mycotoxins, spores and fragments which are toxic to human and results in health problems [128],[132].

Building walls should be protected from fungus growth to improve durability and occupants' health. Fungus growth facilitating factors should be identified and they should be eliminated to avoid fungus growth [132]. The most common fungus treatment method was applying a sealer or coating system on the wall surface to act as a moisture barrier to avoid moisture absorption. And also, chemicals are commonly used to control the existing fungus on walls. Sodium polyborate, dichlofluanid and iodopropinyl-butyl-carbamate (IPBC) are popular anti fungus additives [128]. Chemical treatments for fungus are not a sustainable and safe prevention method and green building concepts do not encourage chemical usage in sustainable building constructions and operations [133].

2.8. Summary

Water is one of the main requirements of humans and other living creatures. Life cannot be sustained without water, Therefore, ensuring the access of citizens to consume sufficient safe water is one of the responsibilities of a country. A sufficient amount of safe water consumption is essential for public health. A higher portion of the total population of most of the countries in the world has no access to a sufficient amount of safe drinking water; due to the lack of safe natural water resources. Therefore, they provide safe water to the residents after purifying surface water through DWTPs. Most of the residents in Sri Lanka have access to natural water resources; compared to the other countries in the region. The NWSDB is the responsible authority for drinking water purification and distribution. NWSDB consists of DWTPs located all over the country and the total drinking water production is estimated at 30 million m^3 per month.

DWTP process consists of the steps of coagulation, flocculation, sedimentation, filtration and disinfection. Sludge is an unavoidable waste product generated in DWTPs. Total solid sludge production of DWTPs in Sri Lanka can be estimated at $1250m^3$ per month. The nature of sludge depends on suspended solids of raw water quality, coagulant type and chemicals added in the treatment process. Direct disposal of sludge into open lands and water bodies results in contamination of surface water and groundwater; reducing water quality and damaging aquatic ecosystems. Direct discharge of water treatment plant sludge is prohibited by Sri Lankan legislation; as sludge is classified under industrial waste. Different DWTPs practice different sludge treatment methods; such as sludge lagoons, sludge treatment plants, sedimentation tanks, etc.

DWTP sludge is a fine material similar to mud and clay in texture. The sludge is made with coagulant products and chemical elements, organic and suspended matter and microorganisms. Mud and clay are versatile materials that have been used since prehistoric times in the construction industry. Therefore, most of the research was conducted to identify the possible uses of DWTP sludge as an alternative to mud and clay. And also, research studies were conducted to analyze the possibility of DWTP sludge to incorporate into construction material production processes without affecting the properties and performances of the products. According to the research studies the main findings can be concluded as below;

- Sludge in different DWTPs has unique physical and chemical properties; the properties should be identified before incorporate into the material production process.
- DWTP sludge can incorporate in some construction material production processes up to an effective percentage; beyond the effective limit, products failed in standard performances.
- The effectiveness of DWTP sludge incorporation depends on the type of sludge (alum sludge or ferric sludge or lime sludge).
- A production process was not developed to utilize DWTP sludge as the main raw material of a product.

Soil-based walling materials are becoming the new trend of the present construction industry as an eco-sustainability material; such as mud concrete blocks, cement stabilized earth blocks and rammed earth walls. Soil-based walling materials perform as a moisture buffer; to control the humidity of the indoor environment; a thermal insulator; to provide thermal comfort, and improve the indoor air quality of the building. Walls constructed with soil-based walling materials require protective coating for both exterior and interior surfaces. Cement-based plasters are not compatible with soil-based walling materials. Cement-based plasters are highly rigid materials and do not facilitate moisture transmission and natural wall movements of soil-based building walls. As a result, detachment of cement-based plaster from the building wall reduces the optimum performance of soil-based walling materials. Cement-based pastes are not suitable for repairs of soil-based walls; soil-based walls repaired with cement-based mixtures were cracked easily and allowed trapped rainwater inside the wall. A soil-based wall finisher and a mixture; for repairs of soil-based building walls, are required to obtain optimum performances of soil-based constructions. Wall putty is a common wall finisher used in the present building sector; therefore, soil-based wall putty will be a sustainable and green solution.

Wall putty is a wall plastering material used as a wall finisher and filler. Putty is a thick mix of finely powdered calcium carbonate (whiting) and acid-refined linseed oil. Calcium carbonate is normally found as a white mineral (calcite) that occurs naturally in chalks, limestone and marbles. Calcium carbonate extraction results in environmental degradation and natural resource depletion. Advantages were identified as what can be obtained with soil-based wall finishers compared to conventional wall finishes. Soil-based wall finishes are applied to different building wall types; such as, rammed earth walls, adobe walls, concrete walls, wood walls, brick walls and straw bale walls. Soil base wall finishes perform as an insulator for heat, moisture, sound, odor and noise. And also, soil-based wall finishes creating thermal comfort for occupants against the temperature variation of the outdoor environment while maintaining optimum indoor humidity. Soil-based wall finishes contribute to improving indoor air quality compared to conventional wall finishes. With the knowledge gathered from the literature, this research was conducted to develop a wall putty mix using DWTP waste alum sludge.

CHAPTER 03: SELECTION OF DWTP TO COLLECT SLUDGE

3.1. General

DWTP sludge is identified as a fine material similar to mud and clay in texture and made with organic and suspended matter, coagulant products, microorganisms and chemical elements. The properties of the sludge depend on;

- The geographical location of the plant
- Climatic conditions
- Raw water quality
- Suspended solids
- Treated water quality
- Water treatment process
- Coagulant type
- Chemical added in the treatment process
- Sludge treatment process

Therefore DWTP sludge of each plant consists of unique properties [3],[29] and the properties of the sludge in each DWTP should be studied separately. According to that, sludge samples from three different DWTPs; where practices three different sludge treatment processes, were collected; and a series of experiments were carried out to identify the properties. The physical properties of each sample were identified and the suitable DWTP to collect sludge for further studies was selected considering solid content and moisture content of the samples. Further physical and chemical properties of the selected sludge sample were studied after that. Selection of DWTP for collecting sludge will be discussed in this chapter.

3.2. Selection of a DWTP

In Sri Lanka, NWSDB is responsible for drinking water purification and supply throughout the country. NWSDB is consist of DWTPs located all over the country to secure a safe and sufficient water supply. This research study was conducted with the collaboration of NWSDB and required permissions were approved at the beginning of the study for DWTP visits, data collection and sample collections.

There are different sludge treatment methods available in the world such as sludge treatment plants, sludge settling tanks, sludge lagoons and constructed wetlands. According to NWSDB, sludge treatment plants, sludge lagoon and sludge drying beds are available in DWTPs in Sri Lanka. In this research three DWTPs were selected for sludge sample collection. Three DWTPs located in Ambathale, Biyagama and Kandana were selected and the plant locations are shown in Figure 3.1.

Figure 3.1: Locations of selected DWTPs; (a) Biyagama DWTP (b) Ambathale DWTP (c) Kandana DWTP

3.2.1. Ambathale DWTP

Ambathale DWTP is located at Kelani River bank and it is one of the major water sources of NWSDB with a capacity of 549,000m^3 per day. The plant produces 518,000m^3 of water per day for Colombo city. The plant consists of three water intakes and two storage reservoirs. A raw sludge sample was collected from the Ambathale plant as shown in Figure 3.2 (a).

3.2.2. Kandana DWTP

Kandana DWTP is located at Kandana, Horana and the plant is constructed under the Kalu Ganga water supply project. The plant is designed with a capacity of 60,000m^3 per day and around 300,000 people who live in the southern part of Colombo benefit. There are large tanks called 'sludge lagoons', which store the raw sludge of the plant. In the lagoons' wet sludge is left to sun drying and dried sludge cake is produced. Dried sludge is sent for land fillings. Wet sludge samples from sludge lagoons were collected from Kandana DWTP (Figure 3.2 (b)).

3.2.3. Biyagama DWTP

Biyagama DWTP is located at Kelani River right bank and providing safe drinking water to cities covering the Northern part of the Western Province in Sri Lanka, including, Biyagama, Kelaniya, Kiribathgoda, Kadawatha, Ragama, Wattala, Kandana, Ja-Ela, Seeduwa and Ganemulla. The plant is designed to produce drinking water of 180,000m^3 per day at its' full capacity. Raw water for the plant is extracted from the Kelani River; and the treated water is produced with a conversion rate of 95% and the 5% loss happened during raw water transmission, sludge dewatering and backwashing.

Biyagama DWTP is designed with a conventional treatment process; a physic-chemical process, consisting of the major processes as, raw water extraction, pumping, screening, mixing chamber, flocculator, lamella clarifier, sand filter, clean water tank and distribution network. There is a sludge treatment plant in Biyagama DWTP. The sludge, generated in sedimentation and backwashing processes, is thickened through a sludge thickener. Sludge is dewatered in the sludge decanter and produces 'sludge cake' to send to landfill sites. Samples of the sludge cake were collected from the Biyagama DWTP (Figure 3.2 (c)).

(a)

(b)

(c)

Figure 3.2: Collected sludge samples; (a) Raw sludge from Ambathale DWTP (b) Sludge from sludge drying beds in Kandana DWTP (c) Dewatered sludge from Biyagama DWTP

3.3. Experimental Analysis of Sludge Properties

Sludge samples were collected from selected three DWTPs and the experiments were conducted in University of Moratuwa laboratories. Initial tests were conducted to identify the basic physical properties of the sludge samples to select the most suitable sludge sample to develop a wall putty. To that wet sieve analysis and moisture content were tested.

3.3.1. Moisture and solid content analysis

The workability of a soil-based mixture depends on the moisture content and the effectiveness of the mix depends on the solid content; therefore, the moisture and solid content of each sludge sample were tested. According to the literature weight basis, oven dry method was conducted to analyze the moisture content of soil-based mixtures according to the ASTM D 2216-98 standard [134][113]. The moisture content and solid content were analyzed according to the weight basis oven dry method [135],[136].

Methodology:

Three replicates of each plant sludge sample were taken and the wet weight (Ww) of each sample was measured and recorded. After that, the samples were oven dried, at 110°C temperature for 24 hours to remove moisture completely (Figure 3.3). Dried samples were weighted until the weight become constant. And then the dry weight (Dw) of each sample was measured and recorded. With the collected data, moisture content (MC) and the solid content (SC) of each sample was calculated according to equation 3.1 and 3.2. And the average value of the three replicates was calculated and the results are shown in Table 3.1.

$$MC(\%) = \frac{Ww - Dw}{Ww} \quad \text{.......... Equation 3.1}$$

$$SC(\%) = 100 - MC \quad \text{.......... Equation 3.2}$$

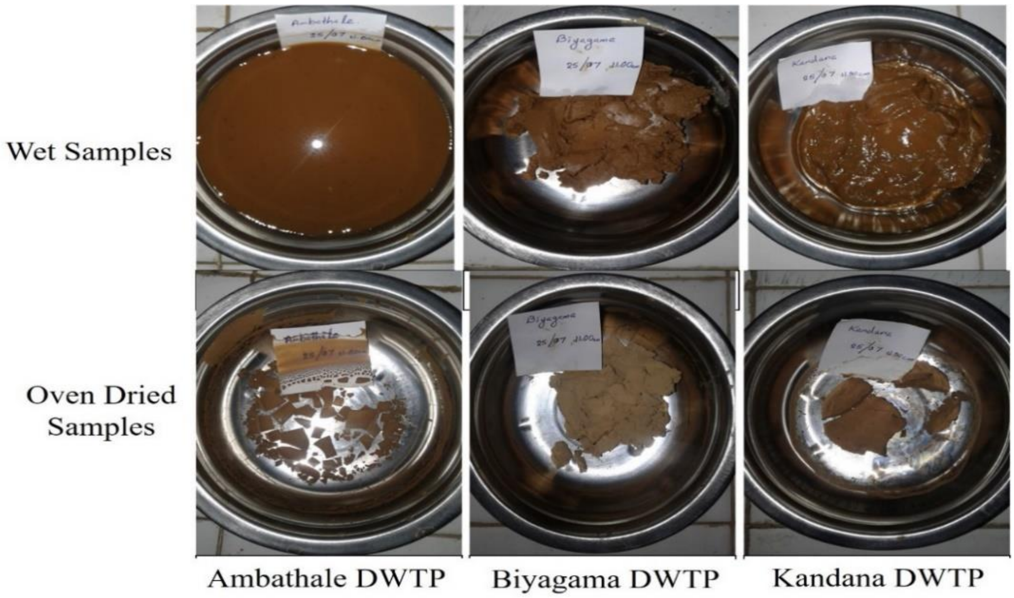


Figure 3.3: Moisture and Solid content measuring test

Table 3.1: Weight basis Moisture and Solid content of sludge samples

Sample	Moisture Content (%)	Solid Content (%)
Ambathale DWTP	97.70	2.30
Biyagama DWTP	68.38	31.62
Kandana DWTP	86.32	13.68

Results and Discussion:

According to the test results, the Ambathale DWTP sludge sample has the highest moisture content (97.7%) and lowest solid content (2.3%). Kandana DWTP sludge sample has the second highest moisture content (86.32%) and second lowest solid content (13.62%). Biyagama DWTP sludge has the lowest moisture content (68.38%) and the highest solid content (31.62%).

According to the literature, bonding strength and shrinkage are directly affected by moisture content. When the moisture content increase bonding strength decreases while shrinkage increases [113],[114]. However, those properties depend on the clay content also; therefore, to analyze the particle size distribution of the solid fraction of each sludge sample, a wet sieve analysis was conducted.

3.3.2. Wet Sieve Analysis

The clay content of the sludge directly affects the properties of the sludge. According to the literature, increasing the clay content of a mix increase the bonding strength reducing shrinkage [137],[114]. Therefore, the clay sand ratio must be optimized to develop a clay plaster [113]. To that, analyzing the particle size distribution of the sludge is important. Wet sieve analysis was conducted to analyze the particle size distribution of each sludge sample according to IS:13077-1991.

Methodology:

Equal portions (1kg) of each wet sludge sample were measured and three replicates from each sample were analyzed. Measured sludge samples were put into a 75µm sieve. The wet samples were sieved continually stirring by hand and adding water. The sludge portion retained in the sieve was oven dried at 110^0C for 24 hours and measured the dry weight (Ws). The effluent was collected and sundried to reduce the water amount. The sundried sample was oven dried to obtain dry weight (Wc). With the recorded data, the sand percentage and clay and silt percentage of each sludge sample were calculated and the average of the three replicates was taken. The results are shown in Figure 3.4.

Results and Discussion:

According to the test results, silt and clay content is highest in Ambathale DWTP sludge and lowest in Biyagama DWTP sludge. The sand content is highest in Biyagama DWTP sludge and lowest in Ambathale DWTP sludge. When comparing the results with the standard values; as shown in Table 3.2, the particle size distribution of each sample is not in the standard range defined to develop mud plaster. Therefore, further improvements should be done to the sludge mix to optimize the particle size distribution to develop a wall putty.

Sludge collected from Ambathale and Kandana contains high moisture content and is required to remove moisture before use in the study. Therefore, Biyagama DWTP was selected to collect sludge considering the lowest moisture content and the highest solid content.

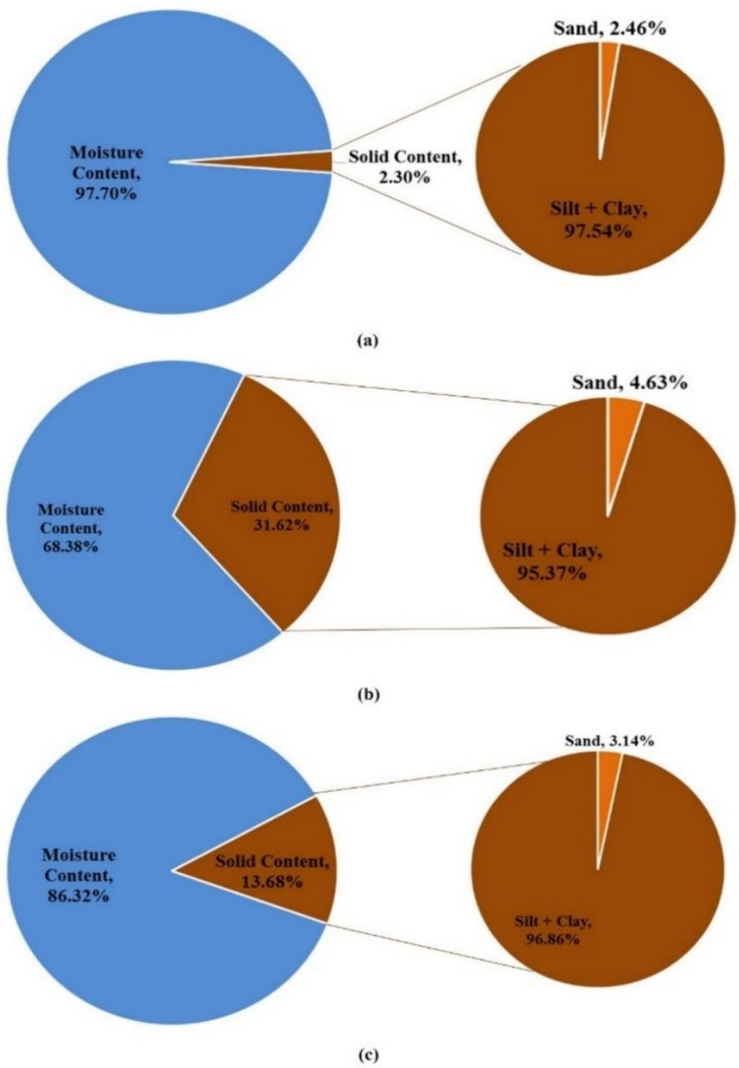


Figure 3.4: Particle size distribution of sludge samples; (a) Ambathale DWTP sludge (b) Biyagama DWTP sludge (c) Kandana DWTP sludge

Table 3.2: Particle size distribution of DWTP sludge

	Sand	Silt + Clay	Reference
The standard for mud plaster - IS:13077-1991	30%-40%	58%-64%	[117]
Mud plaster	52%	48%	
Clay from quarries of Spain	43.4%	56.6%	[50]
DWTP sludge from Sant Joan Despí DWTP in Spain	10.6%	89.4%	
Ambathale DWT sludge	2.46%	97.54%	
Biyagama DWTP sludge	4.63%	95.37%	
Kandana DWTP sludge	3.14%	96.86%	

3.4. Summary

DWTPs practice different sludge removal processes and removing sludge has different properties identical to the sludge removal process. Therefore, DWTP should be selected to collect sludge for experiments considering favorable conditions to develop a wall putty. To that sludge samples were collected from Ambathale, Biyagama and Kandana DWTPs; and each plant practice different sludge removal methods. Laboratory tests were conducted to identify the properties of each plant sludge sample. After a comparison of the properties of samples, a DWTP was selected to collect sludge.

According to the test results, the Ambathale DWTP sludge sample has the highest moisture content and the lowest solid content compared to the other two samples. Biyagama DWTP sludge; which was collected from the sludge treatment plant, has the lowest moisture content and highest solid content; therefore, Biyagama DWTP was selected to collect sludge for the study. According to the particle size distribution of the sample, it was identified that further improvements to the sludge are needed to develop a wall putty. After that, laboratory experiments were conducted to identify the chemical and physical properties of Biyagama DWTP sludge as discussed in the next chapter.

CHAPTER 04: ANALYSING PUTTY PROPERTIES OF DWTP WASTE ALUM SLUDGE

4.1. General

According to the results of the initial tests; discussed in the previous chapter, Biyagama DWTP was selected to collect sludge for this research. Identical properties of the material should be studied to proceed with further experiments. Biyagama DWTP sludge was not utilized as the main raw material in the material production process. Therefore, standard experiments proceeded to identify the chemical and physical properties of DWTP sludge. Experimental procedures and the results will be discussed in this chapter.

4.2. Chemical Properties of DWTP Waste Alum Sludge

According to the literature, sludge properties vary with the sludge type (Table 2.1). And the sludge type depends on the chemical composition [31],[37]. Therefore, the identification of the chemical composition of DWTP sludge is important. To identify the chemical properties of DWTP sludge, X-Ray Fluorescence (XRF) analysis, X-Ray Diffraction (XRD) analysis and inductively coupled plasma mass spectrometry (ICP-MS) analysis were conducted. Chemical elements of the sludge sample were analyzed by conducting an XRF analysis. XRD analysis was performed to identify the minerology of DWTP sludge. Heavy metal identification was conducted by performing an ICP-MS analysis.

4.2.1. XRF Analysis

XRF analysis was conducted with the collaboration of the Sri Lanka Institute of Nano Technology (SLINTEC). The sludge sample was sun-dried and powdered. The powdered sample was sieved through a 100µm sieve to prepare a sample for the test. The test was conducted using HORIBA Scientific XGT- 5200 X-ray Analytical Microscope. The sample was pasted on the sample stage using double tapes and six different places were analyzed. The test was conducted with the parameters of, 200s live time; 100µm XGT Diameter; 50kV X-ray tube volume and P2 processing time.

Results and Discussion:

Chemical elements of the sludge sample were identified through XRF analysis [138] and the results are shown in Figure 4.1. According to the XRF test results Al, Si, S, K, Ca, Ti, Mn and Fe were detected. And Si (42.23%) is detected in the highest percentage, and Mn (0.25%) is detected in the lowest percentage in DWTP sludge. According to the literature, chemical elements of clay samples and sludge collected from different DWTPs were identified by conducting XRF analysis as shown in Table 4.1. When comparing the chemical composition of DWTP sludge in this study with the results of the previous research studies; it can be concluded that the percentages of each chemical element are in the range of chemical elements of clay and DWTP sludge samples analyzed in previous research studies.

SLINTEC
SRI LANKA INSTITUTE OF NANOTECHNOLOGY (PVT) LTD.

4. Results

Sample 01

Element	Spot 1 Mass %	Spot 2 Mass %	Spot 3 Mass %	Spot 4 Mass %	Spot 5 Mass %	Spot 6 Mass %
13Al	27.09	25.98	22.99	26.47	21.84	24.60
14Si	40.78	39.85	41.79	37.20	45.01	45.10
16S	0.49	0.44	0.37	0.52	0.39	0.42
19K	2.45	4.45	7.91	1.53	1.85	2.57
20Ca	5.52	4.84	4.27	5.58	4.75	5.89
22Ti	1.44	1.60	1.52	1.66	1.58	1.18
25Mn	0.18	0.21	0.20	0.40	0.20	0.17
26Fe	22.07	22.64	20.95	26.64	24.38	20.07

Chemical Element	Al	Si	S	K	Ca	Ti	Mn	Fe
Mass (%)	24.43	42.23	0.44	2.35	5.34	1.48	0.25	23.47

Figure 4.1: XRF analysis results

Table 4.1: Chemical elements of DWTP sludge

Sample	Al (%)	Si (%)	S (%)	K (%)	Ca (%)	Ti (%)	Mn (%)	Fe (%)	Mg (%)	Na (%)	Reference
Red clay from Turkey	19.2	60.6	-	2.8	0.4	1.2	0.2	7.7	0.8	0.3	[113]
Yellow clay from Turkey	16.9	63.7	-	2.4	0.6	1.1	0.1	6.5	1.0	0.4	[113]
Clay from Brazil	33.4	52.4	-	0.3	-	2.1	0.1	0.7	0.1	0.1	[139]
Clay from quarries of Spain	17.3	59.4	-	2.9	2.6	1.0	0.1	6.8	1.5	1.1	[50]
Sludge from St. Joan Despi DWTP in Spain	15.8	53.7	-	3.2	14.4	0.7	0.1	5.0	3.6	0.4	[50]
Sludge from Urban DWTP in Morocco	40.0	25.0	0.8	1.6	0.8	0.3	0.2	3.1	0.7	0.6	[140]
Sludge from Bangkhen DWTP in Thailand	24.6	58.9	-	1.5	0.6	0.1	-	0.4	1.2	7.3	[141]
Sludge from DWTP from Egypt	16.6	34.4	2.6	0.4	4.5	0.9	0.2	8.2	0.7	0.2	[56]
DWTP sludge in the study	**24.4**	**42.2**	**0.4**	**2.3**	**5.3**	**1.5**	**0.3**	**3.5**	**-**	**-**	

4.2.2. XRD Analysis

XRD analysis for the DWTP sludge was conducted at the University of Moratuwa. XRD analysis was conducted to identify the chemical compounds of the DWTP sludge [138]. Three sludge samples were sun-dried and powdered. The powdered samples were sieved through a 100μm sieve to prepare a sample for the test (Figure 4.2 (a)). XRD analysis was conducted using the X-ray diffractometer- Eco D8 Advance for Structure Analysis (Figure 4.2 (b)). The test was conducted with the parameters of Co, Cu and Mo radiation, 2theta from 20◦ to 130◦, step size of 0.03◦, 10s per step and the 30 min total run time for each sample. Bruker diffraction EVA version 4.2 software package was used to collect data and interpret the diffraction patterns of the samples (Figure 4.2 (c)).

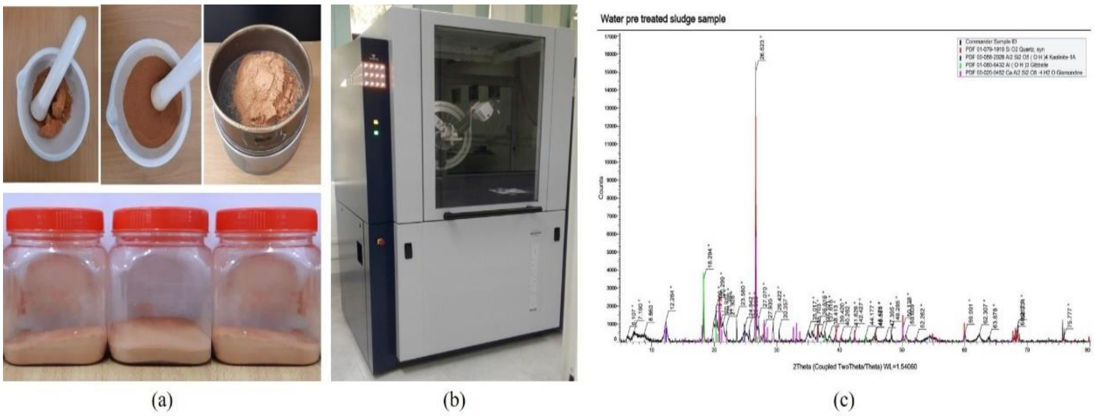


Figure 4.2: XRD analysis; (a) Sample preparation; (b) X-Ray Diffractometer; (c) XRD test report

Results and Discussion:

According to the XRD analysis results, chemical compounds of DWTP sludge were identified as, Kaolinite ($Al_2Si_2O_5(OH)_4$), Quartz (SiO_2), Calcite ($CaCO_3$) and Ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}(H_2O)_{26}$). Compared to the findings of previous research, it can be concluded that the chemical composition same as other clay and DWTP sludge samples.

Table 4.2: Chemical compounds of DWTP sludge

Sample	Clayish Earth	Yellow & Red clay	DWTP sludge	Sludge from Giza DWTP	DWTP sludge	**Sludge in the study**
Country	Portugal	Turkey	Brazil	Egypt	Spain	**Sri Lanka**
Chemical Compounds	Quartz Illite Kaolinite Hematite Dolomite Calcite	Kaolinite Illite	Kaolinite Quartz	Quartz Albite	Mica Calcite Quartz chlorite	**Kaolinite Quartz Calcite Ettringite**
Reference	[115]	[113]	[142]	[143]	[144]	

4.2.3. Heavy Metal Analysis

Heavy metals are present in nature below the harmful level, when heavy metal concentration increases the harmful level, it creates adverse environmental impacts. Heavy metals do not generate through natural phenomena; heavy metals are added to the natural environment through anthropogenic activities [145]. Surface water reservoirs in some countries and some locations are contaminated with heavy metals due to industrial disposals and soil contamination. However, when a DWTP collects water from a surface water source that is contaminated with heavy metals, the sludge generated from the plant included heavy metals. Because heavy metals have relatively high density compared to water and are settled with sludge in the purification process [146]. According to the literature, some DWTP sludge contaminated with heavy metals was identified as shown in Table 4.3. Contaminated sludge with heavy metals cannot be directly discharged or incorporated into the material production process [147].

There is a ‘maximum permissible limit’ define for heavy metals in each application of materials. The maximum permissible limit presents the applicable limit of heavy metals without harm. Exceeding the permissible level creates contamination associated with potential health risks or ecological risks [148]. The maximum permissible limit differs with the country, product, location, climatic conditions and purpose. Therefore, the contaminated sludge with heavy metals should be treated up to an acceptable level before discharge; also, in the literature, it was identified that sintering sludge above 1000ºC can immobilize heavy metals in the material. But all these options are high-cost processes [31]. Therefore, it is important to analyze the heavy metal concentration of the DWTP sludge.

ICP-MS Analysis:

ICP-MS analysis was conducted with the collaboration of NWSDB and ITI to analyze the heavy metal concentration of the DWTP sludge. Samples were prepared according to the nitric acid digestion standard method. A 5g portion of the sample was weighed into a PTFE beaker, and 10mL of HNO_3 and 5ml of H_2O_2 were added. The mixture was heated on a hot plate. The residue was then dissolved in 25ml of deionized water. The solution was filtered and diluted into a 50ml and analyzed using NIOX300D inductively coupled plasma mass spectrometry. Test conducted with parameters as; 20-30min stabilization, focus lens and radio frequency power at 1550 W to minimize interference effects and to maximize the signal, carrier gas in auxiliary flow at 0.8 mL/min and nebulizer flow of 1.0 mL/min and 5.3 mL/min.

Table 4.3: Contaminated DWTP sludge with heavy metals and identified solutions in the literature

Reference	Classification	Concentration	Sludge use	Main finding
[149]	Non-hazardous	Low	Ceramic brick	Slight increase in Cd concentration at the increased firing temperature
[28]	Hazardous	High As and Fe content	Ceramic brick	Above 3% sludge-mix showed leaching
[35]	Non-hazardous	High Al content	Lightweight composite concrete	Al concentration above that established by the Brazilian standard
[31]	Non-hazardous	Low	Lightweight aggregate	The concentration of heavy metals below the regulatory thresholds
[150]	Non-hazardous	Low	Ceramsite	The concentration of heavy metals below the regulatory thresholds
[47]	Hazardous	Very high Pb, Zn, Cd, Ni, Cr and Cu content	Eco-cement clinker	The concentration of heavy metals below the regulatory thresholds
[151]	Non-hazardous	High Cr and Zn content	Cement clinker	The concentration of heavy metals below the regulatory thresholds
[48]	Non-hazardous	Very low	Concrete mix	The concentration of heavy metals below the regulatory thresholds
[59]	Non-hazardous	High Fe content	Paving tile	The concentration of heavy metals below the regulatory thresholds
[152]	Not reported	High Zn, Fe and Cr content	Geopolymer	Slight increase in Zn, Fe and Cr concentration when SiO2/Al2O3 ratio increases

Results and Discussion:

According to the results of the ICP-MS test, Cadmium (Cd) (<0.1ppm), Lead (Pb) (4.3ppm), Mercury (Hg) (<0.1ppm) and Arsenic (As) (0.9ppm) were identified as heavy metals in the sample. When comparing the heavy metal concentration with the findings of literature it can be concluded that the sludge has very few heavy metals with very low concentrations; as shown in Table 4.4. To identify the potential impact of the present heavy metals in the wall putty development process, the values were compared with the maximum permissible limits defined by Sri Lankan legislation for wall top coatings. As observed, the heavy metal concentration of the alum sludge is lower than the maximum permissible limit as shown in Figure 4.3. Therefore, the heavy metal concentration presence of the sludge has no potential harm in the sense of human health and the ecological.

Table 4.4: Heavy metal concentration of DWTP sludge

Source	Sample	As	Ba	Cd	Cr	Cu	Hg	Ni	Pb	Zn
[50]	Clay from quarries of Spain (mg/kg)	0.23	499	0.2	81	22.3			36	98
	DWTP sludge from St Joan Despí DWTP in Spain (mg/kg)		495	1.4	93	62	0.08	34	74	195
	Reference value based on uncontaminated soils in Netherland (mg/kg)	29	200	0.8	100	36	0.3	35	85	140
[146]	Agricultural soils from Southwestern Nigeria (mg/kg)	50		0.03	200	9.14		15.24	28.37	31.17
	Permissible limit (mg/kg)	2.4		10	81.2	50		100	200	250
[153]	Raw alum sludge from DWTP in Malaysia (mg/l)	0.02	0.06	0.01	0.02	0.47		0.05	0.03	0.21
[154]	Sintering red mud from alumina refining plant in Guizhou, China (ppm)	267.3	212	27.1	537.8	78.2	67.3	984.9	56.6	103.2
	Bayer red mud from alumina refining plant in Guizhou, China (ppm)	246.7	197.2	14.4	416.9	213.6	58.7	578.6	48	76.3
	DWTP sludge in the study (ppm)	**0.9**	**-**	**<0.1**	**-**	**-**	**<0.1**	**-**	**4.3**	**-**
	The maximum permissible limit defines by Sri Lankan legislation (ppm)	**1.4**	**-**	**2**	**-**	**-**	**0.5**	**-**	**6**	**-**

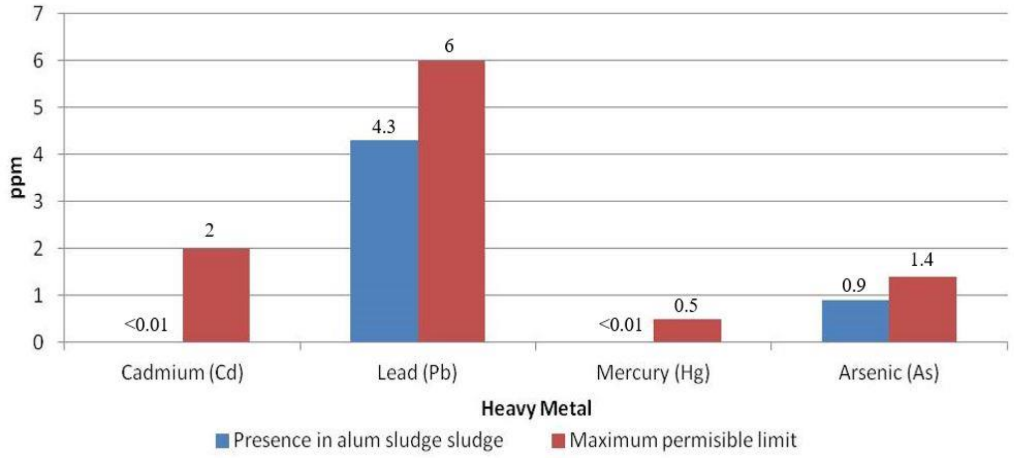


Figure 4.3: Heavy metal concentration of sludge and maximum permissible limits

4.3. Observational Shrinkage of DWTP Waste Alum Sludge

Shrinkage is one of the elementary properties of clay-based materials. According to the USCS soil classification system, DWTP sludge is categorized under clay. Therefore; the determination of the shrinkage of DWTP sludge is a major requirement before being used as a raw material. Shrinkage can be measured in two ways; volumetric shrinkage and observational shrinkage, as shown in Figure 4.4.

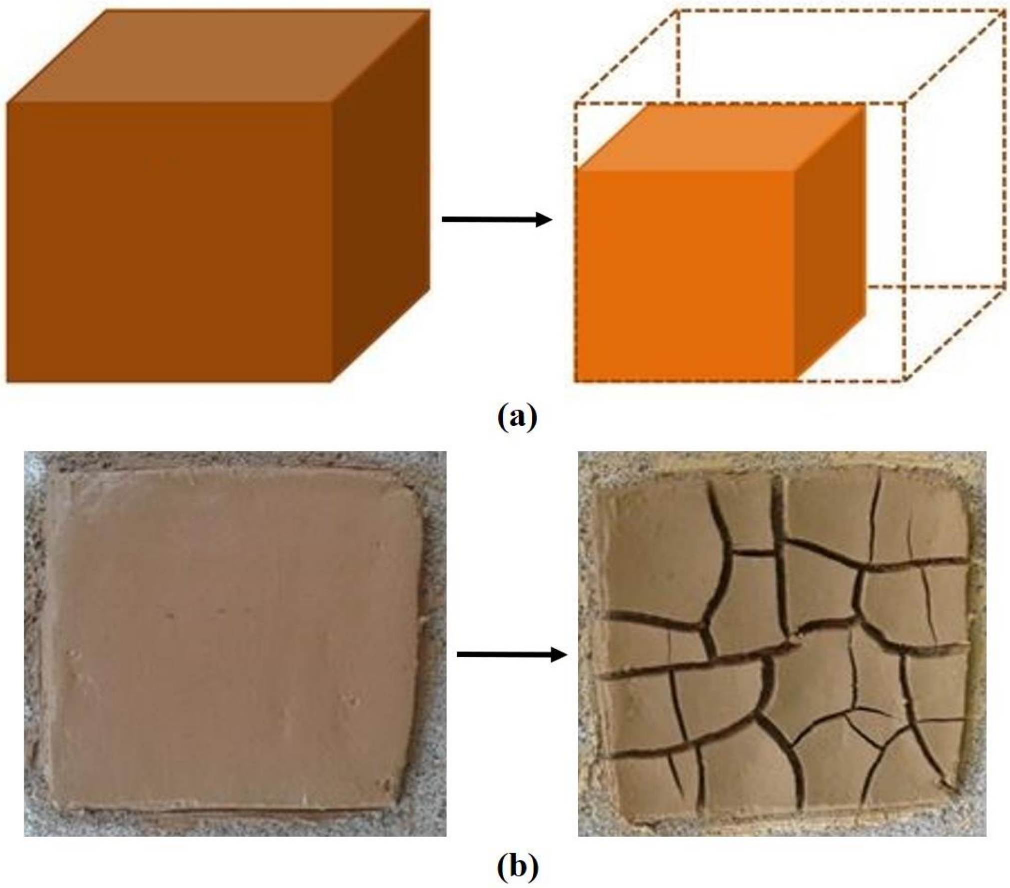


Figure 4.4: Measuring shrinkage [113]**; (a) Volumetric shrinkage (b) Observational shrinkage**

Volumetric shrinkage measures the loss in volume of clay-based mixtures after drying, and it depends on the clay content, moisture content and particle size [113]. Observational shrinkage is the drying shrinkage, after application of a clay-based mixture in a thin layer. Due to the drying shrinkage of the mixture drying cracks occurred on the surface after drying. By measuring crack formation time and analyzing the severity of the cracks observational shrinkage can be measured and compared.

Observed shrinkage of the mixture can be deduced by comparing the cracks formed on the surface in wet and after dried. Observational shrinkage test results reveal the adhesiveness of the mixture. The crack pattern and intensity of cracking can characterize the nature of the internal bonds of the mixture; and the bonding strength between the mixture and the substrate can characterize the adhesiveness of the mixture [113],[114].

Observational shrinkage test:

An observational shrinkage test was conducted to determine the drying shrinkage of DWTP wet sludge. In the literature, shrinkage was tested according to DIN 18947,2013 standards and the observational shrinkage was conducted by applying the wet wall finishing mix to the compatible base material [113]. In the test, cement sand plaster panels were cast with the dimensions of 1inch×1feet×1feet, to use as the base; as shown in Figure 4.5. Sand and cement were mixed in a 5:1 ratio and mixed with water. Casted samples were unmoulded after 24 hours and dried for seven days. After plaster panel preparation wet sludge was applied as a thin layer with 1mm thickness in an area of 8inches×8inches using a scraper. Three replicates were applied and dried for 24 hours and drying cracks were observed. To analyze drying crack initiation depends on the applying area, in the next step wet sludge was applied with three different areas (3inches×3inches; 4inches×8inches; 8inches×8inches); as shown in Figure 4.7.

Figure 4.5: Sand cement plaster panel casting for observational shrinkage test

Results and Discussion:

Drying cracks of each sample were observed after 24 hours and observed that observational shrinkage doesn’t change with the applied area. Samples applied with different areas, cracked with the same severity. Drying cracks of the wet sludge samples applied on the plaster base with an area of 8inches×8inches were observed to determine the observational shrinkage and the results are shown in Figure 4.6. according to the test results, it was observed that the sludge mix was completely cracked and detached from the plaster surface. According to the literature the wet sludge mix's adhesiveness and binding properties should be improved to develop a wall putty mix.

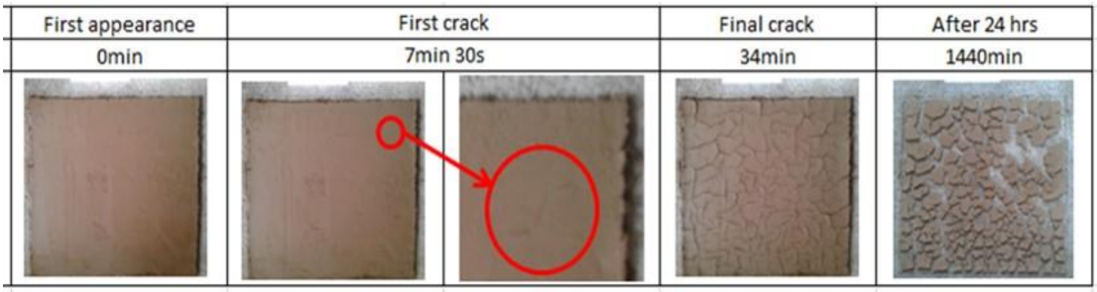


Figure 4.6: Observational shrinkage test results

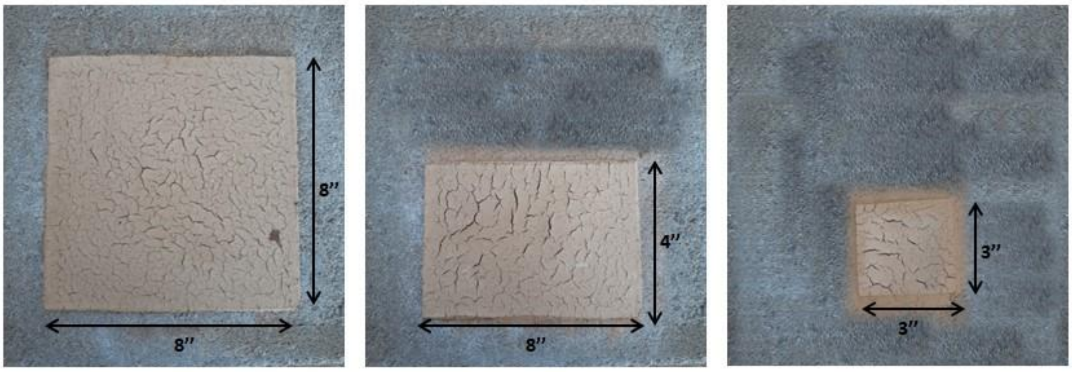


Figure 4.7: Observational shrinkage with different application areas

4.4. Physical Properties of DWTP Waste Alum Sludge

According to the literature DWTP sludge's physical properties depends on;

- The geographical location of the plant
- Climatic conditions
- Raw water quality
- Suspended solids
- Treated water quality
- Water treatment process
- Coagulant type
- Chemical added in the treatment process
- Sludge treatment process

Out of these factors, the geographical location of the plant, treated water quality, coagulant type, chemicals, conditions of the water treatment process and sludge treatment process remain constant with time. But the climatic conditions, raw water quality, suspended solids and chemical application dosage change with time. Considering raw water quality and suspended solids, plat daily dosage of chemicals and coagulant is decided. Therefore, physical properties variation of sludge considering those variable factors should be studied. For that sludge, samples were collected daily from the Biyagama DWTP sludge treatment plant for six months duration (from 1st of January to 30th of June 2020) (Figure 4.8). Collected samples in plastic containers were transported to the University of Moratuwa and laboratory tests were conducted. In the DWTP, chemicals (Alum, Lime, Chlorine and Polymer) are added daily for the water purification process. Chemical addition data and climatic data (Highest and Lowest temperatures of the day and Humidity) of each day were collected from Biyagama DWTP data records. Recorded data (Appendix – I) were statistically analyzed to identify the variation of physical properties of sludge with chemicals apply in the plant and climatic factors. Statistical analysis was performed using ‘Minitab 21’ statistical software.

Figure 4.8: Sludge samples collected from DWTP

4.4.1. Shrinkage variation with chemicals and climatic factors

According to the literature, the volumetric shrinkage test was conducted according to DIN 18947,2013 test standard [113]. The wet sludge sample was mixed using a mechanical mixture to avoid compaction of the sample during transportation. Three replicates from each sludge sample were cast in a mold oil applied metal mold with the dimensions of $70\times70\times70$ mm^3. Casted samples were unmoulded after 7 days and let to dry; as shown in Figure 4.9. Three-dimensional measurements were taken weekly until 35 days; where volume was constant after completely drying. Volumetric shrinkage was measured considering the difference between initial volume and dried volume after completely drying; as shown in Figure 4.10. The volumetric shrinkage of each mixture was calculated according to equation 4.1; where VS is volumetric shrinkage, V1 is the initial volume (70^3mm^3) and V2 is the final volume at the measuring date [17],[6]. The average of the shrinkage values of three replicates was calculated as the volumetric shrinkage of each sludge sample.

$$VS(\%) = \frac{V1 - V2}{V1} \qquad \text{Equation 4.1}$$

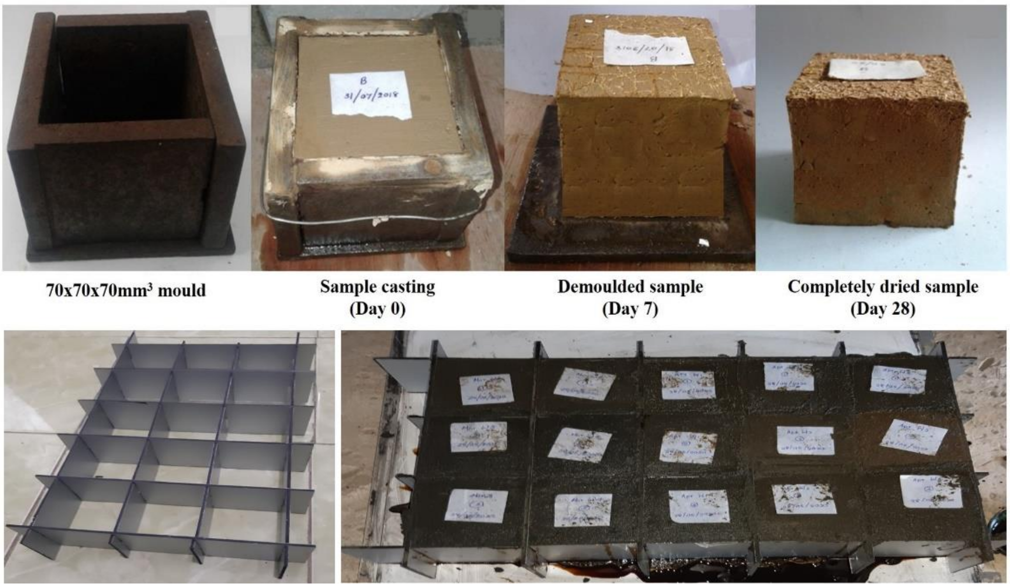


Figure 4.9: Casting cubes for volumetric shrinkage test

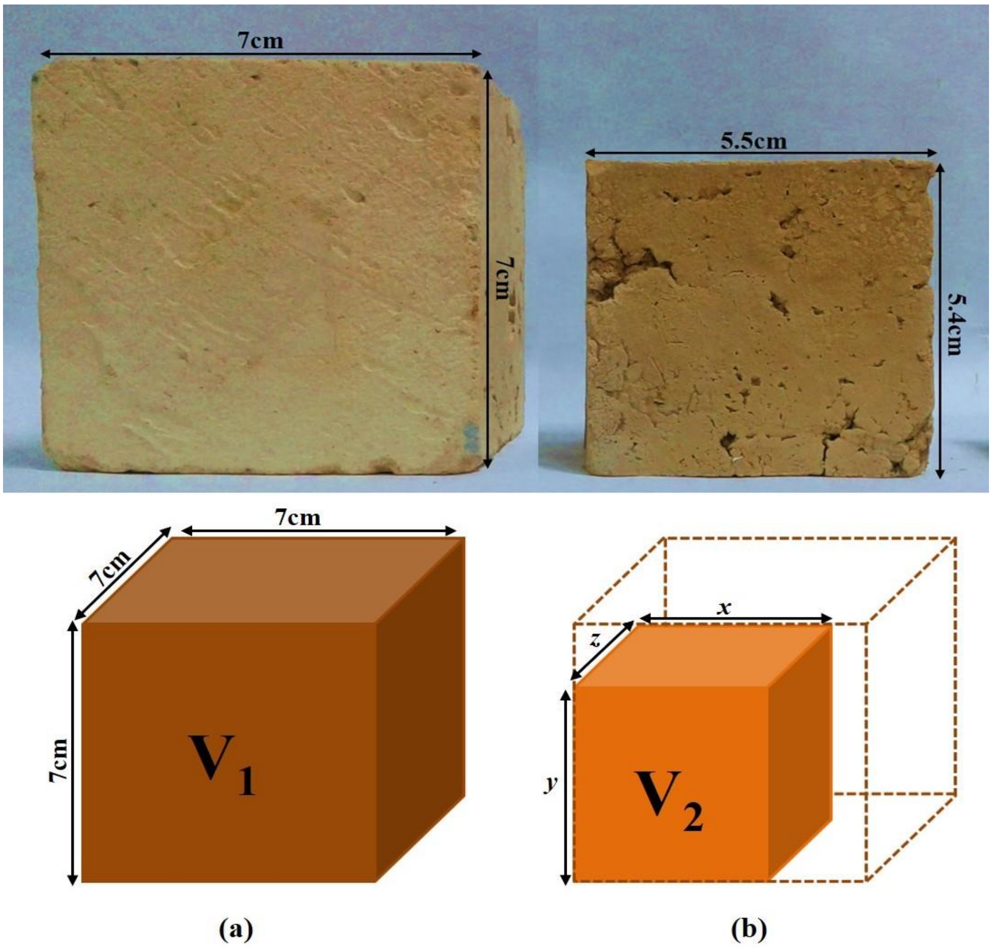


Figure 4.10: Volumetric Shrinkage Test; (a) Initial volume (b) Volume after completely dry

Results and Discussion:

According to the test results, the volumetric shrinkage variation of DWTP sludge is shown in Figure 4.11. according to the test results, DWTP sludge volumetric shrinkage varies between 59.82% and 93.62%; with an average value of 83.91%. When comparing the shrinkage value with previous findings; as shown in Table 4.5, DWTP sludge shrinkage is very high. According to the literature volumetric shrinkage depends on moisture content and clay content. Shrinkage of DWTP sludge is high due to the high moisture content and clay content.

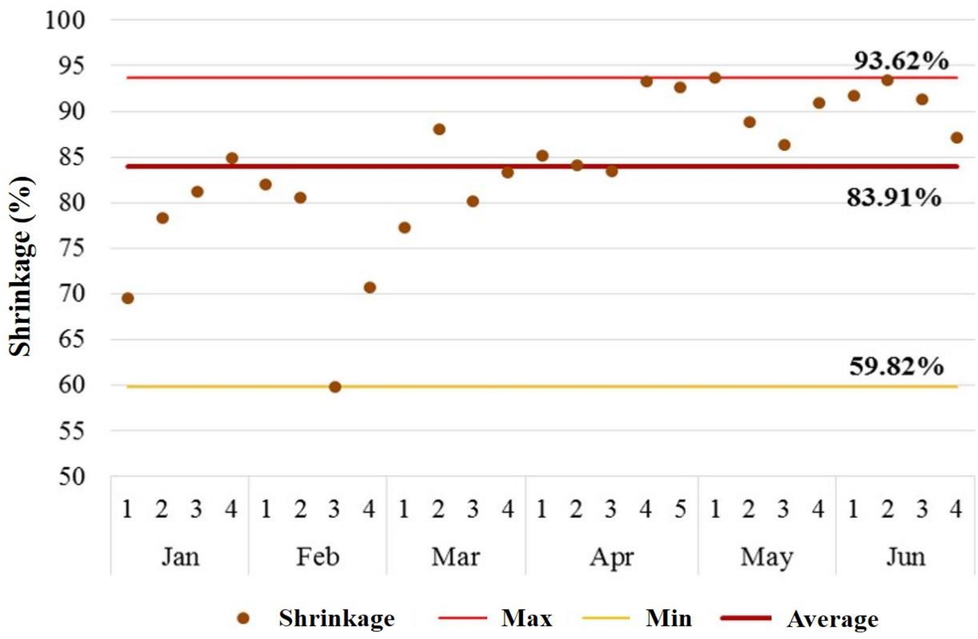


Figure 4.11: Volumetric shrinkage test results

Table 4.5: Volumetric shrinkage of DWTP waste alum sludge

	Shrinkage (%)	Reference
Yellow Clay from Turkey	14.4	[113]
Red Clay from Turkey	13.7	
Montmorillonite-rich clays from India	12 - 23	[155]
Sludge from Chin-Tan DWTP in Taipei	40 - 50	[149]
DWTP sludge in the study	**59.82 - 93.62**	

Regression analysis was performed, to statistically analyze the variation of sludge shrinkage, with chemicals applied in the DWTP and climatic conditions. According to the results, the p-value of humidity was lower than 0.05 ($P<0.05$) and the p-value of other factors was higher than 0.05 ($P>0.05$) (Appendix – II). Therefore, humidity (P-value = 0.006) is the only significant climatic factor effect on shrinkage variation of DWTP sludge, from selected factors. Other climatic factors and chemicals are not significant in the volumetric shrinkage variation of DWTP sludge. There is a positive correlation (Coef = +1.163) between sludge shrinkage and humidity (Figure 4.12). Scatterplots of sludge shrinkage versus chemicals and climatic factors are shown in Figure 4.13. According to the scatterplots regression line of humidity and shrinkage has the highest R^2 value (R^2 = 0.64). Humidity is the concentration of water vapor present in the air. Increasing humidity in the air reduces the moisture evaporation from the sludge; therefore; the moisture content of sludge is high on days with high humidity compared to low humid conditions. High moisture content results in high shrinkage of DWTP waste alum sludge. Therefore, increasing humidity increase the volumetric shrinkage of DWTP waste alum sludge.

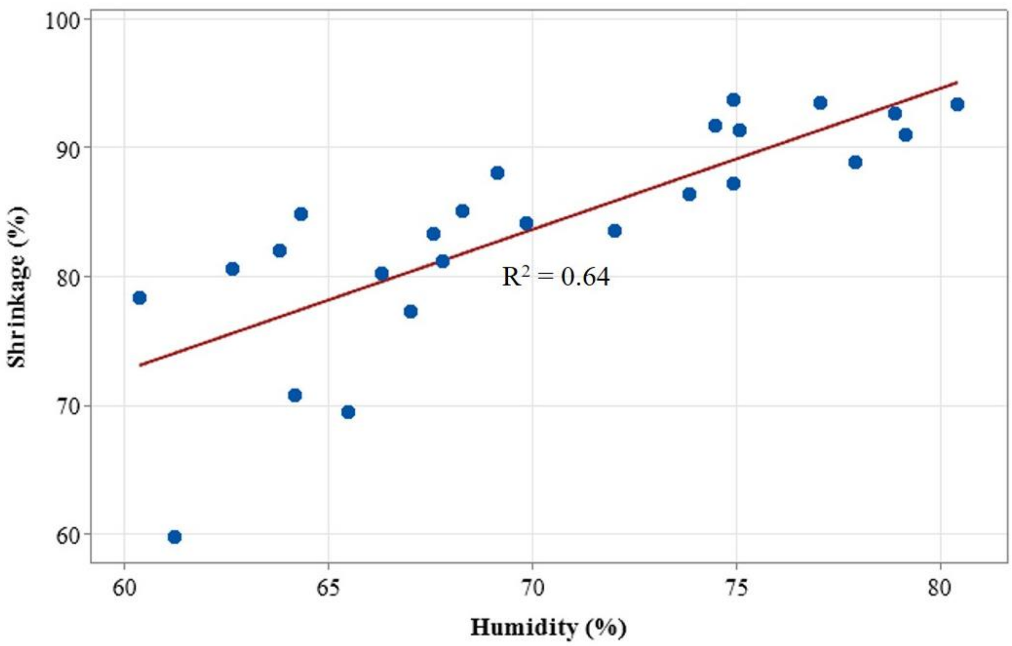


Figure 4.12: Scatterplot of sludge shrinkage Vs humidity

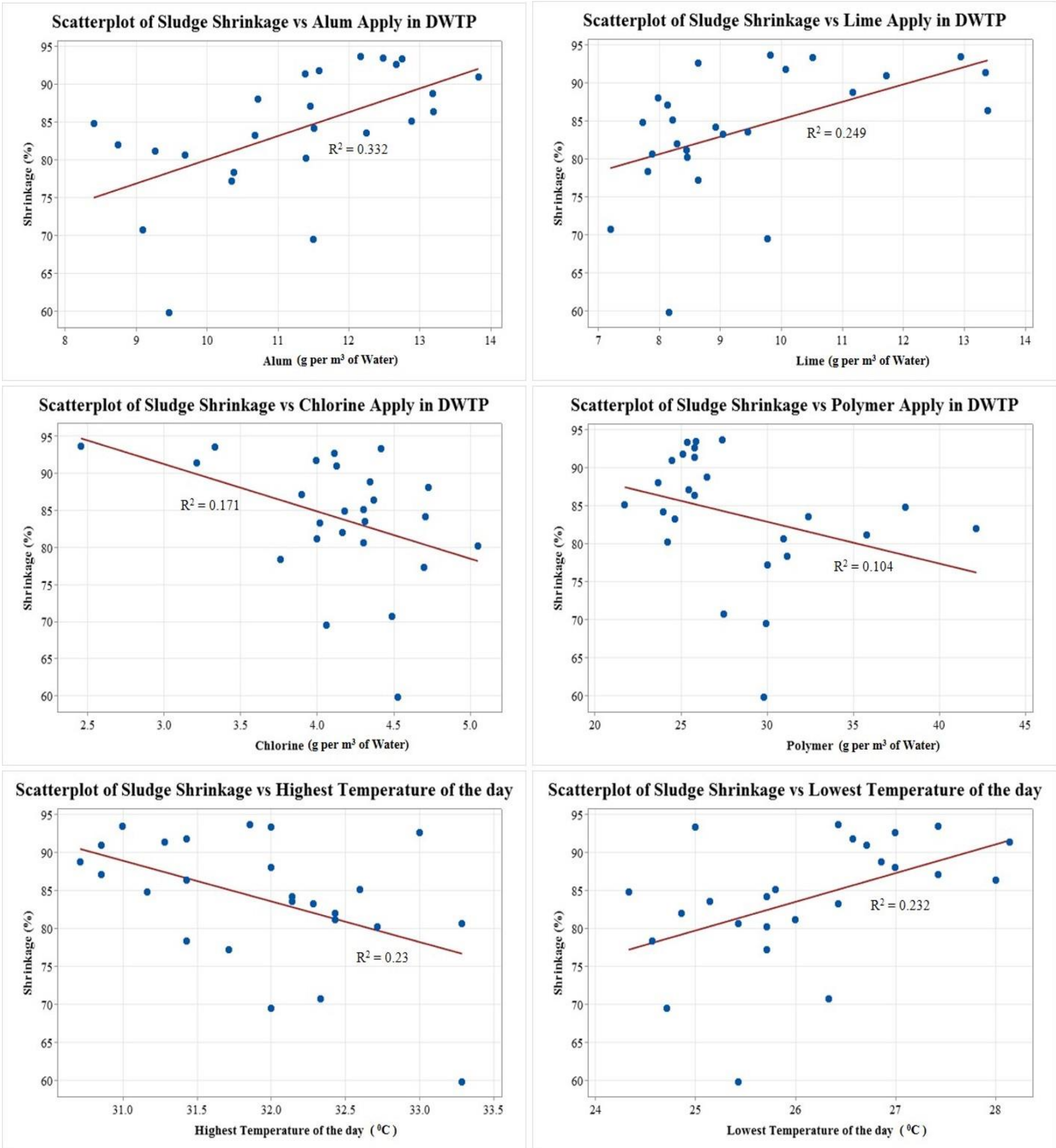


Figure 4.13: Scatterplots of sludge shrinkage Vs chemicals and other climatic factors

4.4.2. Moisture content variation with chemicals and climatic factors

The moisture content of each sample was tested by conducting the weight basis oven-dry method according to the ASTM D 2216-98 standard [135],[136]. Three replicates from each sample were tested and the average was calculated. The wet weight (Ww) of each sample was measured and recorded. After that, the samples were oven dried, at 110°C temperature for 24 hours; until the weight become constant. And then the dry weight (Dw) of each sample was measured and recorded. With the collected data, the moisture content of each sample was calculated according to equation 3.1; and the results are shown in Figure 4.14. According to the test results, the moisture content of DWTP sludge varies between the values of 62.31% and 84.72% with an average of 76.26%.

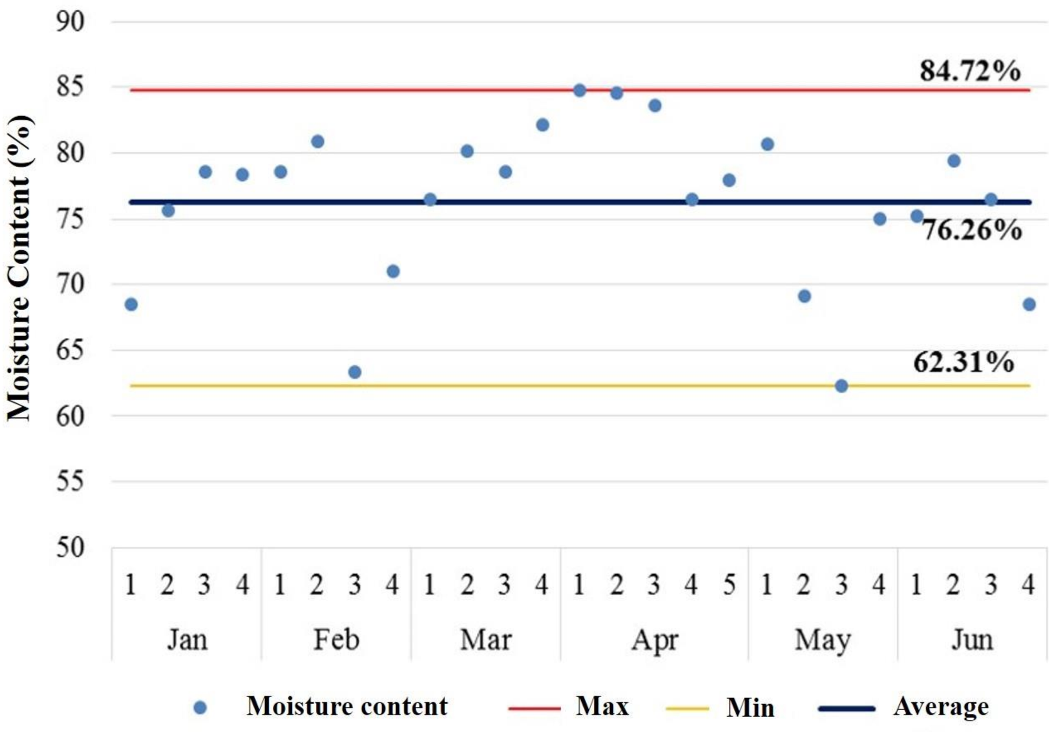


Figure 4.14: Moisture content test results

Regression analysis was performed to statistically analyze the variation of sludge moisture content with chemicals applied in the DWTP and climatic conditions. According to the results, all the p values were greater than 0.05 ($P>0.05$) (Appendix – III). Therefore chemicals (Alum, Lime, Chlorine and Polymer) and climatic factors (Highest and Lowest temperatures of the day and Humidity) are not significant factors effect on the moisture content of DWTP waste alum sludge. Scatterplots of sludge moisture content versus chemicals and climatic factors are shown in Figure 4.15. The sludge treatment plant process dewatered sludge; therefore, the moisture content of the dewatered sludge depends on the sludge treatment process conditions.

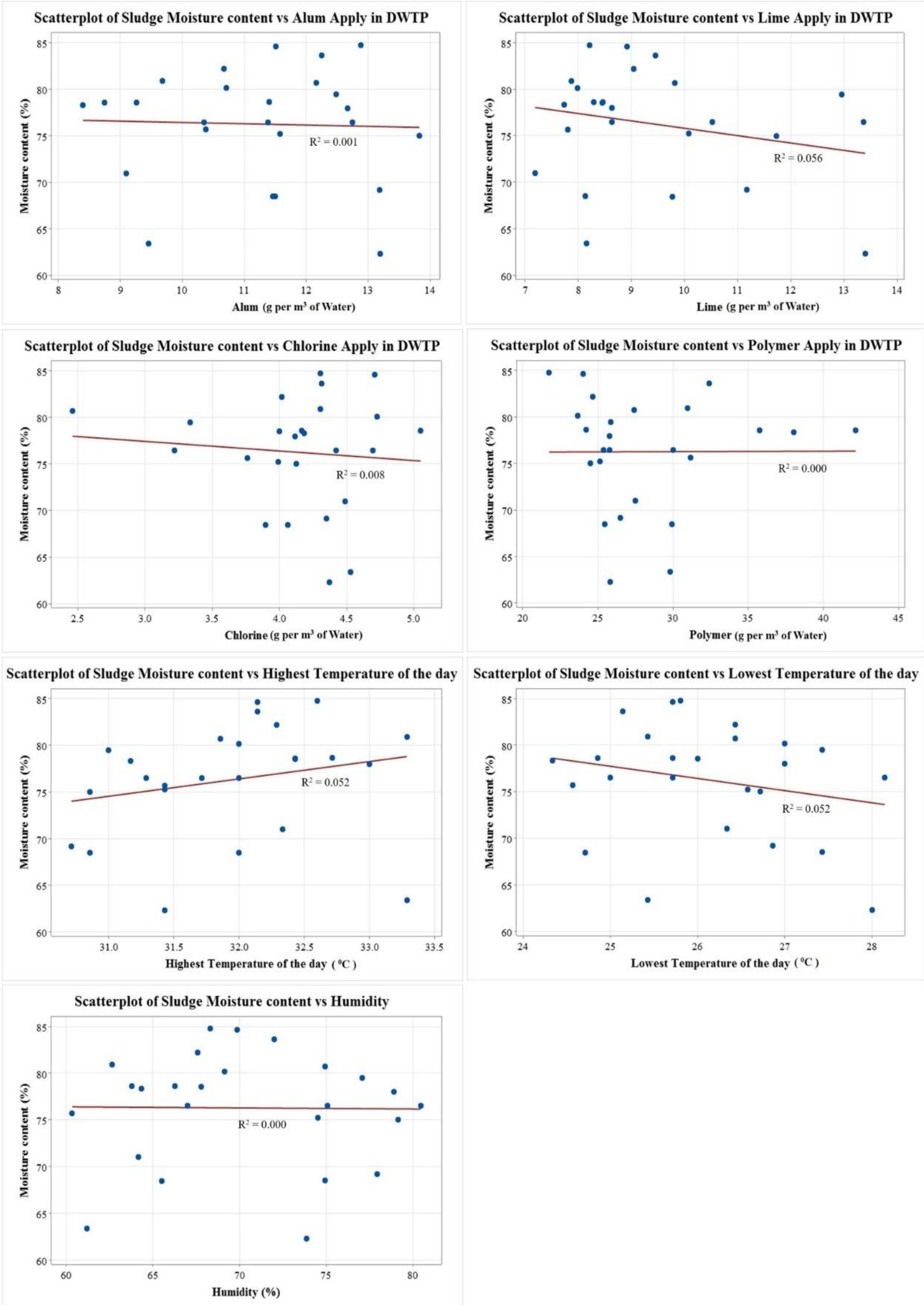


Figure 4.15: Scatterplots of sludge moisture content Vs chemicals and climatic factors

4.5. Summary

Biyagama DWTP was selected to collect sludge for the experiments. According to the findings of the previous chapter Biyagama DWTP sludge has the lowest moisture content and the highest solid content compared to sludge samples collected from Ambathale and Kandana DWTPs. Experiments in this chapter were conducted to analyze the putty properties of DWTP waste alum sludge. Therefore, laboratory experiments were conducted to study the chemical and physical properties of DWTP sludge. According to the chemical composition analysis (XRF analysis), Si (42.23%) is the main chemical element included in DWTP sludge; and the chemical element variation in the range of values identified in the literature. According to the XRD analysis test results, DWTP sludge chemical composition consists of kaolinite, quartz, calcite and ettringite. And also, the chemical composition is significant to the findings in the literature. According to the heavy metal analysis test results Cadmium (Cd) (<0.1ppm), Lead (Pb) (4.3ppm), Mercury (Hg) (<0.1ppm) and Arsenic (As) (0.9ppm) were identified in the sludge sample as heavy metals; but the available quantities are lower than the maximum permissible level define for wall top coatings in Sri Lanka. Therefore, there is no harmful impact on human health or the environment when developing a wall putty with DWTP waste alum sludge.

Laboratory tests were conducted to identify the shrinkage and moisture content of the sludge. According to the findings of the observational shrinkage test, observational shrinkage is not affected by the applied area and the DWTP sludge layer is completely cracked and detached from the plaster surface. Volumetric shrinkage of DWTP sludge varies between the values of 59.82% and 93.62% with an average of 83.91% according to the volumetric shrinkage test results. Moisture content test results reveal that DWTP sludge moisture content varies between the values of 62.31% and 84.72% with an average of 76.26%. Statistical analysis was performed to identify significant factors that affect on physical properties of the sludge. According to the statistical analysis results, it is revealed that humidity is the significant climatic factor effect on the shrinkage of DWTP sludge with a positive correlation.

CHAPTER 05: OPTIMIZING PUTTY PROPERTIES OF DWTP WET ALUM SLUDGE

5.1. General

After the identification of the putty properties of DWTP sludge, the next step of the research was to optimize the putty properties of raw wet sludge. According to the results of the laboratory experiments, DWTP sludge has high shrinkage; both observational and volumetric shrinkages, and low adhesiveness. To develop the raw sludge to a wall putty observational and volumetric shrinkages must be reduced and adhesiveness should be increased. Therefore, the next steps of the study were performed to enhance the putty properties of the wet raw sludge and the experimental procedures and results will be discussed in this chapter.

5.2. Selection of Additives

According to the literature, research studies were conducted to study the possible usages of DWTP sludge, as a raw material in the production industry. Different construction materials; such as bricks, roof tiles, lightweight aggregates, cement, concrete and geopolymers, were tested for incorporating DWTP sludge [23],[32],[57],[59]. Each research concluded that the integration of DWTP sludge with some products succeeded and did not succeed with some products; the shrinkage of DWTS was identified as the major issue of concern when used in the construction material production process [113].

Shrinkage is one of the elementary properties of the clay-based materials production process. Shrinkage can be measured in two ways; volumetric shrinkage and observational shrinkage [113]. Observational shrinkage is measured as the drying shrinkage after application of clay plasters and the volumetric shrinkage measures loss in volume after drying quantitatively. Shrinkage depends on the clay content, moisture content and particle size. According to historical evidence natural fibers, binders and additives were mixed with clay plasters to overcome shrinkage [95],[102]. As the DWTP sludge is characterized under clay; according to the USCS soil classification, it is required to reduce shrinkage. The effectiveness of different additives to reduce the shrinkage of DWTP sludge can be studied before being used as a raw material [23],[113].

There is historical evidence available all over the world for soil and mud-based plasters and wall finishes which were lasting for thousands of years. According to the historical evidence, natural additives were added to soil mixtures to overcome the shrinkage as shown in Table 5.1. A detailed inventory of additives was prepared after referring literature. From those, a few additives were selected for the study considering the availability and preferable properties.

Table 5.1: Additives in historical soil-based plasters

Source	Soil Plaster Type	Country	Additives
[95]	Plaster in Caves; Exterior and Interior	Bhaja Caves, India	Raw soil, Slacked lime, Rice husk, and Proteinaceous adhesive
[96]	Wall Plaster	Mali and African Countries	Wet mud fermented with rice husks and proteins (milk and animal blood)
[30]	Blood Lime Plaster	Europe, China, and Mexico	Animal blood and lime
[102]	Plaster of Sigiriya Fresco	Sri Lanka	Paddy husk and coconut fiber

5.3. Physical Additives to Improve Putty Properties

DWTP sludge should be with low shrinkage and high adhesiveness to apply as a wall putty mix. As the sludge has high shrinkage, the wet mix should be improved to reduce shrinkage. Physical additives are used to reduce shrinkage in historical soil-based plasters. Therefore, the shrinkage reduction with physical additives was quantitatively measured and analyzed in this section. For the test few different physical additives were selected; including sand and three natural fibers.

5.3.1. Analyzing the effectiveness of sand

Sand is the most commonly used aggregate in the construction industry and it is a naturally available material in Sri Lanka [156]. River sand is used in this study and the sand was sun-dried to remove moisture. The dried sand sample is sieved from a 300μm sieve; to eliminate coarse particles and have a uniform aggregate size distribution in all samples (Figure 5.1).

Figure 5.1: Sieved sand for the test

5.3.2. Volumetric shrinkage variation of wet alum sludge with sand

Nine different mixtures were prepared by mixing sand and wet sludge according to the mix design shown in Table 5.2. Mixtures were prepared by mixing them in a mechanical mixer (Figure 5.2). The volumetric shrinkage test was conducted according to DIN 18947,2013 standards [113]; as described in the previous chapter. Three cubes (three replicates) from each mix were cast to measure volumetric shrinkage. Three-dimensional measurements of each cube were taken after 4weeks (after complete drying of the cubes) and volumetric shrinkage was calculated using Equation 4.1.

Figure 5.2: Mixing with mechanical mixer and cube casting for volumetric shrinkage test

Table 5.2: Mixing ratios of sand and sludge

Mix	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9
Sludge (%)	100	95	90	80	70	60	50	40	30
Sand (%)	0	5	10	20	30	40	50	60	70

Results and Discussion:

Volumetric shrinkage variation with different sand percentages is shown in Figure 5.3. According to the test results, shrinkage becomes 0 at 70% of sand. Possible mixtures to conduct the volumetric shrinkage test could be prepared only up to 70% of sand; cubes required for the volumetric shrinkage test were unable to be cast with mixtures beyond 70% sand. Particle size distribution (clay/sand ratio) of the mix affected the workability and the clay content affect the adhesiveness of clay-based mixtures. Therefore, wet sludge mixtures over 70% of sand are not workable enough to cast cubes as the increasing sand percentage lowers the adhesiveness of the mix [113],[117]. Volumetric shrinkage of wet sludge is reduced with increasing sand but reduces the adhesiveness of the mix. Although sand positively effects to reduce shrinkage it is not effective to improve the adhesiveness of DWTP wet sludge. To determine the optimum sand mixing ratio with wet sludge, a ball drop test was conducted.

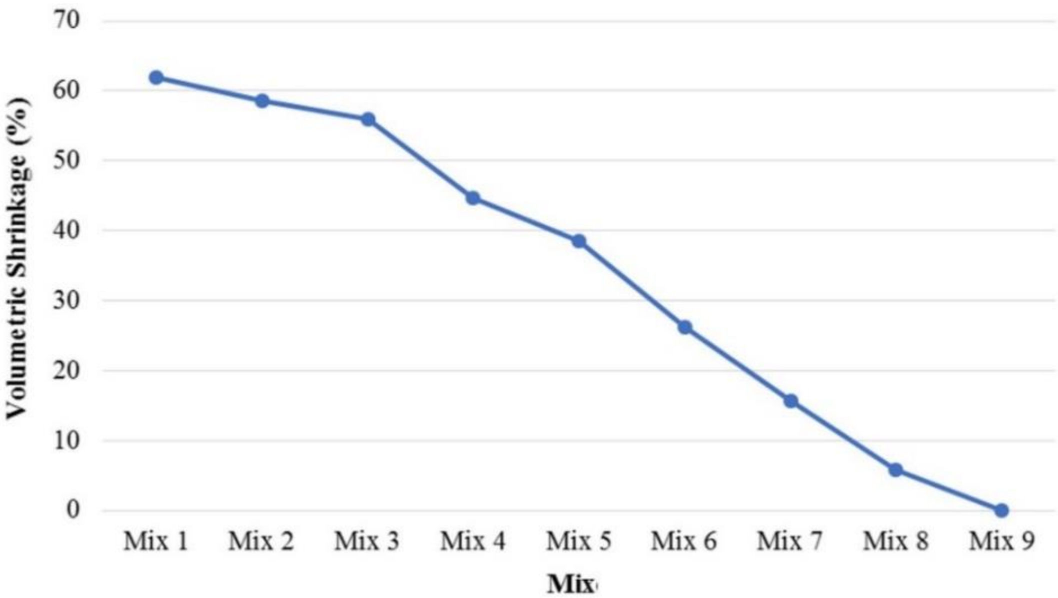


Figure 5.3: Volumetric shrinkage variation with sand

5.3.3. Analyzing optimum sand/wet alum sludge mixing ratio (Ball drop test)

Clay/sand ratio of the mixture effect the shrinkage and adhesiveness of the mix. Increasing sand percentage reduce shrinkage and adhesiveness also; therefore, the optimum sand/wet sludge mixing ratio should be identified. The ball drop test is one of the field tests used to predetermine the effective clay sand mixing ratios to develop clay-based plasters [113]. In this test, a ball of the mixture with around 4cm diameter is released freely from a height of 1.5m, onto a flat surface. Various results can be observed in this test, as shown in Figure 5.4. The mixtures with high clay content resulted in a dropped sample with a shiny and smooth surface and slightly cracked with no cracking (Figure 5.4 (a)). If the mixture is poor in clay content, results in a dropped sample with a dull surface and fragments into rubbles (Figure 5.4 (b)). The mixture with optimum clay content results in a dropped sample with a semi-shiny surface with a small number of surface cracks and no fragmenting (Figure 5.4 (c)). A mixture with optimum clay and sand ratio is suitable to develop a plaster. A ball drop test was conducted for three replicates of all nine mixtures and the test results are shown in Figure 5.5.

Results and Discussion:

According to the ball drop test results, optimum clay and sand content was observed between the sand percentage of 30% to 60%. Below 30% of sand percentage, the clay content is high in mixtures and beyond 60% clay content is low; and the mixtures were not consistent with suitable putty properties. Therefore, wet sludge mixtures with a sand content of 30% to 60% were suitable for a wall putty mix. However, the identified mixture has optimum shrinkage performance, but the adhesiveness should be improved in the mix to develop a wall putty.

(a) High clay content (b) Poor clay content (c) Optimum clay content

Figure 5.4: Ball drop test results demonstration [113]

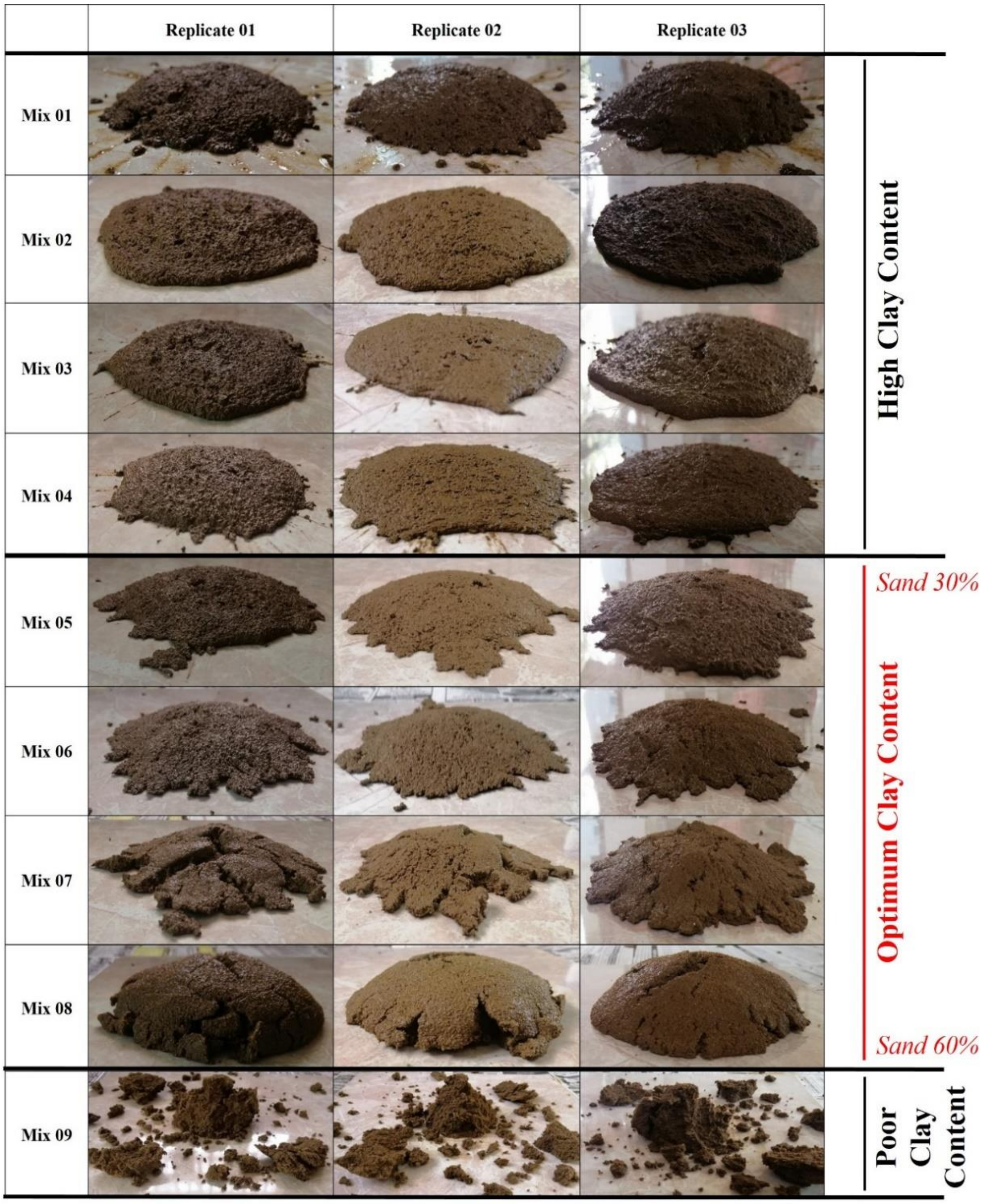


Figure 5.5: Ball drop test results

5.3.4. Analyzing the effectiveness of natural fibers

To study the effect of physical additives on the volumetric shrinkage of sludge, natural fibers were also tested. According to the literature, it was identified that natural binders were added in historical soil-based plasters to reduce shrinkage. And also, it was identified that fiber type, fiber length and concentration depend on the effectiveness of natural fibers [157][158]. Natural fibers used as additives in previous research studies and historical plasters were studied through a literature survey. A natural fiber inventory was prepared to refer to literature; as shown in Table 5.3, and selected possible three natural fiber types for the test. Three fibers were selected considering availability, cost, production process and intrinsic properties. Sugarcane fiber, Coir fiber and Banana fiber (Figure 5.6) were selected for the test.

Table 5.3: Natural fiber inventory

Natural fiber	Density (g/cm^3)	Tensile Strength	Young's modulus	Elongation (%)	Reference
Coir	**1.15-1.46**	**95 - 593**	**2.8 - 6**	**15 – 51.5**	[159] [160] [161]
Kenaf	1.2 – 1.45	223- 930	14.5 - 53	1.5 – 6.9	
Flax	1.38- 1.5	343 - 2000	27 - 103	1.2 – 3.3	
Bamboo	0.6 – 1.4	140 - 1000	11 – 35.91	1.4 – 3.7	
Abaca	1.5	400 - 980	6.2 - 20	1 - 10	
Jute	1.23- 1.5	187 - 800	8 - 78	1 – 3.1	
Sisal	1.2 – 1.5	363 - 855	9 - 38	1.9 - 7	
Ramie	1 – 1.55	220 - 1000	24.5 - 128	1.2 - 4	
Cotton	1.5 – 1.6	287 - 800	5 - 13	3 - 10	
Banana	**1.35**	**500 - 914**	**8 - 32**	**1.5 - 10**	
Hemp	1.35-1.5	270 - 1110	23.5 -90	1 – 4.5	
Pineapple	1.5	170 - 1627	1.5 – 82.5	1 - 3	
Henequen	1.2	430 - 570	10.1 – 16.3	3.7 – 5.9	
Bagasse	**1.2 – 1.25**	**20 - 290**	**17 – 27.1**	**1 - 3**	

Figure 5.6: Natural fibers selected for the study

5.3.5. Volumetric shrinkage variation of wet alum sludge with natural fibers

Selected fibers were collected in dry conditions. The fibers were cut in 10mm lengths to obtain uniform fiber length in the samples. According to the literature 10mm fiber length was concluded as the optimum fiber length for fiber additives in soil-based plasters [162],[155]. Selected fibers were cut using a 'Laboratory Cutting Mill SM 200' (Figure 5.7). Fiber samples were cut into small pieces and fed into the cutting mill. The mill operates at 50Hz speed and the cut fibers were collected after being sieved from the bottom sieve with the size of 10mm.

(a) (b)

Figure 5.7: Cut natural fiber samples; (a) Laboratory cutting mill SM 200; (b) Cut fiber samples with 10mm

Ten different mixtures were prepared by mixing fiber and wet sludge in different percentages and three sets of samples were prepared for tree fiber types as shown in Table 5.4; mix 1, was the controller which includes only sludge. Sludge and fiber amounts were measured by weight according to the percentages. A volumetric shrinkage test was conducted according to DIN 18947,2013 standards [113]; as described in the previous chapter, for three replicates of each mix, an average value was calculated for each mix.

Table 5.4: Mixing ratios of natural fibers and sludge

Sugarcane Fiber			Coir Fiber			Banana Fiber		
Mix	**Sludge (%)**	**Fiber (%)**	**Mix**	**Sludge (%)**	**Fiber (%)**	**Mix**	**Sludge (%)**	**Fiber (%)**
1	100	0	**1**	100	0	**1**	100	0
2	99	1	**2**	99	1	**2**	99	1
3	98	2	**3**	98	2	**3**	98	2
4	97	3	**4**	97	3	**4**	97	3
5	96	4	**5**	96	4	**5**	96	4
6	95	5	**6**	95	5	**6**	95	5
7	94	6	**7**	94	6	**7**	94	6
8	93	7	**8**	93	7	**8**	93	7
9	92	8	**9**	92	8	**9**	92	8
10	91	9	**10**	91	9	**10**	91	9
11	90	10	**11**	90	10	**11**	90	10

Results and Discussion:

Volumetric shrinkage variation with different fiber types and percentages is shown in Figure 5.8. According to the test results, fiber can be effectively mixed up to 10% by weight with DWTP sludge. Volumetric shrinkage of the sludge is reduced when increasing the fiber percentage of the mixture. Shrinkage reduced gradually up to 8% and shrinkage reduction rate reduced beyond 8% can be observed for every fiber type. And 8% was identified as the optimum fiber mixing ratio. When comparing three fiber types, the lowest shrinkage is recorded with Banana fiber while the highest shrinkage is recorded with Sugarcane fiber. Therefore, Banana fiber is identified as the most effective fiber type to reduce volumetric shrinkage of DWTP sludge when compared to the other two fiber types. But then consider the mass production of these fibers, sugarcane fiber is a waste product generated in the sugar production process and banana and coir fiber is produced as an industrial raw material. Therefore, there is high potential for to use of sugarcane fiber on a mass scale in putty production with wet alum sludge than the other two fiber types.

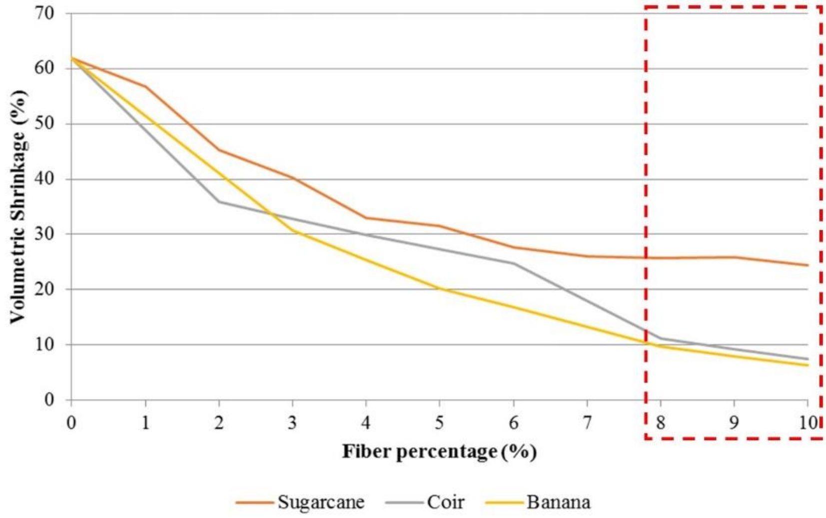


Figure 5.8: Volumetric shrinkage variation with natural fiber type

5.4. Binders to Improve Putty Properties

Binder is any material or substrate which holds other materials together to form a bond mechanical or chemical, by adhesion or cohesion [158],[163]. Binders can tightly bind clay particles of the sludge to overcome the shrinkage. Binders can be simply classified as;

- Organic - bitumen, animal and plant glues, polymers
- Inorganic - lime, cement, gypsum, liquid glass

According to the literature it was found that natural binders extracted from plant-based materials were added to soil mixtures to develop soil-based plasters [164]. Historical evidence is available all over the world for soil-based plasters which last for thousands of years. In Sri Lanka, historical evidence was found in the 'Sigiriya' rock castle built by King Kashyapa in the 5th century AD. The mirror wall and the frescoes were soil-based plasters that last for thousands of years [165].

After analyzing literature on the compositions of historical soil-based plasters, three natural binders and one synthetic binder were selected for the study; as shown in Figure 5.9. Natural binders were extracted according to the indigenous technologies and the styrene-acrylic binder was collected from the available market; the binder was selected as the synthetic biner of the study, considering its wide usage in the paint production industry [163].

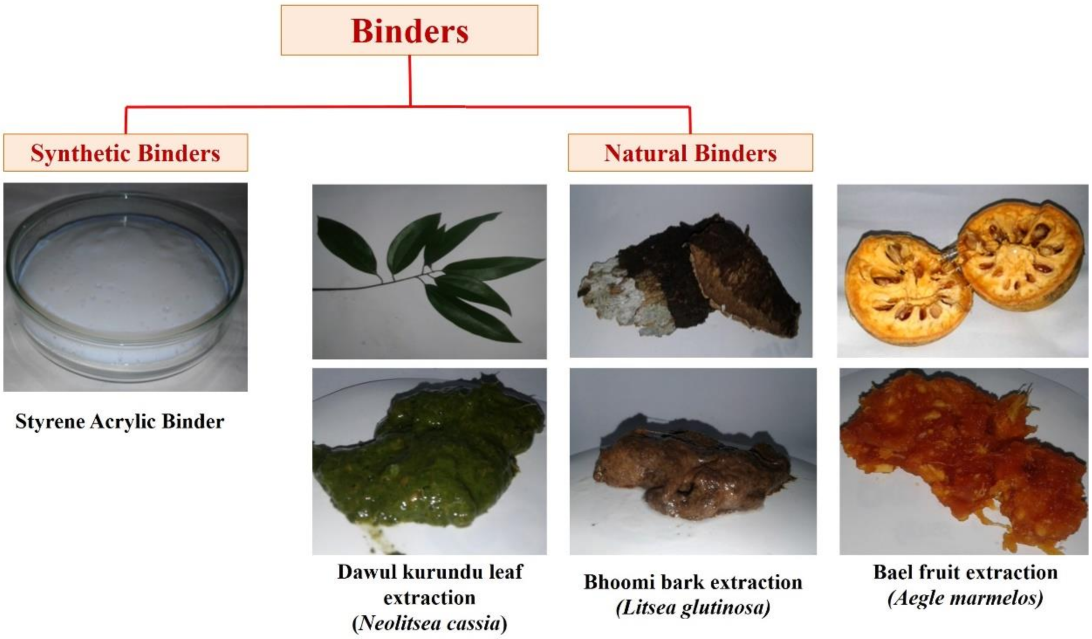


Figure 5.9: Binders selected in the study

Dawulkurundu leaf extraction: Dawulkurundu leaf extraction was used in the food production process and as a binding material in ancient wall paints according to indigenous knowledge of Sri Lankan society [164]. The binder from Dawulkurundu was extracted from leaves. Dawulkurundu leaves were collected and crushed into small pieces. The crushed leaves were blended with a small amount of water in a mechanical blender and Dawulkurundu leaf extraction was prepared.

Bhoomi bark extraction: Bhoomi is a medicinal plant and the plant extraction is used in ayurvedic medicine; as a binding agent with medicinal properties [166],[167]. Binder from Bhoomi was extracted from tree bark. Bhoomi tree bark was cut off from the tree and it was cut into pieces and blended with a small amount of water to prepare Bhoomi bark extraction. A styrene acrylic binder was purchased from the market.

Bael fruit extraction: Binder of the Bael fruit was used in the historical soil-based plasters, including the Sigiriya mirror wall and plaster of the Sigiriya fresco [164]. Binder of Bael is included in Bael fruit and the binder was extracted from ripened Bael fruits.

5.4.1. Analyzing putty properties variation of wet alum sludge with binders

To analyze the putty properties variation of wet sludge with binders, experiments were conducted to test moisture content, observational shrinkage and fungus growth test. Five sludge mixtures were prepared by mixing DWTP wet sludge with the binders according to the mix design shown in Table 5.5. Mixtures were prepared by mixing them in a mechanical mixer. After the preparation of sludge mixtures, observational shrinkage, moisture content and fungus growth were tested for tree replicates of each mix.

Table 5.5: Mix design for wet sludge mixtures with natural binders

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
DWTP Sludge	x	x	x	x	x
Styrene Acrylic Binder	o	x	o	o	o
Dawulkurundu Leafe Extraction	o	o	x	o	o
Bhoomi Bark Extraction	o	o	o	x	o
Bael Fruit Extraction	o	o	o	o	x

x – Added in the mix, o - Not added in the mix

5.4.2. Moisture content variation of wet alum sludge with binders

The weight basis oven-dry method was used to measure moisture content and the test was conducted according to the ASTM D 2216-98 standard; as mentioned in previous chapters. Test results are shown in Figure 5.10. According to the test results moisture content increase when mixing binders with wet sludge compared to the moisture content of raw sludge.

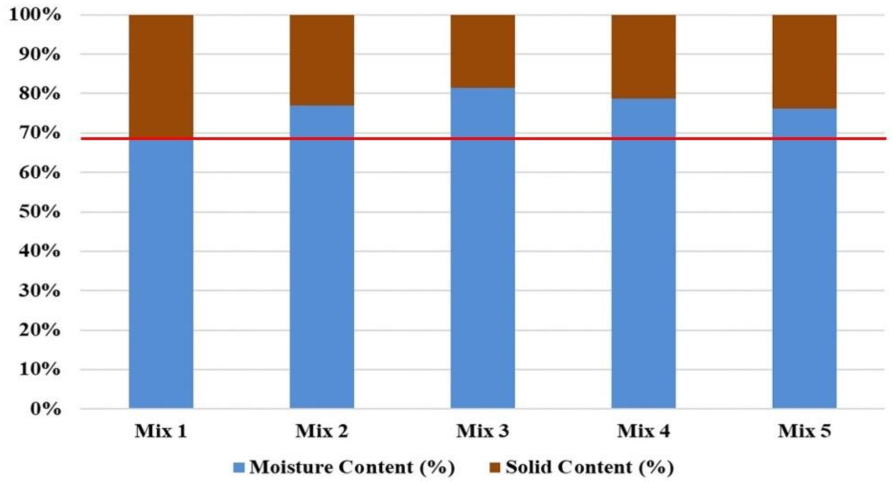


Figure 5.10: Moisture content variation of wet sludge mixtures with binders

5.4.3. Observational shrinkage variation of wet alum sludge with binders

An observational shrinkage test was conducted to determine the drying shrinkage of DWTP wet sludge with the presence of a binder. The test was conducted according to DIN 18947,2013 standards as mentioned in previous chapters. Mixtures were applied on sand cement plaster panels and dried for 24 hours. After samples were completely dry, drying cracks on the surface were observed. Shrinkage test results are shown in Figure 5.11. According to the observational shrinkage test results cracking patterns differed with the binder type. When the sludge was applied in wet raw condition, it was completely cracked without binding to the panel surface after 24 hours. The rest of the mixtures prepared by mixing with binders were cracked with different crack patterns according to the binder type after 24 hours. However, the mixtures with binders were bound to the panel more tightly than the wet raw sludge. The presence of a binder reduced the severity of the cracks while increasing the adhesiveness of DWTP wet sludge.

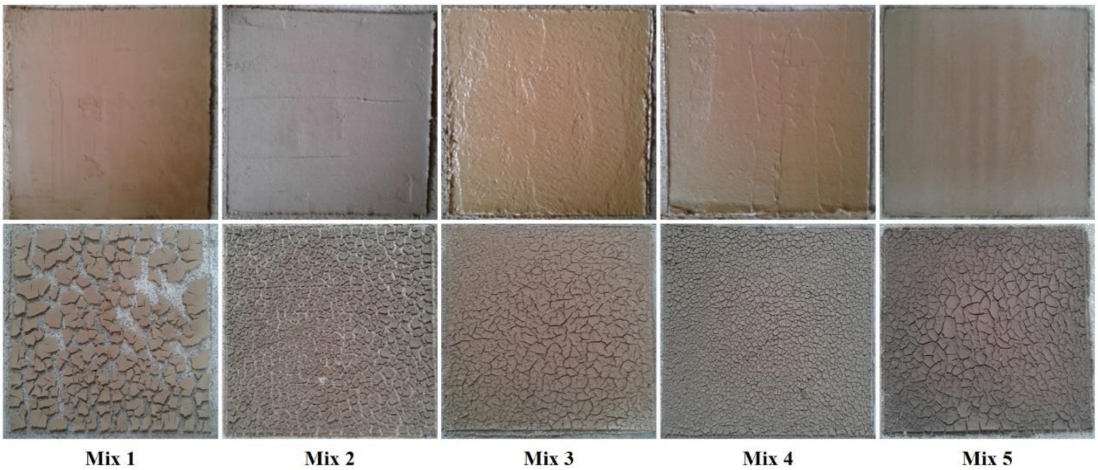


Figure 5.11: Observational shrinkage of wet sludge mixtures with binders

5.4.4. Analyzing fungus growth of wet alum sludge with binders

A fungus growth test was conducted according to the ASTM D3273-94 test standards [168],[62]. Cement plaster panels were cast according to the size of 5cmx15cmx2.5cm. Mixtures were applied on one surface of each sample with 1mm thickness and cured the samples until completely dry (Figure 5.12). After 14 days of the incubation period, test samples were vertically hung in the chamber as shown in Figure 5.12. Samples were hanged for four weeks (one month) and after that samples were taken out from the chamber and the putty surfaces were captured. Putty surfaces were compared before and after to identify fungus growth on the putty surface and the fungus growth was rated according to the rating system defined by ASTM D 5590-00 standard; as shown in Table 5.6 [115].

Figure 5.12: Sample preparation and fungus growth test

Table 5.6: Fungus growth rating system – ASTM D 5590-00 [115]

Scale	Description	Fungus growth Percentage
0	None	0
1	Trace of growth	<10%
2	Light growth	10 – 30%
3	Moderate growth	30 – 60%
4	Heavy growth	>60%

Results and Discussion:

The results of the fungus growth test are shown in Figure 5.13. According to the observations, fungus growth of the samples applied mix 1 and 2 were rated on scale 1; as a trace of fungus growth observed in the samples. Fungus growth of the samples applied mix 3,4 and 5 were rated as scale 4; as heavy fungus growth was observed on the samples. According to the observations, it can be concluded that the fungus growth of wet sludge increases with natural binders. Synthetic binder (Styrene acrylic binder) does not facilitate fungus growth as natural binders. Natural binders increase the organic matter content of the mix which facilitates fungus growth. Therefore, natural binders cannot be recommended as an effective additive to develop wall putty mix with DWTP sludge due to the increasing fungus growth.

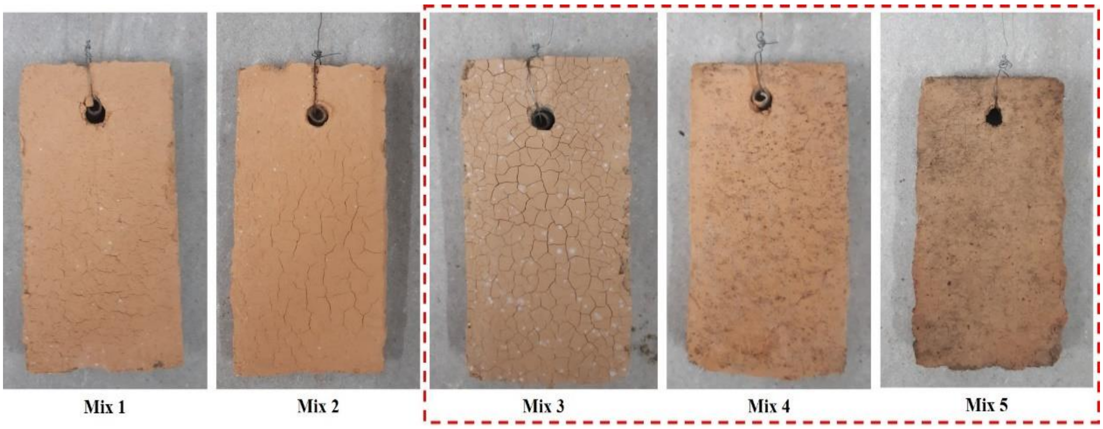
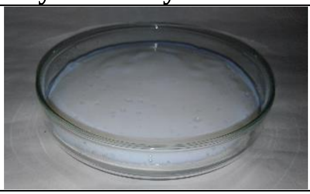


Figure 5.13: Fungus growth test results

5.5. Analyzing Putty Properties of Wet Alum Sludge Mixture

Experiments were conducted to identify the effectiveness of physical additives and binders to optimize the putty properties of the DWTP wet sludge. Considering the findings, one synthetic binder and two physical additives were selected as shown in Table 5.7.

Table 5.7: Additives and binder selected to improve optimum wet sludge mix

Synthetic Binder	**Physical Additives**	
Styrene Acrylic Binder	**Sand**	**Fiber**
		
• A synthetic binder • Does not facilitate fungus growth • Reduce drying cracks of wet sludge • Improve adhesiveness of wet sludge	• Dry sand sieved from a 300µm sieve was used • Reduce volumetric shrinkage of wet sludge • Improve clay/sand ratio of wet sludge mix	• A waste product in the sugar production process • Fiber cut with 10mm length pieces • Reduce volumetric shrinkage of wet sludge

Mix Design:

Eight different mixtures were prepared by mixing selected additives with sludge in a mechanical mixer (Figure 5.14), according to the mix design shown in Table 5.8. After the preparation of mixtures, experiments were conducted to test the volumetric shrinkage and observational shrinkage of each sample.

Figure 5.14: Mixtures preparation in a mechanical mixer

Table 5.8: Mix Design

Mixture	Ingredients			
	Sludge	Sand	Fiber	Synthetic Binder
Mix 1	x	o	o	o
Mix 2	x	x	o	o
Mix 3	x	o	x	o
Mix 4	x	x	x	o
Mix 5	x	o	o	x
Mix 6	x	x	o	x
Mix 7	x	o	x	x
Mix 8	x	x	x	x
x – Added in the mix, o - Not added in the mix				

5.5.1. Volumetric shrinkage variation with additives

A volumetric shrinkage test was conducted according to DIN 18947,2013 standards [113]; as described in the previous chapter, for three replicates of each mix. Volumetric shrinkage was calculated using equation 4.1. and an average value was calculated for each mix. Volumetric shrinkage test results are shown in Figure 5.15. According to the test results, the lowest volumetric shrinkage was observed with mix 4; which was prepared by mixing both sand and fiber with wet sludge. And the mix 8; which was prepared by mixing the binder with both physical additives has the second lowest shrinkage.

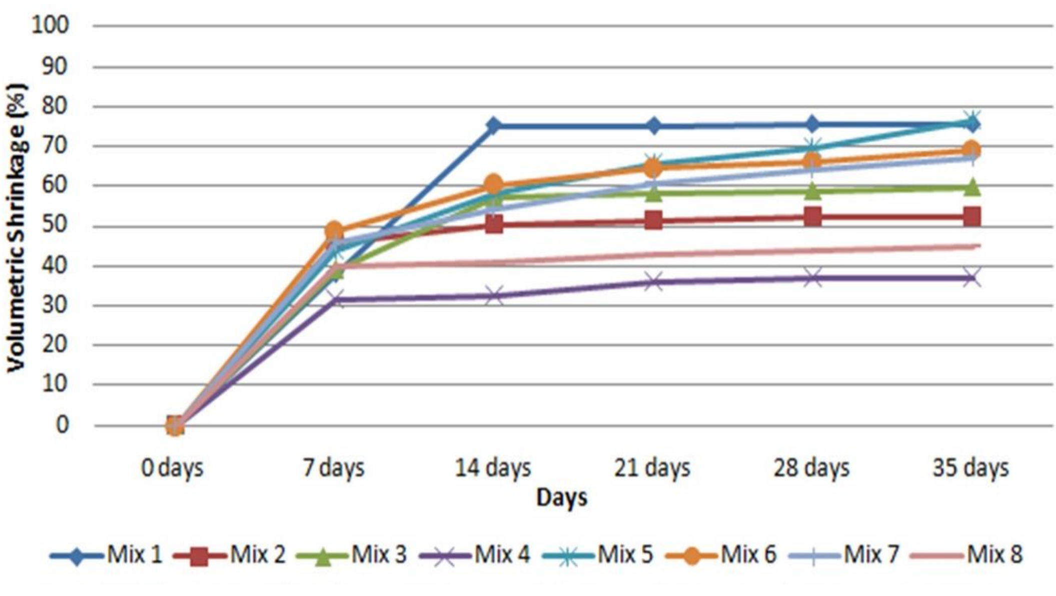


Figure 5.15: Volumetric shrinkage variation of wet alum sludge with additives

5.5.2. Observational shrinkage variation with additives

An observational shrinkage test was conducted to determine the drying shrinkage of each mix. The test was conducted according to DIN 18947,2013 standard as mentioned in previous chapters. Three replicates of each mixture were applied on sand cement plaster panels and dried for 24 hours. After samples were completely dry, drying cracks on the surface were observed. Shrinkage test results are shown in Figure 5.16. according to the test results it can be observed that mix 8; was prepared by mixing both physical additives along with the binder. When comparing the mixtures with and without a binder; mixtures with the binder (Mix 5,6,7 & 8) are more tightly bound to the plaster surface than the mixtures without a binder (Mix 1,2,3 & 4).

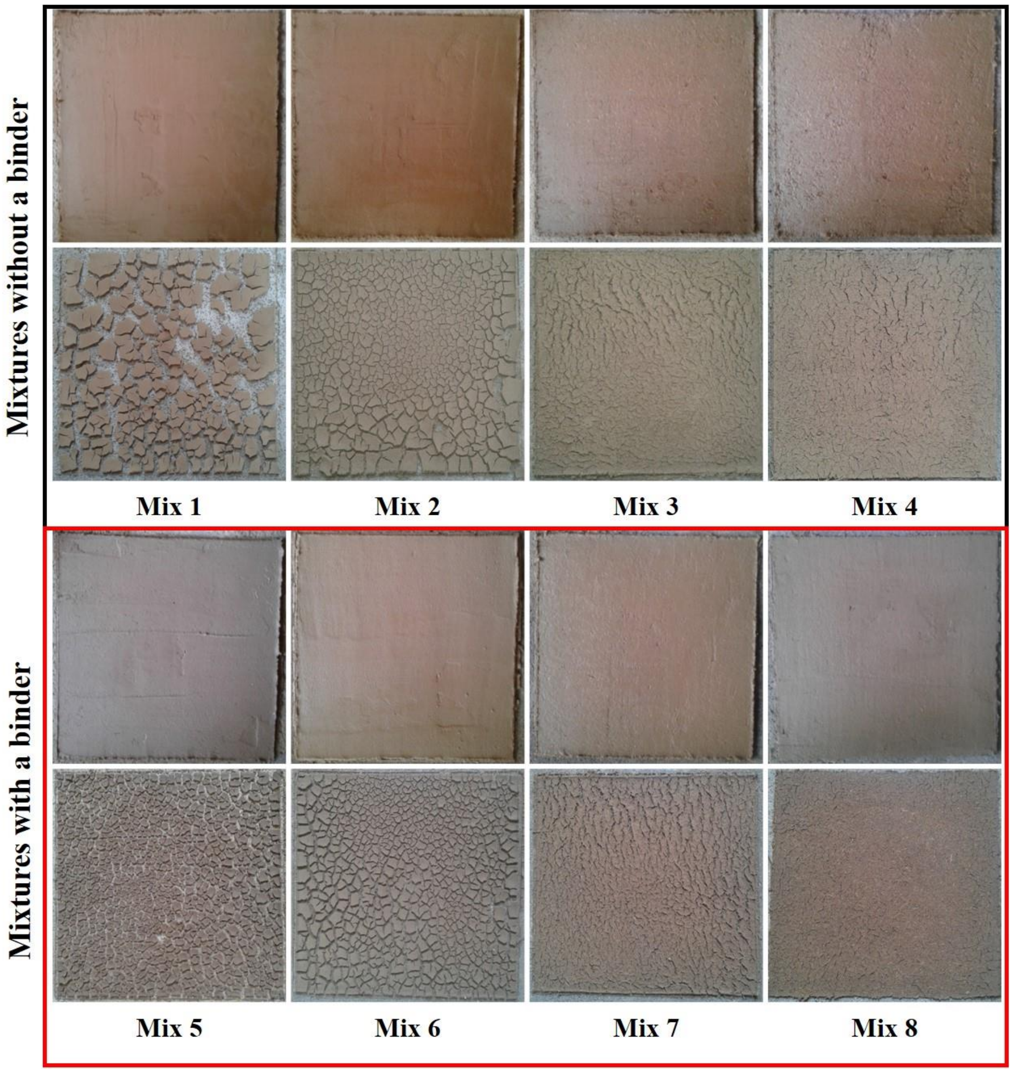


Figure 5.16: Observational shrinkage variation of wet alum sludge with additives

5.5.3. Wet alum sludge mixture with optimum putty properties

According to the test results, it was identified that volumetric shrinkage can be reduced by mixing additives with wet sludge. And also, it was identified that the adhesiveness of the wet sludge mix improved with additives. Therefore, the putty properties of the wet sludge can be improved by additives, and an optimum wall putty mix with DWTP wet sludge was developed considering shrinkage (observational and volumetric) test results, as shown in Figure 5.17. The developed wet sludge mixture was tightly bonded with the plaster surface and low with drying cracks. And scale-off was not observed from the dried putty surface. But the mix consists of a few defects; as macro level drying cracks are present on the dried putty surface and fibers pop up from the surface reducing the smoothness of the surface. Existing wall putty mixtures consist of micro-cracks on the dried putty surface, which were not visible to the naked eye; but no macro cracks. And also, existing putty surfaces have a smooth finish. Therefore, the wall putty mix developed with the wet alum sludge is not consistent with potential putty properties. The next section of this research was conducted to develop a dry powder with putty properties, using wet alum sludge.

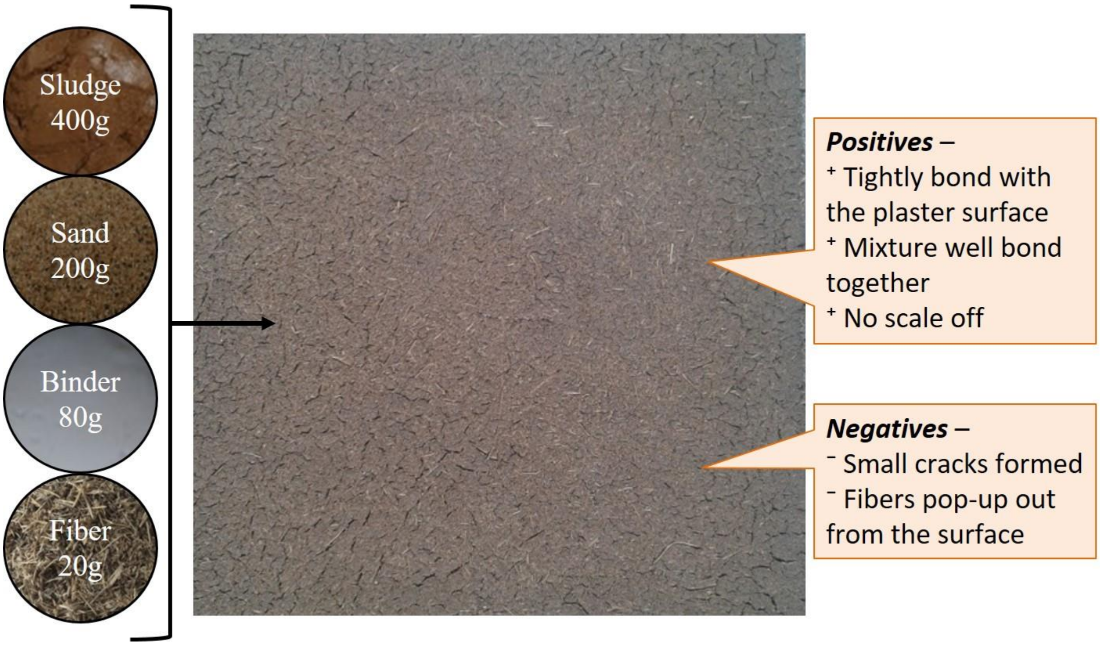


Figure 5.17: Wet sludge mix with optimum putty properties

5.5. Summary

DWTP sludge properties were identified in the previous chapter. According to the results, shrinkage was identified as the main drawback of wet sludge when developing a wall putty. Therefore, the next experiments were conducted to improve the putty properties of wet sludge. According to the identified properties of the wet sludge, adhesiveness should be increased while reducing the drying shrinkage of the mix. According to the literature and historical evidence, it was found that additives; such as fibers, sand and binders were added to soil-based plasters to reduce shrinkage while increasing adhesiveness. Therefore, different additives were selected and their performances to improve the putty properties of wet sludge were studied.

Sand and natural fibers were selected as physical additives and mixtures were prepared by mixing with wet sludge. Different mixtures were prepared by mixing sand in different percentages and volumetric shrinkage and ball drop tests were conducted for each mix. According to the test results, the addition of sand reduced the volumetric shrinkage and the shrinkage becomes zero at 70% sand percentage, but it is not practically applicable in developing a putty mixture. To identify the optimum sand percentage, a ball drop test was conducted. According to the ball drop test results, it was identified that wet sludge mixtures with a sand percentage of between 30% to 60% have optimum clay and sand contents to develop wall putty mix. Although the mix has optimum shrinkage performances, the adhesiveness of the mix should be developed.

Three natural fibers were selected for the study and mixtures were prepared by mixing fiber with wet sludge according to the developed mix design. A volumetric shrinkage test was conducted for each mix. According to the test results addition of fiber reduced the volumetric shrinkage and banana fiber is the most effective natural fiber type to reduce volumetric shrinkage of wet sludge compared to coir fiber and sugarcane fiber.

After identifying the effectiveness of physical additives, the effectiveness of binders was tested. According to historical evidence, natural binders can be identified when added to historical soil-based plasters. Three different plant-based natural binders were selected for the study. And a synthetic binder was selected to compare the performances of natural binders. Different wet sludge mixtures were prepared by mixing natural binders and a synthetic binder with wet sludge according to the developed mix design and tests were conducted to measure moisture content, observational shrinkage and fungus growth. According to the test results crack patterns of wet sludge mixture vary with the binder type and the moisture content of the mix increased with the addition of natural binders. But fungus growth in the mix increase with natural binders. Therefore, natural binders are not effective as an additive to develop wall putty with DWTP sludge.

After studying the physical additives and binders, next experiments were conducted to optimize the putty properties of the wet alum sludge. Wet alum sludge was mixed with the synthetic binder and physical additives in different mixing ratios. According to the test result, it was revealed that physical additives reduced drying shrinkage while binders increase the adhesiveness of wet sludge mixtures. According to that the most effective method to enhance the putty properties of wet sludge is adding both synthetic binder and physical additives. With the findings an optimum wet sludge mixture with low volumetric shrinkage, low drying cracks and high adhesiveness was developed; but the mix has few defects as the presence of small surface cracks and fibers pop up from the surface when applied as a wall putty. Therefore, the wall putty mix developed with the wet alum sludge is not consistent with potential putty properties. The next section of this research was conducted to develop a dry powder with putty properties, using wet alum sludge.

CHAPTER 06: DEVELOPMENT OF DRY POWDERED ALUM SLUDGE

6.1. General

In the previous chapter, experiments were conducted to enhance the putty properties of DWTP wet alum sludge to develop wall putty from wet alum sludge. According to the test results, a wet alum sludge mix was developed with optimum putty properties, but some defects were identified. According to the high moisture content and low solid content, the shrinkage of wet alum sludge is considerably high. Therefore, it is difficult to develop wall putty directly with wet alum sludge. When the wet alum sludge dries to remove moisture, it is hard as stone according to the activation of alum (Figure 6.1). Therefore, the sludge cannot be dry directly to produce a dry powder. Therefore, the next step of the study was conducted to develop dry powdered alum sludge applicable as a wall care putty. Thermal properties of DWTP alum sludge were identified and a process was developed to produce dry powdered alum sludge. The experimental procedures and results will be discussed in this chapter.

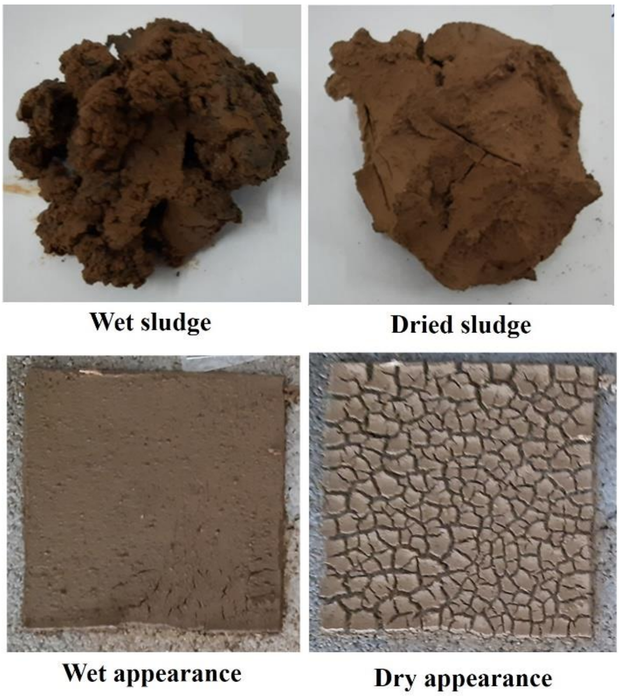


Figure 6.1: Wet and dry sludge

6.2. Thermal Properties of DWTP Waste Alum Sludge

Heat has a significant influence on soil-based materials such as clay, soil and mud. The exposure to heat with different temperatures for different time durations alters the soil-base material properties significantly as shown in Figure 6.2 [169],[153]. Therefore, identification of the thermal alteration properties of DWTP alum sludge is essential to developing dry powdered alum sludge[170].

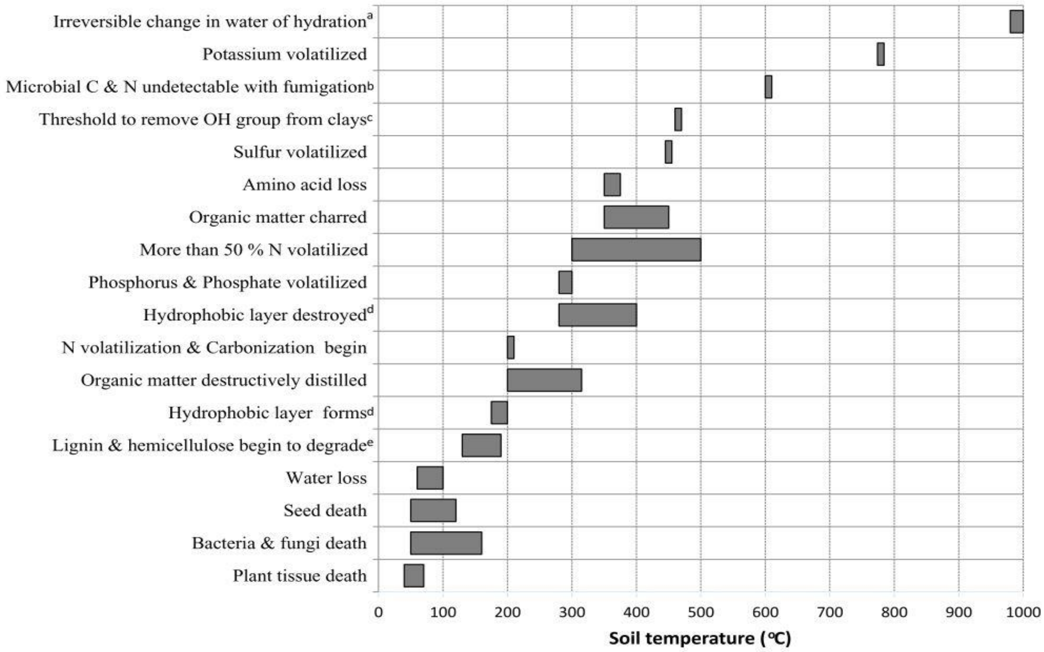


Figure 6.2: Thermal alterations of soil at different temperatures [169]

DWTP alum sludge was oven dried at 105ºC for 24 hours duration until the weight become constant to remove the moisture (Figure 6.3 (a) & (b)). Dried sludge samples were heated in a muffle furnace at ten set temperatures between 100ºC to 1000ºC (temperatures as 100ºC, 200ºC, 300ºC, 400ºC, 500ºC, 600ºC, 700ºC, 800ºC, 900ºC and 1000ºC) (Figure 6.3 (c) & (d)). The variations of the density and color due to the thermal alterations of the sludge at ten different temperatures were measured and observed.

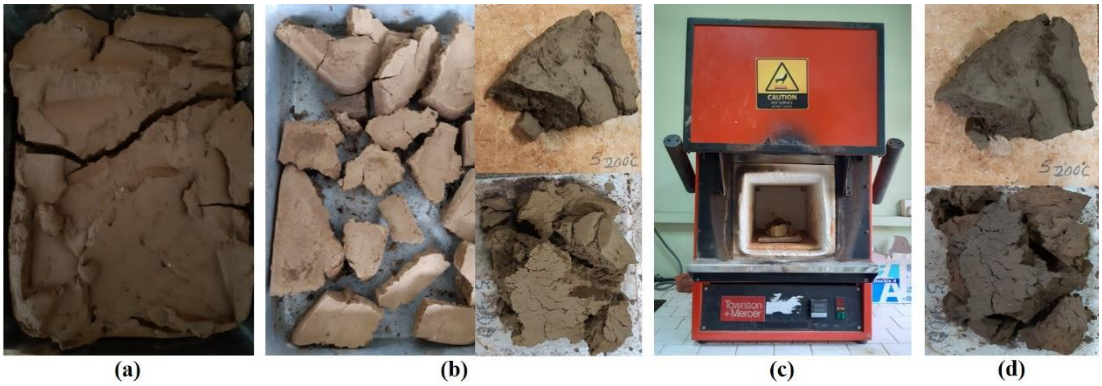


Figure 6.3: Heating sludge for determination of thermal alterations

6.2.1. Color Variation

Images of sludge samples were taken at three different stages. The first image was taken when collecting wet sludge samples from the Biyagama DWTP. The second image of the sludge sample was taken at the end of heating; when the sample was under dry conditions. After that, the dry samples were submerged in water at room temperature for 24 hours duration and the third image of each sample was taken under wet conditions. After arranging the images according to the heated temperature, color variation was observed (Figure 6.4). According to the observations color of the sludge is variants with the temperature. From 100°C to 400°C the color becomes darker in both dry and wet conditions. Beyond 400°C color become lighter up to 700°C and become constant up to 1000°C.

Figure 6.4: Colour variation of sludge with heat

6.2.2. Density Variation

Density can be defined as the mass of a given volume of substance under given conditions. There are various test methods for density measurements of different materials. Dried sludge is consisting of unevenly shaped solid particles; therefore, the density calculation was conducted according to EN 1097-3 standard [115],[117]. Dried sludge particles were powdered and sieved using a 300μm sieve (Figure 6.5). After that, powdered sludge samples were compacted in a box with a known volume (8cm^3) and the weight was measured (Figure 6.6). After recording the weights of each sample, the density was calculated using equation 6.1; where Wb refers to the empty weight (g) of the box, Ws refers to the weight (g) of the sludge compacted box and V refers to the volume (cm^3) of the box. Measurements were taken three times (three replicates) for each sample and the average value was calculated.

$$Density\ (gcm^{-3}) = \frac{Ws-Wb}{V} = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 6.1}$$

(a) Grinding uneven shapes dried sludge particles | (b) Powdered dried sludge | (c) Sieving powdered dried sludge | (d) Powdered dried sludge

Figure 6.5: Powdered dried sludge preparation for density test

(a) Empty box with known volume | (b) Weighing empty box | (c) Sludge powder compacted box | (d) Weighing sludge powder compacted box

Figure 6.6: Density measuring test of dried sludge

Results and Discussion:

After calculating the density values of each heated sludge sample, values were statistically analyzed to study the density variation with the heating temperature. And the results are shown in Figure 6.7. When comparing the density values of heated sludge samples, the highest density was achieved at the temperature of 900°C and the lowest density was achieved at 500°C. According to the graph, density values of the heated sludge samples are gradually reduced from 100°C up to 500°C and beyond the 500°C, density again gradually increases up to 900°C temperature. According to the results, it can be concluded that density increased when applying heat to sludge and the lowest density was recorded at 500°C temperature.

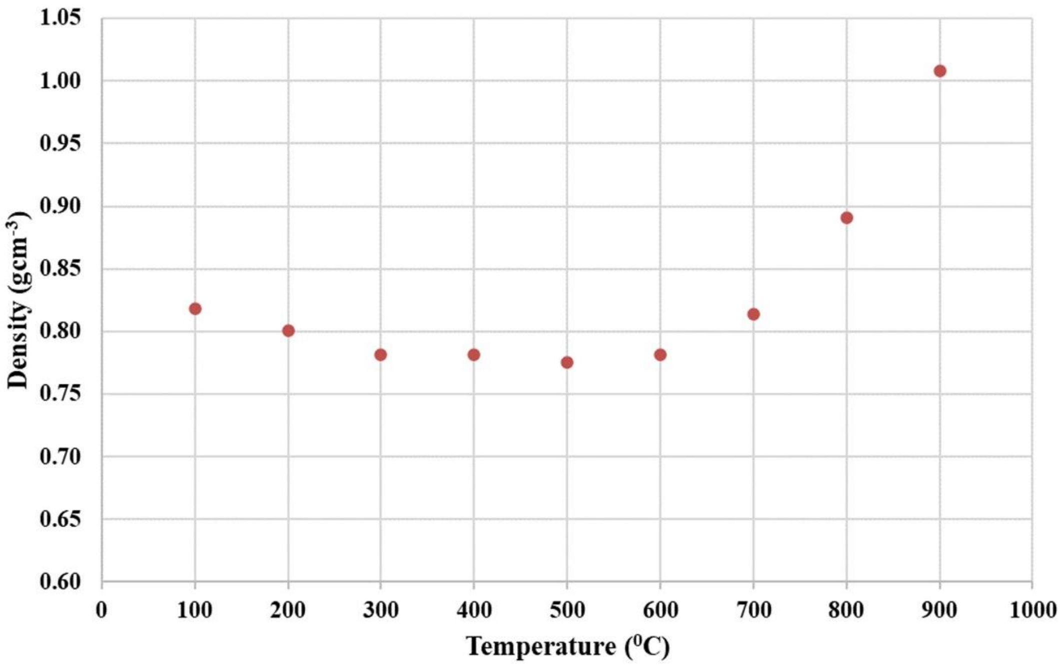


Figure 6.7: Density variation of dried sludge with heating temperature

6.3. Overcome Alum Activation of DWTP Waste Alum Sludge

In DWTPs, raw water from surface water sources is collected and treated to drinking quality. In the surface water sources, negatively charged colloids are suspended and they do not sediment under gravity due to their lightweight. To neutralize the negative charge of the colloids, alum is added to the treatment process as a positively charged coagulant [41],[171]. After adding alum, neutralized colloids are bonding together as shown in Figure 6.8, and the flocculation process will be started. In the flocculation process, micro-flocs are forming and become macro-flocs. In the water treatment process a polymer is added to tightly bind the macro-flocs together and the colloids sediment with the gravity due to the increase of weight in the flocculation process. Sediments of the water treatment process are removed as sludge and when the sludge is dried it is harder due to alum activation [3],[36]. Therefore, alum activation should be overcome to produce dry powdered alum sludge. Next experiments were conducted to identify effective lubricant and optimum processing conditions to develop a dry powder production process.

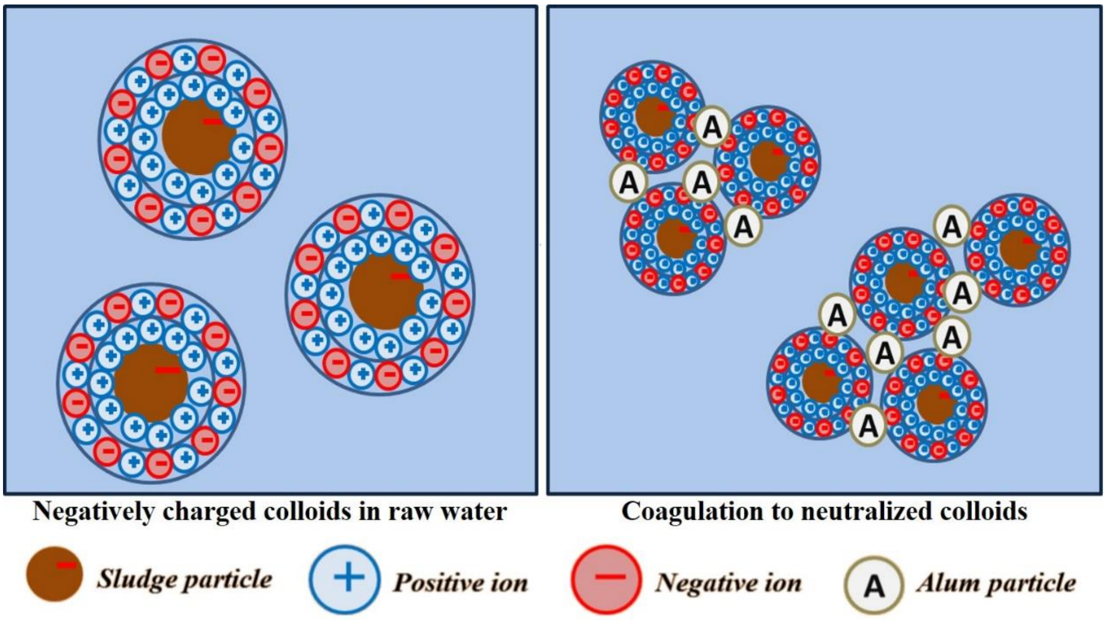


Figure 6.8: Coagulation process

6.3.1. Selection of a lubricant

When the wet sludge was dried as it is, it harder than a stone; according to the activation of alum, which is very difficult to grind and needed more energy to grind to a powder. Therefore, a method should be developed to dry alum sludge in powder form. According to the literature, there was no available method to produce dry powdered sludge overcoming the alum activation. To overcome the alum activation a lubricant can be added to the sludge before applying heat. When mixing a lubricant with wet sludge, lubricant particles should be attached to the sludge particles. The lubricant should be boiled out letting the sludge particles loosely bound when adding heat. Therefore, the lubricant should be a non-drying oil; to remain liquid phase in the at room temperature without solidifying to mix effectively with the wet sludge, and with a lower boiling point; to remove from the dry powder without influencing the putty properties of the powder [169],[153].

When selecting the lubricant oil petroleum oils were excluded considering the harmful emissions when burning; from the other non-drying oils, coconut oil was selected due to its lower boiling point (177ºC - 232ºC) compared to other non-drying oils. Coconut oil is locally produced non-drying oil and has no harmful emissions results when burning. Therefore, coconut oil is selected considering the favorable conditions as mentioned in Figure 6.9.

Figure 6.9: Coconut oil as the lubricant

6.3.2. Dry powdered sludge production with coconut oil

As the first step of the study, dry powdered sludge was produced after mixing with coconut oil to study the effectiveness of coconut oil as a lubricant to overcome alum activation of DWTP sludge. In the dry powder production process, wet sludge was mixed with 10% of coconut oil in a mechanical mixture and the dry powdered sludge was produced following the steps shown in Figure 6.10.

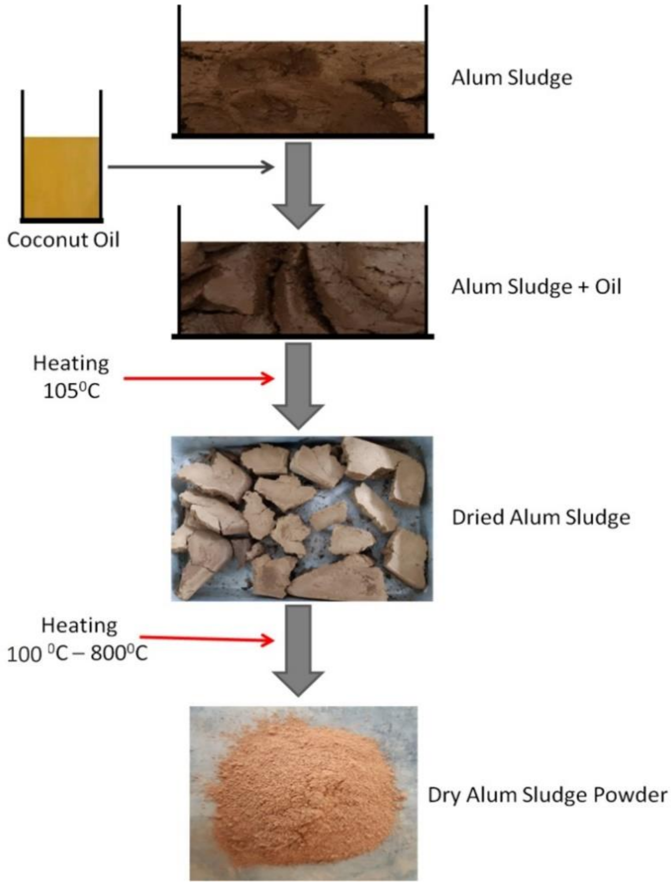


Figure 6.10: Production process of dry powdered sludge with coconut oil

In the process oil mixed sludge samples were burned at ten different temperatures (temperatures as 100°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, 900°C and 1000°C) in a muffle furnace and ten dry powder samples were prepared as shown in Figure 6.11. Parallel to that, ten samples of dry powdered sludge samples were prepared without mixing coconut oil (Figure 6.11). And the properties of each sample were tested and the results were compared to identify the effectiveness of coconut oil as a lubricant to overcome alum activation.

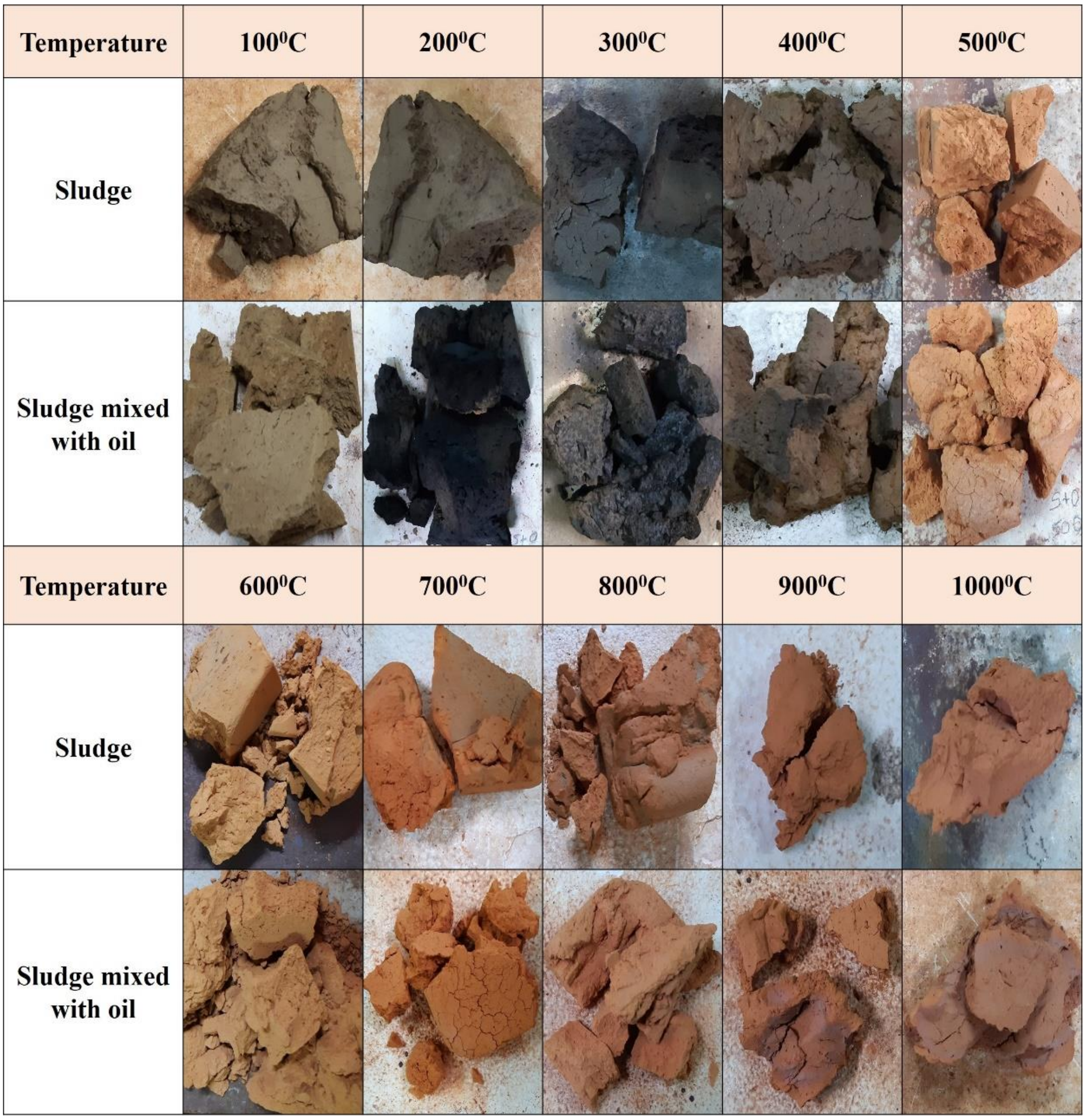


Figure 6.11: Comparison of burned sludge samples with and without coconut oil

6.3.3. Identification of effectiveness of coconut oil as a lubricant

Coconut oil was selected as the lubricant for the study. The effectiveness of coconut oil to overcome alum activation should be studied next. Therefore, the next experiments were conducted to study the performance of coconut oil as a lubricant. Properties of dried sludge samples; burned with and without coconut oil, were tested and compared with both results. In the study density and easiness to grind to powder were tested.

The appearance of the samples was captured and arranged according to the heated temperature; as shown in Figure 6.11, and both samples were compared. According to the test results, sludge samples burned without mixing coconut oil were harder with the increase the temperature. And also, the particles were tightly bound and need extra energy to grind to a powder. When compared the samples with sludge samples; which burned after mixing coconut oil, particles were loosely bound and easy to grind to a powder. The sample dried at 100ºC temperature consists of coconut oil; as the boiling point is higher than 100ºC, therefore, the powdered sample cannot be mixed with water due to the hydrophobic properties of the containing oil. According to the observations both samples have the same color at each temperature. And also, samples burned beyond 800°C temperature, are harder again and do not easy to grind. Therefore, around 700°C is the optimum temperature to burn sludge mixtures produced in the dry powder production process. According to the test results mixing coconut oil with wet sludge mixture before burning has an effect to reduce the hardness of the sample when increasing the temperature up to 700°C without effect on the color of the sample. And can be concluded that coconut oil is an effective lubricant to overcome alum activation of DWTP sludge.

6.3.4. Identification of optimum temperature

The density of each sludge sample burned with coconut oil was tested and study the variation with temperature to study the optimum temperature for the dry powder production process. Samples were powdered and measurements were taken according to Figure 6.5 and Figure 6.6. After the collection of data, density was calculated according to equation 6.1. The density values of each heated sludge sample with oil were compared with the density value of the heated sludge sample without oil. And the results are shown in Figure 6.12. When compared to the density values, all the values of heated sludge samples with oil are significantly lower than the density values of heated sludge samples without oil. The highest density was achieved at the temperature of 900°C and the lowest density was achieved at 700°C. According to the graph, density values of the heated sludge samples gradually decrease from 100°C up to 700°C and gradually increase from 700°C up to 900°C. According to the results, it can be concluded that the lowest density was recorded at 700°C temperature which is the optimum temperature to produce dry powdered sludge.

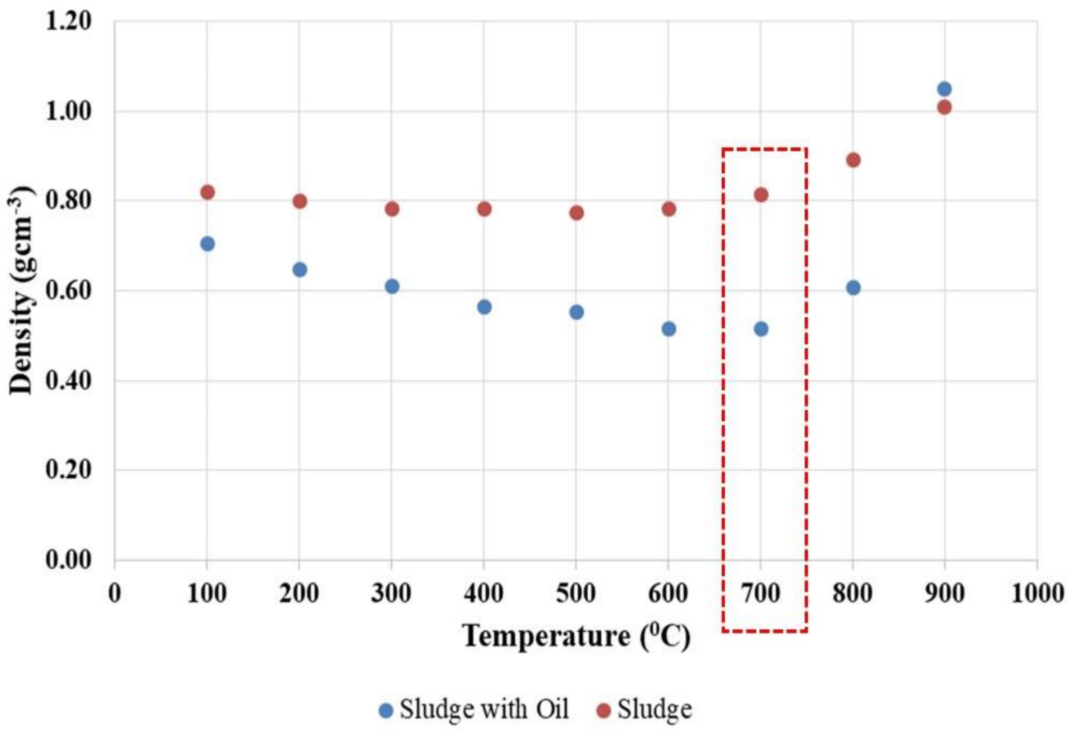


Figure 6.12: Density variation of sludge burned with coconut oil

6.3.5. Identification of optimum coconut oil mixing ratio

After identifying the optimum temperature to burn wet alum sludge after mixing with coconut oil, the next experiment was conducted to identify the optimum mixing ratio of coconut oil for dry powdered alum sludge production. In the test, five mixtures were prepared by mixing oil with wet sludge from 2% oil to 10%. Mixtures were mixed in a mechanical mixer. Mixtures were burned at 700°C and burned sludge particles were ground using a mortar and pestle to powder and the results are shown in Figure 6.13. According to the test results, samples with 2% and 4% of the oil were too hard and unable to grind to a powder using mortar and pestle. The sample with 6% oil was not too hard as samples with 2% and 4% oil and ground but was unable to grind to a fine powder. Samples with 8% and 10% of the oil were not too hard compared to other samples and were easily ground to powder using mortar and pestle.

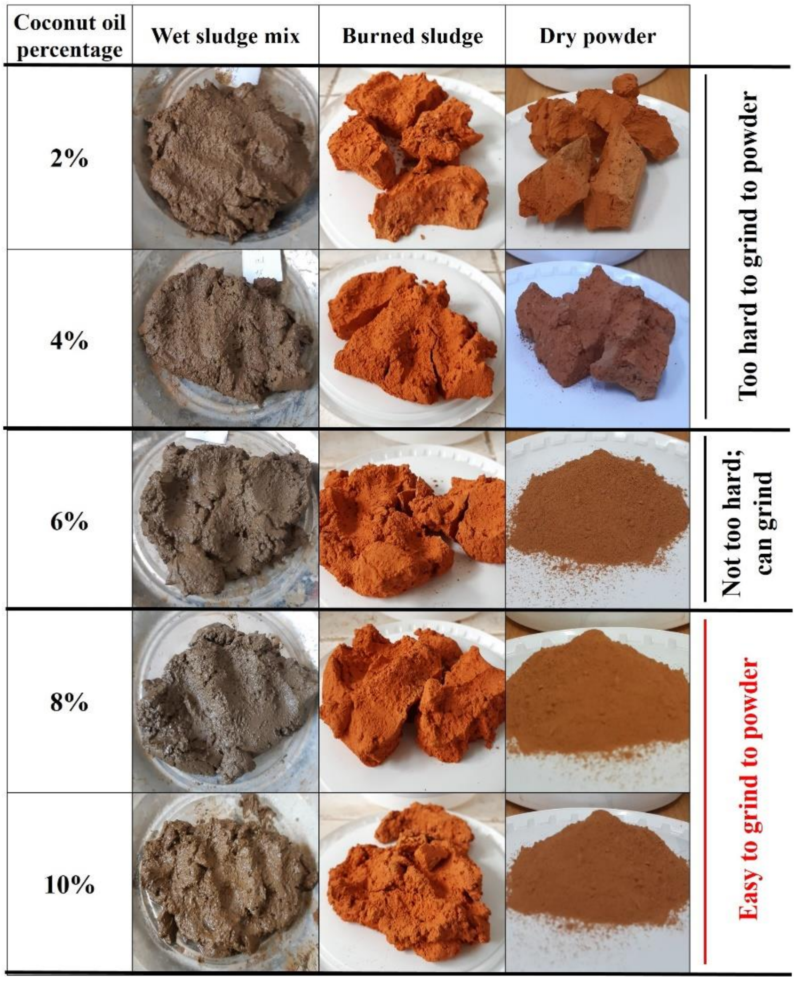


Figure 6.13: Dry powdered sludge production variation with coconut oil percentage

According to the test results samples with coconut oil percentage beyond 8% can be easily powdered and the easiness to powder increase with increasing oil percentage. Up to 8% of oil percentage is not sufficient to overcome alum activation totally and 8% is the minimum oil percentage to overcome alum activation in the dry powder production process. Furthermore, mixing oil in higher percentages will make the process unproductive. Therefore, the optimum coconut oil mixing percentage can be identified as 8% for a productive dry powder production process.

In the study, a process to overcome alum activation was identified and the optimum conditions of the process were defined according to the results obtained so far. As the next step, the putty properties of the produced dry powder should be studied to develop a wall putty mix. Therefore, the next experiments were conducted to identify the putty properties of the developed dry powdered alum sludge.

6.4. Putty properties of dry powdered alum sludge

Following the developed method coconut oil was mixed in 8% by weight with wet alum sludge and a sludge mixture was prepared. And then the mixture was oven dried at 105°C for 24 hours to remove moisture. The moisture-removed mixture was burnt in a furnace up to the temperature range of 100°C – 800°C. The burnt mixture (Figure 6.14) was ground with mortar and pestle and sieved through a 300µm sieve to produce alum sludge dry powder as shown in Figure 6.15. Eight samples of dry powdered alum sludge were produced by heating with eight different temperatures in the range of 100°C – 800°C. Next experiments were conducted to identify the putty properties of developed sludge powders; to identify optimum dry powder to develop the wall putty. Therefore, an observational shrinkage test was conducted for each sample.

Figure 6.14: Burned sludge samples with coconut oil

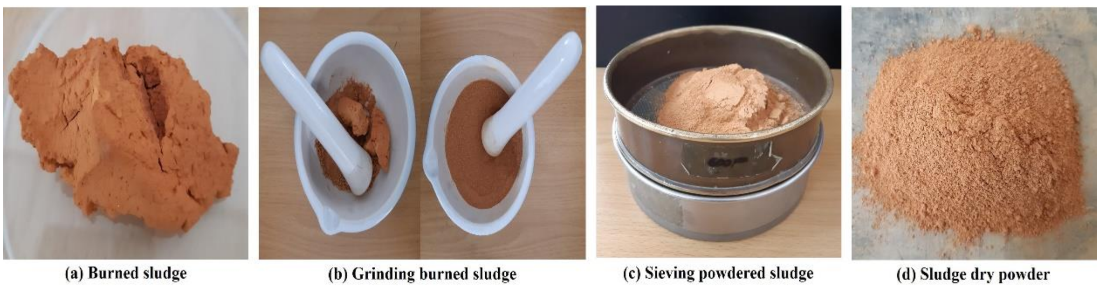


Figure 6.15: Sludge dry powder production process

6.4.1. Analysing observational shrinkage

An observational shrinkage test was conducted for each dry powder mix to identify the powder sample with the potential to develop wall putty. The dry powders were mixed with water and apply to sand cement plaster surface using a scraper as shown in Figure 6.16. Sample burned at 100ºC cannot be mixed with water, due to the presence of oil; therefore, an observational shrinkage test was conducted for the other seven samples. Samples were applied on plaster panels with an area of $25cm^2$ (5cm x 5cm) and three replicates from each mix. After application samples, wet appearance was captured and plaster panels were let dry for 24 hours duration and dry appearance was captured. Wet and dry appearances were compared to identify drying shrinkage and the results are shown in Figure 6.17. According to the test results, drying cracks were observed on the samples burned at temperatures from $200^{\circ}C$ to $600^{\circ}C$, and no drying cracks were observed on the samples burned at $700^{\circ}C$ and $800^{\circ}C$. Therefore, the dry sludge powder sample burned at $700^{\circ}C$ temperature was the optimum dry sludge powder sample to develop wall putty. However, the sample dried with zero cracks but it was scaled off from the surface; and the putty properties of the mix should be optimized. Next experiments were conducted to select an effective stabilizer to develop wall care putty from the dry sludge powder mix.

(a) Sludge dry powder (b) Adding water and mixing (c) Applying on plaster panel (d) Drying

Figure 6.16: Dry powder mix preparation for observational shrinkage test

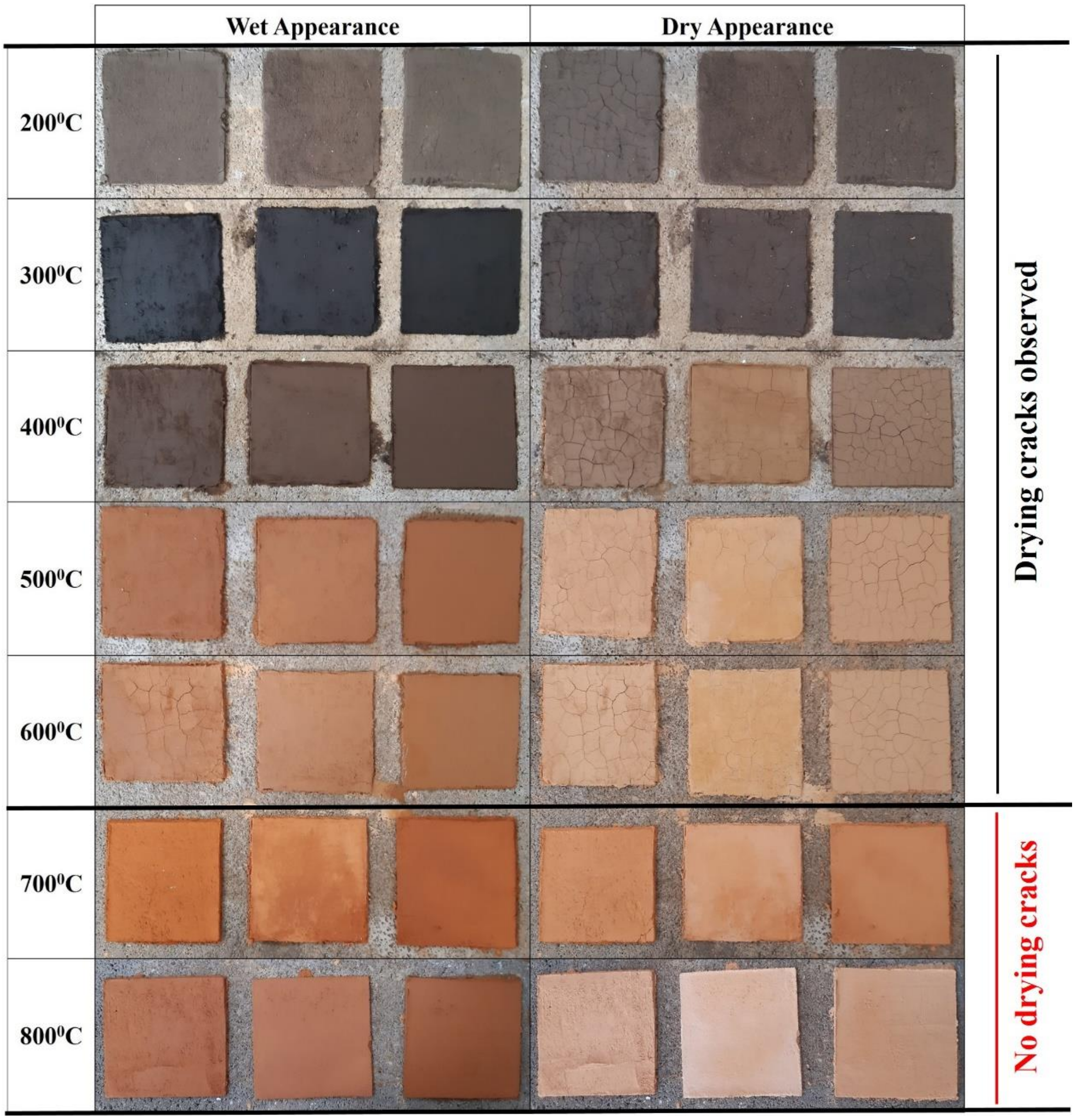


Figure 6.17: Results of observational shrinkage test

6.4.2. Analyzing effectiveness of stabilizers

Optimum dry sludge powder was identified in the previous section, and there are drying cracks observed on the dry surface of the mix. But a small scale off from the surface was observed. Therefore, a stabilizer should be selected to add to the mix to enhance the putty properties of the mix. In this step of the study, two stabilizers were selected and an observational shrinkage test was conducted for each mix mixing both stabilizers. And the effectiveness of the stabilizer was analyzed according to the observations. In the study, two stabilizers; lime and cement, were tested (Figure 6.18). Mixtures were prepared by mixing dry sludge powder with both stabilizers (with the percentage of 10% by weight) separately (Figure 6.19). Samples were left dry for two days and drying cracks and scale off of the surface were analyzed. The results are shown in Figure 6.20.

Figure 6.18: Selected stabilizers

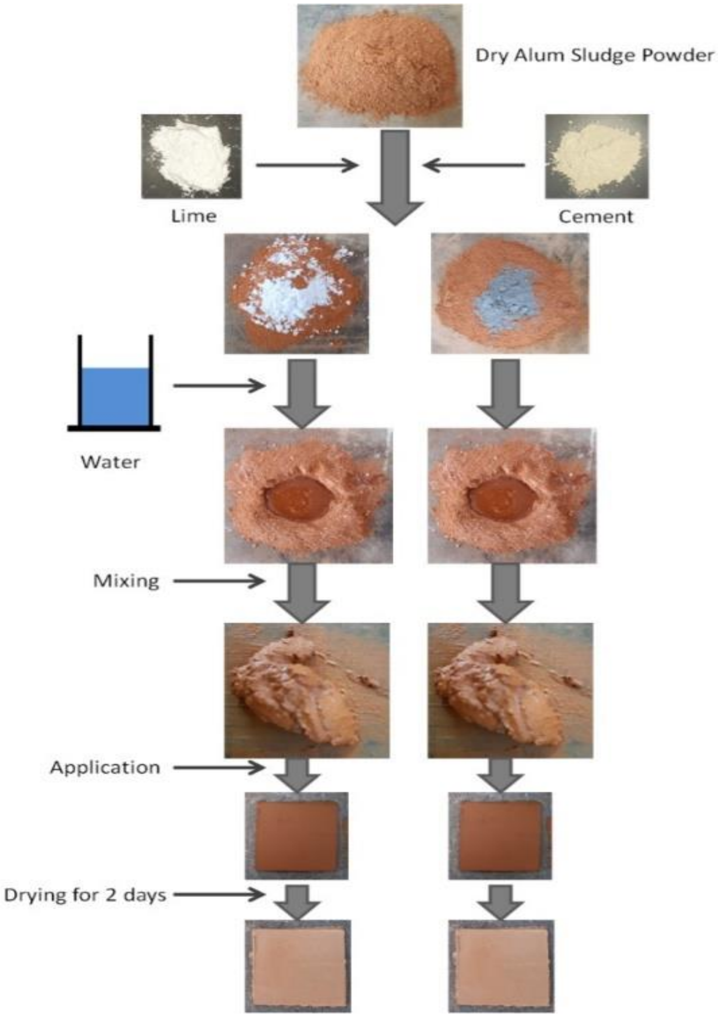


Figure 6.19: Stabilization of dry powdered sludge

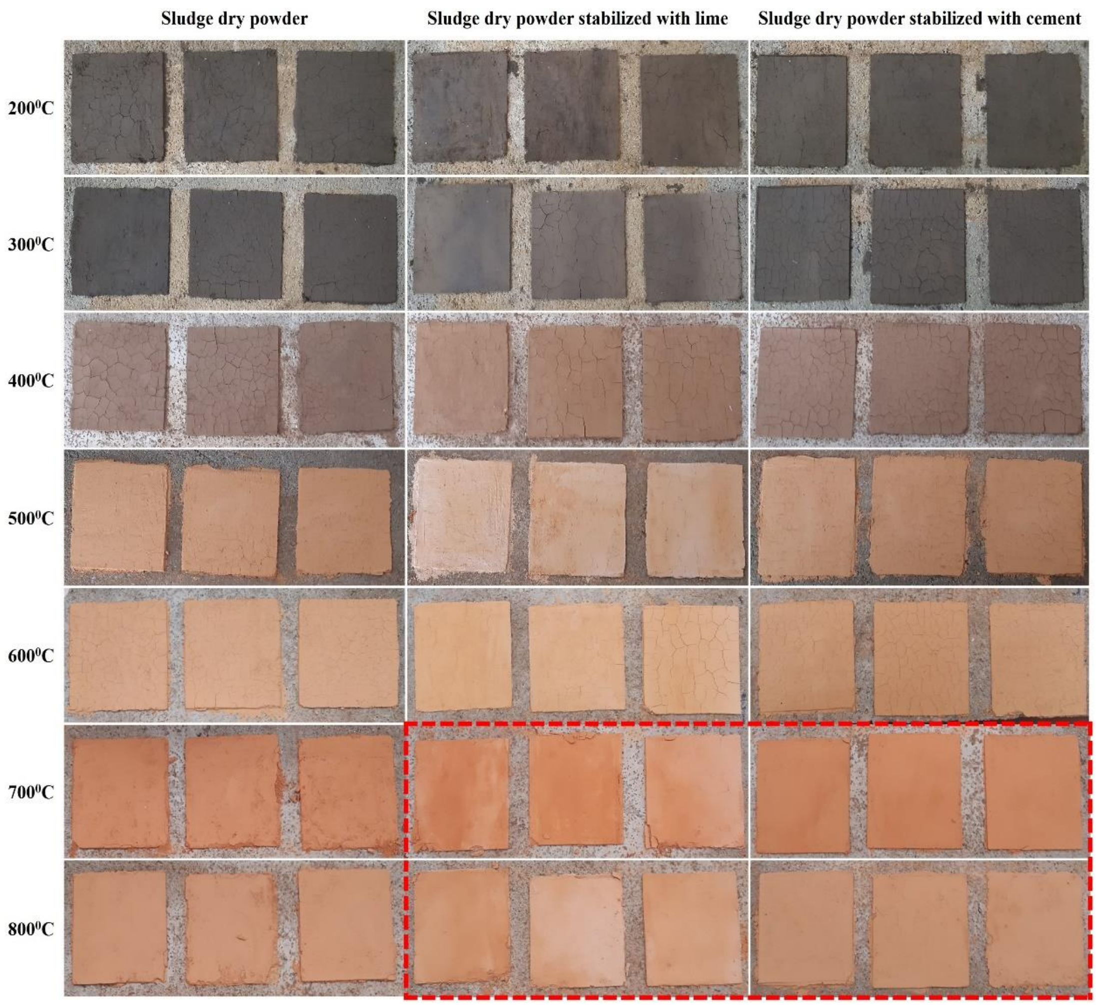


Figure 6.20: Observational shrinkage with stabilizers

According to the test results, drying cracks were observed on all samples burned at temperatures from 200°C to 600°C, and no drying cracks were observed on the samples burned at 700°C and 800°C. And also, the dry sludge powder samples burned at 700°C and 800°C temperatures were tightly bound to the plaster surface and did not scale off. Therefore, both stabilizers effectively enhanced the putty properties of the dry sludge powder sample. Furthermore, the samples mixed with lime have lighter colors compared to other samples, and samples mixed with cement have darker colors compared to other samples. Both stabilizers affect the color of the mix while enhancing putty properties. According to the results of the test, it can be concluded that a wall putty mix can be developed with the sludge dry powder with a stabilizer (lime or cement).

6.5. Summary

In the previous chapter, experiments were conducted to develop a wet sludge mix with putty properties. With the experiments, a wet sludge mix was developed but the mix was with few defects and has no potential to apply as a wall putty mix. Therefore, a process was required to produce dry powdered sludge overcoming alum activation of wet sludge. In this chapter, experiments were conducted to develop a dry powdered sludge with putty properties. DWTP wet alum sludge is harder when dry, due to the activation of alum and it is difficult to powder.

In the first step of this chapter, the thermal properties of DWTP sludge were studied. In the test, ten dried sludge samples were prepared by burning at ten different temperatures between 100°C and 1000°C. Color variation and density of each sample were measured. According to the observations color of the sludge is variants with the temperature and from 100°C to 400°C the color becomes darker in both dry and wet conditions. Beyond 400°C color become lighter up to 700°C and become constant up to 1000°C. When comparing the density values, the highest density was achieved at the temperature of 900°C and the lowest density was achieved at 500°C. Density values of the heated sludge samples are gradually reduced from 100°C up to 500°C and beyond the 500°C, density again gradually increases up to 900°C temperature. According to the results, it can be concluded that density increased when applying heat to sludge and the lowest density was recorded at 500^{0}C temperature.

Next experiments were conducted to select a lubricant and to analyze its effectiveness of that. Coconut oil was selected as the lubricant for the dry powder production process considering the preferable intrinsic properties and availability. Dry powdered sludge samples were prepared by burning wet sludge mixtures after mixing with coconut oil at ten different temperatures. According to the test results, coconut oil has the potential to overcome alum activation without effect on the color of the sample. The density of each sample was measured and all the values of heated sludge samples with oil are significantly lower than the density values of heated sludge samples without oil. According to the results, the lowest density was recorded at 700°C temperature and it is concluded as the optimum temperature to produce dry powdered sludge. And also, the optimum coconut oil mixing percentage was identified as 8% by weight, for a productive dry powder production process according to the test results.

Next experiments were conducted to identify the putty properties of developed sludge powders; to identify optimum dry powder to develop the wall putty. Therefore, an observational shrinkage test was conducted for each sample. According to the test results, drying cracks were observed on the samples burned at temperatures from 200°C to 600°C, and no drying cracks were observed on the samples burned at 700°C and 800°C. Therefore, the dry sludge powder sample burned at 700°C temperature was the optimum dry sludge powder sample to develop wall putty. However, the sample dried with zero cracks it was scaled off from the surface; and the putty properties of the mix should be enhanced. Next experiments were conducted to select an effective stabilizer; lime and cement were selected to analyze their effectiveness as stabilizers. According to the results, it can be concluded that a wall putty mix can be developed with the sludge dry powder with a stabilizer. Both stabilizers effectively enhance the putty properties of the dry powdered sludge and also add cement to darker the color of the mix while adding lime to lighter the color of the mix. In this chapter, an effective method was developed and optimum conditions were identified to produce dry powdered sludge from Biyagama DWTP sludge. The developed putty properties should be compared with existing putty products and the real-scale performances of the developed putty mix should be studied, and the relevant experiments were conducted in the next chapter.

CHAPTER 07: DEVELOPMENT OF WALL PUTTY AND REAL-SCALE APPLICATION

7.1. General

The shelter is a main requirement of humans and from prehistoric times shelters were used to prevent extreme natural conditions; such as rain, wind, and UV radiation, and to protect from animals. In the beginning, primitive structures were used as shelters and with civilization building constructions were developed and improved with the technology development. In prehistoric times, a shelter was a protective structure but present structured buildings are designed with wide verities of activities including living, entertaining and manufacturing [61]. In conventional building construction concepts, walls are constructed using different walling materials and applied with three coatings; a sealer, primer and topcoat, as a wall finisher and a protector (Figure 1.1) [172],[162].

Walling materials are for building wall construction and there are solid walling materials and lightweight walling materials available in the world. In Sri Lanka, solid walling materials are used as the country has tropical climatic conditions [80]. In building constructions commonly used walling materials are burnt clay brick, cement block, Cabook block, cement stabilized earth block and mud concrete block (MCB) [61]. A sealer is a coat designed to inhibit capillary action of the porous substrate and sand cement plaster is the most commonly applied sealer. The wall plaster provides a uniform base for the primer while preventing the migration of extractives from the wall into the primer and top coat. The primer is a coating applied to the sealer to ensure the adhesion of the top coat to the sealer. Wall care putty and lime are commonly applied as a primer in Sri Lanka. The primer protects the plaster while providing uniform base for the top coat. The top coat is the finish coat and wall paints are applied as the top coat. Top coat is the final protective coating and present an aesthetically appealing decorative effect to the wall [162].

After a series of experiments, a method was developed to produce dry powdered alum sludge. The developed dry powdered sludge is applicable as a wall putty for the primer.

And also, it was identified that lime and cement are workable stabilizers for the putty mix. The developed putty mix has natural soil color. Most common commercial putty products consist of white color but color wall putty is also available; which was developed to add aesthetics to the wall. Color putty applies according to the architectural purposes and client requirements. However, the properties of the developed wall putty should be studied and compared with the properties of existing wall putty products. Therefore, experiments were conducted to identify the properties including physical properties and durability performances of the developed wall putty and the existing wall finishes. With the findings, the real-scale behavior of the developed wall putty can be analyzed. And the experimental procedures and results will be discussed in this chapter.

7.2. Selection of Stabilizer

The dry powder developed using DWTP waste sludge can apply as a wall putty. As discussed in the previous chapter, a stabilizer should be added to improve the putty properties of the mix. According to the literature, wall putty materials are developed with the characteristics of; high bonding strength, moisture barrier, high durability and low bio-receptivity. To improve those putty properties, the existing wall putty products are also applied after mixing with cement as a stabilizer. Next experiments were conducted to identify a workable stabilizer and the optimum mixing ratio for the sludge wall putty.

Stabilizers such as, cement, lime and styrene acrylic binder (Figure 7.1) were selected for the study. Cement was selected, as it is the stabilizer used with the existing wall putty products. The existing wall putty products are made of lime and styrene acrylic binder is developed with a styrene-acrylic polymer which is used to develop primers; so, lime and styrene acrylic binder were included in the experiments. Ten putty mixtures were prepared by mixing sludge dry powder with selected stabilizers according to the mix design as shown in Table 7.1. Mix 1 was the controller was prepared without a stabilizer. Dry powder and stabilizers mixing proportions were prepared by weight basis according to the mix design and mixed by a mechanical mixer. Experiments were conducted to test the bonding strength, bio receptivity and durability of mixtures; and three replicates from each mixture were used for the experiments.

Figure 7.1: Stabilizers selected for the experiments

Table 7.1: Mix design for sludge putty mixtures with stabilizers

Mix	Sludge Putty (%)	Cement (%)	Lime (%)	Binder (%)
1	100	-	-	-
2	95	5	-	-
3	90	10	-	-
4	85	15	-	-
5	90	-	10	-
6	75	-	25	-
7	50	-	50	-
8	90	-	-	10
9	75	-	-	25
10	50	-	-	50

7.2.1. Bonding strength variation with stabilizers

Bond strength refers to the amount of adhesion between bonded surfaces which generally involves a determination of the stress required to rupture a bond formed by an adhesive between the two surfaces. Bond strength is measured in the terms of force needed to separate a layer of material from the base where it is bonded. The nature of the coating surface affects the bonding strength [173]. The bonding strength of a wall finisher can be described as the adhesion of the wall finishing layer to the plaster surface. When the wall finisher is applied to a plaster surface there are several physical, mechanical and chemical forces created in between the finishing coat and the plaster surface. Those forces bonded the two surfaces together and the bonding strength measured the failure point of those forces where the material was subjected to scaled off from the surface [174],[175].

When considering the bonding strength, cohesion and adhesion are important interactions to be determined. Cohesion refers to the bonding forces of the molecules of the same material. And adhesion refers to the bonding forces between two different surfaces. Both bonding strengths are important to consider when developing a wall finisher [176]. There are different bonding strength test methods for materials with different purposes.

A lap shear test was conducted to test the bonding strength of the mixtures, according to the ASTM D5868-014 test standards [116]. Plaster panels were prepared with the dimensions of 15cm×5cm×2.5cm (Figure 7.2 (a)) and putty mixtures were applied on one surface with 1mm thickness as shown in Figure 7.2 (b). After drying putty samples, a high solid epoxy adhesive was applied to the putty surface and two samples with the same mix were bonded together as shown in Figure 7.2 (c). Samples were cured and after the adhesive dried completely the lapse shear test was conducted using a universal testing machine (Figure 7.3 (a)). A force is applied to the directions as shown in Figure 7.3 (b), and increased until the bond fails. The highest possible joint strength; where the materials separate, is identified, and also the bond-breaking pattern was observed. There are four possible crack patterns identified according to the literature as shown in Figure 7.3 (c) [116]. By identifying the bond-breaking crack patterns adhesiveness of the putty mix can be critically analyzed as shown in Table 7.2 [177].

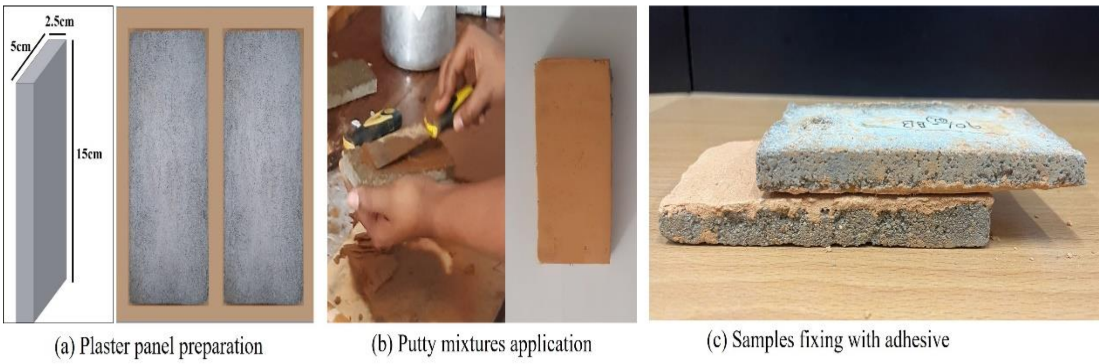


Figure 7.2: Sample preparation for bonding strength test of sludge putty mixtures with stabilizers

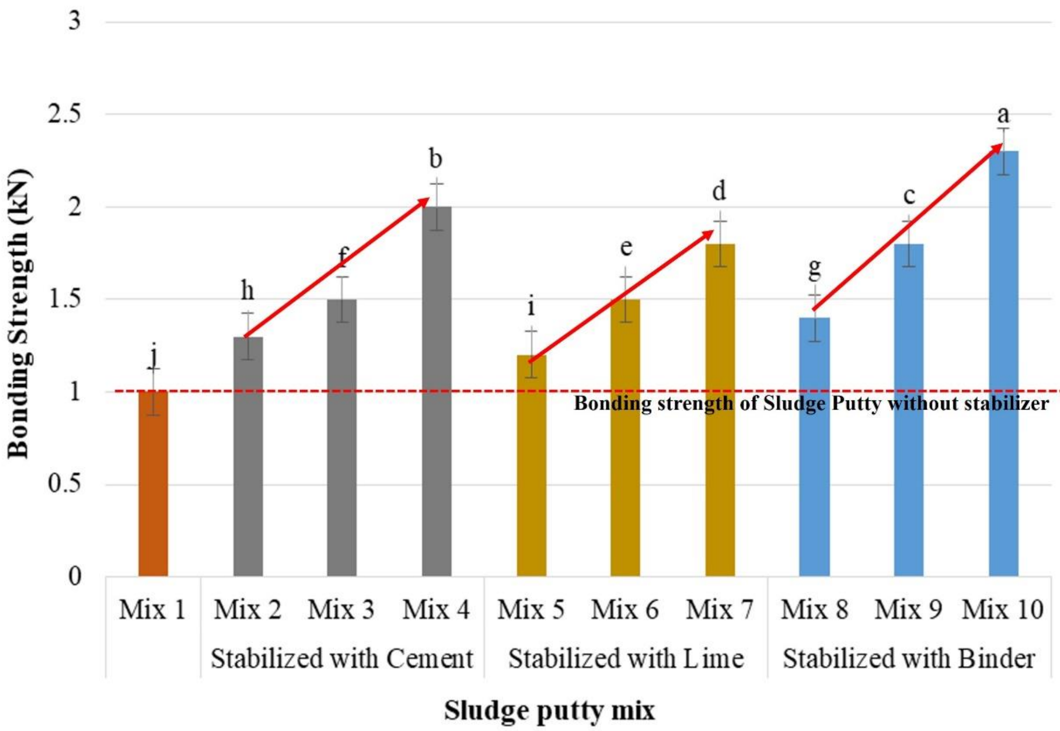
(a) Conducting bonding strength test (b) Shear load applying direction (c) Possible crack patterns

Figure 7.3: Bonding strength test of sludge putty mixtures with stabilizers

Table 7.2: Analysing the nature of bonds between putty mix and plaster according to the crack pattern [116]

Result	Nature of the bond
Fiber-Tear Failure	Bond strength of putty < Bond strength of plaster material
Stock-Break Failure	Bond strength of putty > Bond strength of plaster material
Adhesive Failure	The low bond strength between putty and plaster material
Cohesive Failure	The high bond strength between putty and plaster material

Three replicates of each mix were tested and the average bonding strength value was calculated. Results of the test were statistically analyzed (Appendix – IV) and the variation is shown in Figure 7.4. According to the test results, mix 1 (sludge putty without stabilizer) has the lowest strength value, and mix 10 (putty mix stabilized with 50% styrene acrylic binder) has the highest strength value. All ten mixtures' bonding strength values are significantly different from each other. All the mixtures mixed with stabilizer have a higher bonding strength value than the sludge putty mix without stabilizer; also, the bonding strength value increase with the increase of stabilizer proportion in each mixture. When comparing the three stabilizers, a significant increase in bonding strength value is observed in the mixtures stabilized with styrene acrylic binder compared to other mixtures. However, it can be concluded that stabilizers increase the bonding strength of the sludge putty mix and the crack pattern should be analyzed to select the most workable stabilizer.



*Vertical bars indicate the standard errors of the mean bonding strength value (n = 3)
*Means do not share a same letter are significantly different

Figure 7.4: Bonding strength variation of putty mixtures with stabilizers

In the bonding strength test, three crack patterns were observed from the four possible crack patterns and the frequency of each crack pattern was statistically analyzed as shown in Figure 7.5. According to the observations fiber-tear failure, cohesive failure and adhesive failure are observed within the samples and stoke-break failure is not observed. Cohesive failure is observed with the highest frequency (50%) and fiber-tear failure is observed with the lowest frequency (20%).

The nature of the bond of each mix was analyzed according to the crack pattern as shown in Table 7.3. Adhesive failure is observed in mix1, mix2 and mix 5; so, there is a low bond strength between the putty and the plaster panel of each mix. Fiber-tear failure is observed in mix3 and mix6; so, the bond strength of putty mix is less than the bond strength of plaster. Cohesive failure is observed in mix4, mix7, mix8, mix9 and mix10; so, there is a high bond strength between the putty and the plaster panel of each mix. Therefore, the putty mixtures observed cohesive failure is tightly bound to the plaster panel, and the most workable stabilizers are included also the sludge putty mix do not tightly bound to the plaster panel without a stabilizer. All the putty mixtures prepared by mixing styrene acrylic binder are tightly bound to the plaster panel and other mixtures are tightly bound with the highest percentages only (cement 15% and lime 50%). Therefore, cement and lime should be added in high amounts to increase the bonding strength of the putty mixture while the bonding strength can be increased with a lower amount of styrene acrylic binder; styrene acrylic binder is the most workable stabilizer for sludge putty compared to cement and lime.

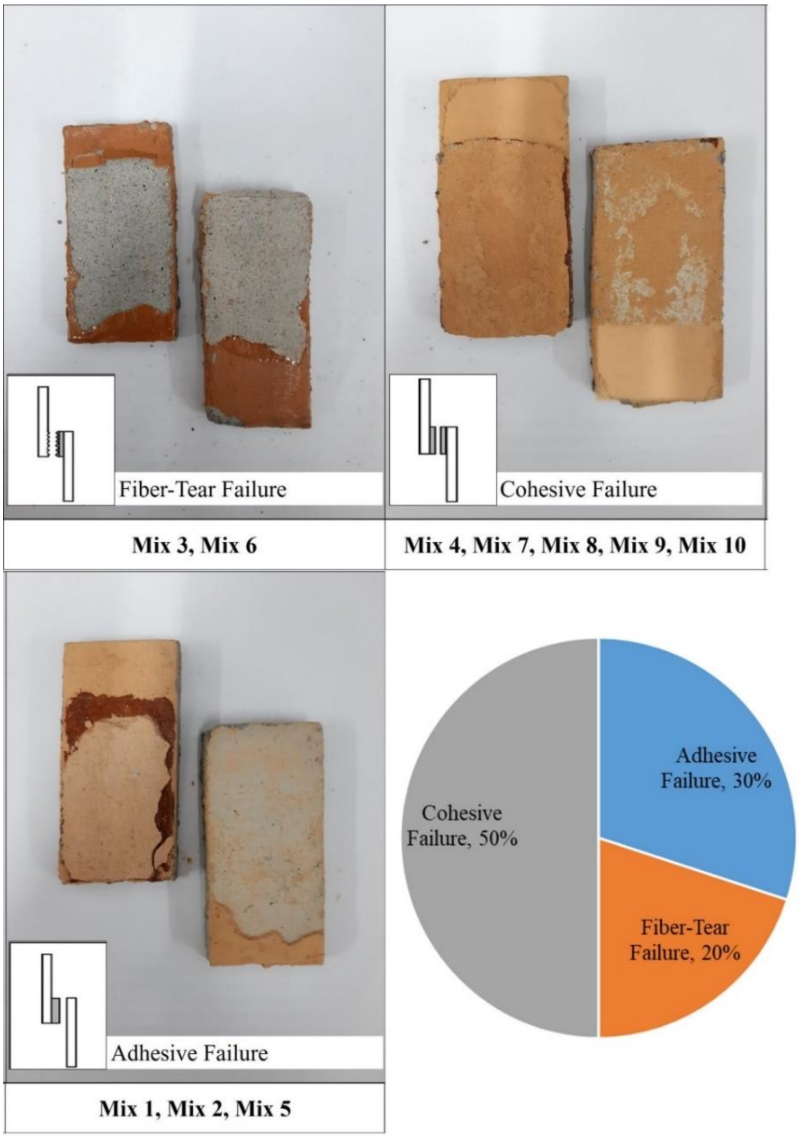


Figure 7.5: Crack patterns variation of putty mixtures with stabilizers

Table 7.3: Analysis of the bond of putty mixtures variation with stabilizers

Mix	Sludge Putty (%)	Cement (%)	Lime (%)	Binder (%)	Observed crack pattern	Nature of the bond of the mix
1	100	_	_	_	Adhesive Failure	Low bond strength between putty and plaster material
2	95	5	_	_	Adhesive Failure	Low bond strength between putty and plaster material
3	90	10	_	_	Fiber-tear Failure	Bond strength of putty < Bond strength of plaster material
4	85	15	_	_	Cohesive Failure	High bond strength between putty and plaster material
5	90	_	10	_	Adhesive Failure	Low bond strength between putty and plaster material
6	75	_	25	_	Fiber-tear Failure	Bond strength of putty < Bond strength of plaster material
7	50	_	50	_	Cohesive Failure	High bond strength between putty and plaster material
8	90	_	_	10	Cohesive Failure	High bond strength between putty and plaster material
9	75	_	_	25	Cohesive Failure	High bond strength between putty and plaster material
10	50	_	_	50	Cohesive Failure	High bond strength between putty and plaster material

7.2.2. Bio receptivity variation with stabilizers

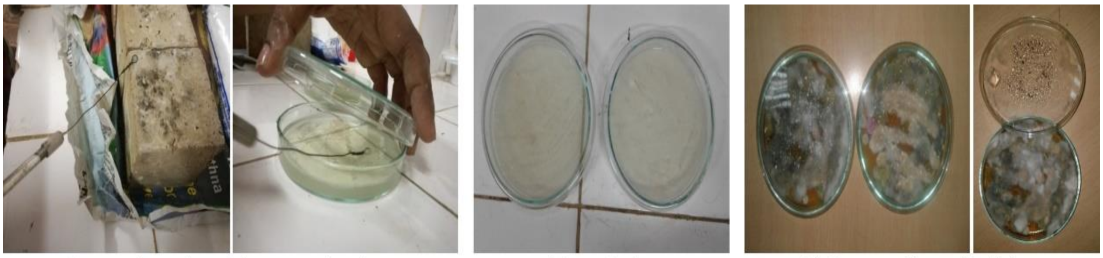
The ability of a material to be colonized by a living organism is defined as the 'Bio-receptivity' [125]. Bio-receptivity of the walling materials is depending on the intrinsic properties of the material [126],[127]. High humid and moist conditions facilitate the bio-receptivity of building walls. Water is the main requirement for living organisms for their metabolic activities. Walling materials absorb water when they are exposed to water during rain or flood conditions or exposed to a high relative humidity environmental condition. Building walls become wet when expose to heavy rain conditions under tropical climatic conditions; and wetted wall finishing materials increase the material bio-receptivity [128],[129]. Fungus growth on wall putty under wet conditions can be identified as the most common effect when exposed to highly humid environments and rain.

A fungus is a microscopic level living creature that is not visible to the human eye. But the fungus is visible to human eyes when they are colonized. Funguses are classified under the kingdom fungi; as eukaryotes. Fungus derives nutrients through the degradation of biological residues containing the surface where the fungus is attached [130],[131]. The fungus can colonize most of the habitats in the world; including land, underground, soil, surface waters and oceans. Fungus growth is accelerated by high humid and moist conditions [131],[130]. Therefore, the fungus can successfully colonize building surfaces under highly humid and moist conditions. Fungus growth results in damage to the building walls while resulting in health problems for the building occupants. The sludge putty is developed to apply to a wall as the primer and the primer should be a protective layer for the wall. Therefore, a fungus growth test was conducted to study the bio receptivity variation of the sludge putty with stabilizers.

Bio receptivity of putty mixtures was tested by conducting a fungus growth test according to the ASTM D3273-94 test standards [168],[62]. Cement plaster panels were cast according to the size of 5cmx15cmx2.5cm as shown in Figure 7.6. Putty mixtures were applied on one surface of each sample with 1mm thickness and cured the putty surface until completely dry.

Figure 7.6: Sample preparation for fungus test of sludge putty mixtures with stabilizers

After the preparation of samples, a fungus test chamber was prepared. To do that fungus, culture was prepared as shown in Figure 7.7. Potato dextrose agar media was used as the culture media and fungus spores; from existing fungus samples on a mud brick, were transformed into the growth media using an inoculating loop and incubated for 7 days. After seven days [124],[62].



(a) Transformation of fungus stock culture (b) Incubation (c) Fungus culture after 7 days

Figure 7.7: Fungus culture preparation

A glass environmental chamber was prepared for the test as shown in Figure 7.8. The chamber was filled with wetted fungus growth media; which contains topsoil, compost and coir dust, up to 1 inch from the bottom. Then the chamber was incubated for 24 hrs. After that, the prepared fungus culture was transferred to the growth media in the environmental chamber and incubated for 14 days.

Figure 7.8: Fungus test chamber preparation

The putty surfaces of the test samples were captured before hanging them in the test chamber. After 14 days of incubation period test samples were vertically hung in the chamber according to the ASTM D3273-94 test standards as shown in Figure 7.9. Samples were hanged for four weeks (one month) and after that samples were taken out from the chamber and the putty surfaces were captured. Putty surfaces were compared before and after to identify fungus growth on the putty surface and to measure the fungus growth area. The results of the fungus growth test are shown in Figure 7.10. According to the observations, fungus growth is not observed on any putty surface. Therefore, it can be concluded that sludge putty mixtures do not support fungus growth and it is not affected by selected stabilizers.

Figure 7.9: Fungus growth test of sludge putty mixtures with stabilizers

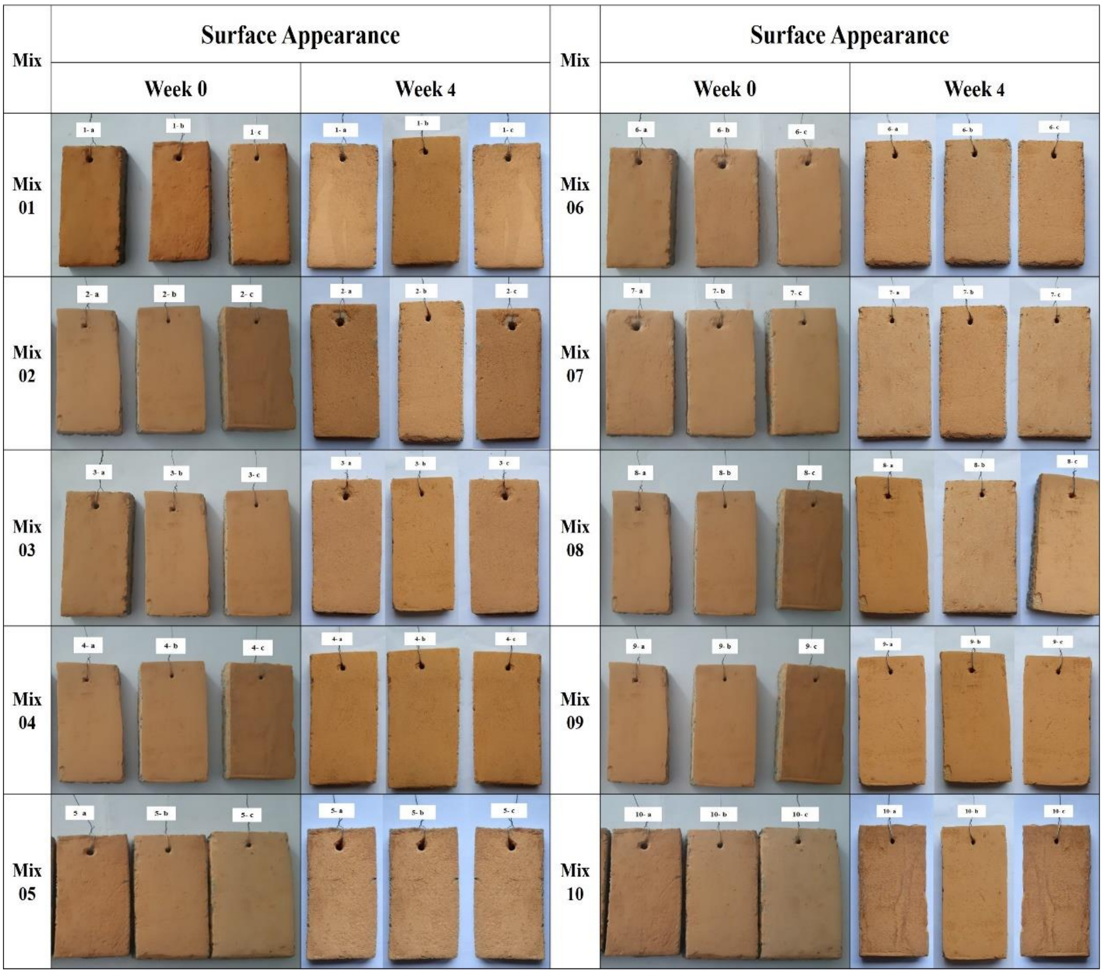


Figure 7.10: Fungus growth comparison of sludge putty mixtures with stabilizers

7.2.3. Durability variation with stabilizers

Durability can be defined as the safe performance of a structure or a portion of a structure for its expected design life. A protective wall finishing surface that resists surfacing deterioration such as wetting, abrasion and drying is required for the durability of the building. The ability to resist deterioration due to cycles of wetting, abrasion and drying characteristics of the humid tropics is the main property depicted by the durable walling surfaces. Abrasion in humid tropical climates is mainly a process of erosion by water flow and by rain impact rather than by wind. These factors cause undesirable properties such as loss of strength when saturated with water, erosion due to wind or driving rain leading to poor dimensional stability in building structures. Therefore, it is important to study the wall putty surfaces in the sense of durability; so, the durability of the putty mixtures was tested considering the rain impact on the surface. Accelerated erosion test was conducted [84],[86],[120].

Samples were prepared to conduct the spray erosion test as shown in Figure 7.11. Cement plaster panels were prepared with the dimensions of 1feet×1feet×1inch and putty mixtures were applied on one surface of the panel. Three replicates from each mix were applied and cured until the putty surface was completely dry. After completion of the test, samples were weighed to record the dry weight of the sample before exposure for the spray erosion test.


(a) Cement plaster panels (b) Putty applied plaster panels (c) Samples weighing before and after the test

Figure 7.11: Sample preparation for spray erosion test of sludge putty mixtures with stabilizers

Once the samples were weighted, a spray erosion test was conducted as shown in Figure 7.12 [86]. In the test, pressurized water was sprayed horizontally onto the material surface for one hour (60 min). Samples were placed at a distance of 500 mm away from a spray nozzle and water was sprayed with a pressure of 50kPa. Each sample was exposed to water for one hour with a surface area of 150 mm diameter. After completion of the test, the sample was dried completely and the weight of the dry sample was recorded to calculate the mass loss of the sample to determine the scaled-off factor (SOF).

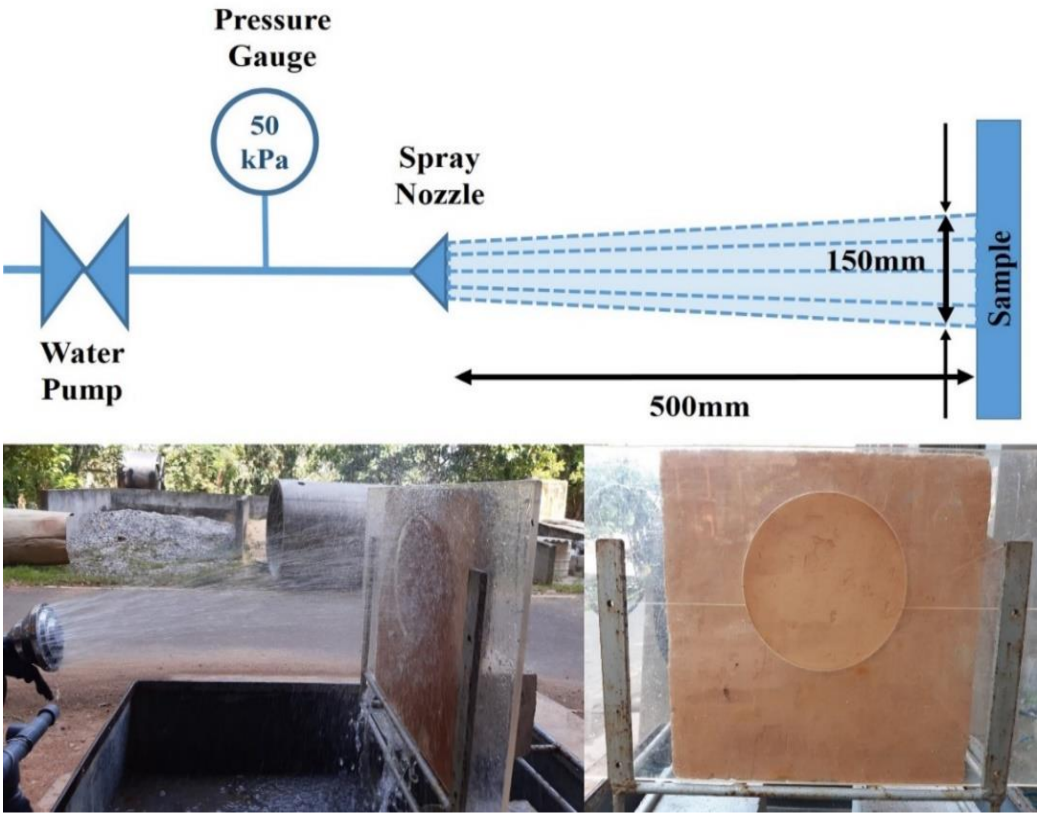
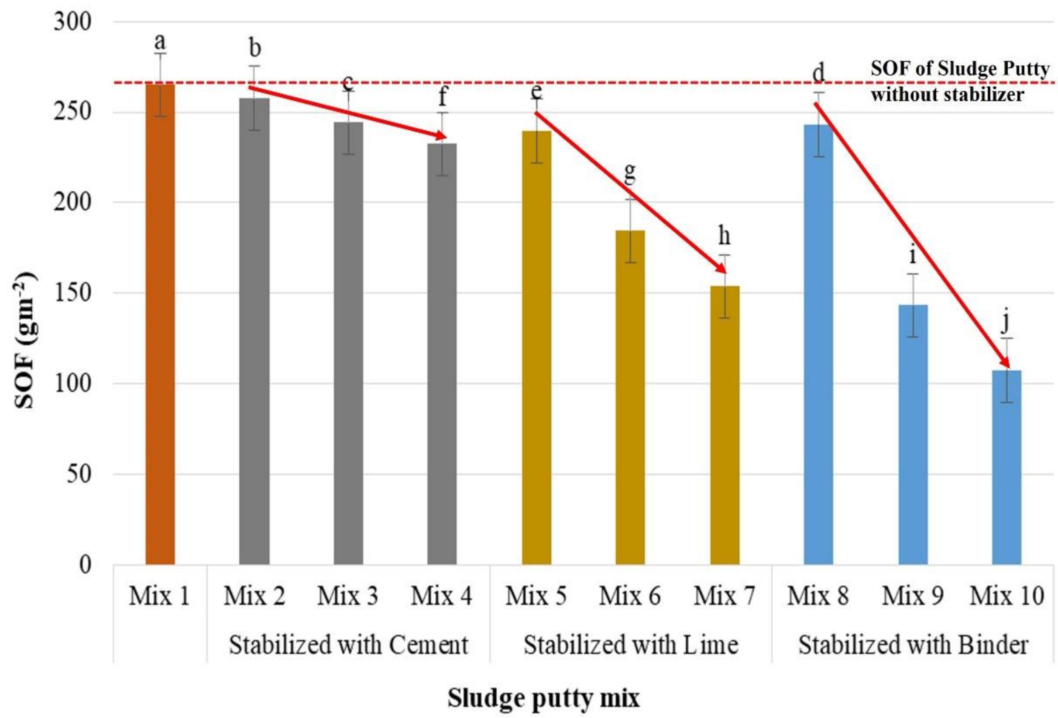


Figure 7.12: Spray erosion test of sludge putty mixtures with stabilizers

SOF was calculated to determine the number of particles that scaled off from the putty surface when expose to heavy rain conditions [75],[120]. SOF was calculated using equation 7.1; where W1 refers to the weight (g) of the sample before the test, W2 refers to the weight (g) of the sample after the test and A refers to the area (m^2) of the sample.

$$SOF\ (gm^{-2}) = \frac{W1-W2}{A} = \text{..Equation 7.1}$$

Three replicates of each mix were tested and the average SOF value was calculated for each mix. Results of the test were statistically analyzed (Appendix – V) and the variation is shown in Figure 7.13. According to the test results, mix 1 (sludge putty without stabilizer) has the highest SOF value, and mix 10 (putty mix stabilized with 50% styrene acrylic binder) has the lowest SOF value. All ten mixtures' SOF values are significantly different from each other. All the mixtures mixed with stabilizer have lower SOF values than the sludge putty mix without stabilizer; also, the SOF value increase with the increase of stabilizer proportion in each mixture. When comparing the three stabilizers, a significant decrease in SOF value with a higher rate is observed in the mixtures stabilized with styrene acrylic binder compared to other mixtures. However, it can be concluded that stabilizers improve the durability of sludge putty mixtures against rain surfaces and styrene acrylic binder is the most workable stabilizer for that.



*Vertical bars indicate the standard errors of the mean SOF value (n = 3)
*Means do not share a same letter are significantly different

Figure 7.13: Spray erosion test results of sludge putty mixtures with stabilizers

7.3. Comparison with Existing Wall Finishes

With the increase in building constructions, the demand for wall finishes is increasing. Wall care putty is the most commonly applied material as the primer layer for both interior and exterior wall surfaces. Wall care putty is applied as a leveling material on the wall plaster and acts as a protective layer for the wall plaster while providing a strong and durable base for the top coat. Wall putty materials are developed with the characteristics of high bonding strength, moisture barrier, high durability and low bio-receptivity. And also the putty materials are developed with the ability to fill dents and hair cracks to level the rough surface of the plaster [108].

Lime was the traditional wall putty material widely applied in past constructions. At present, there are different types of wall putty products available in the market; such as white cement putty, acrylic putty and Plaster of Paris (POP). White cement wall putty is a putty product commercially available in powder form; and it is developed with a mineral, white cement and polymer. The powder is applied after mixing with water. There are different white cement-based wall putty products are available in the market from different commercial brands. Each brand has different properties. Acrylic wall putty is a ready-use putty mix, developed with acrylic polymers and other chemicals. POP is a powder material developed with gypsum and the putty mix is prepared by mixing the powder with water [109]. Talcum, quartz, gypsum and cement are the main raw materials for most commercial wall putty materials and the material should consist of the engineering properties of high bonding strength, good performance of crack resistance, excellent resistance to water, shrinkage as well as flexibility [108].

In this research study, a wall putty was developed from DWTP sludge which is applicable as a primer. And styrene acrylic binder was selected as the stabilizer for the sludge putty. Wall care putty developed from calcium carbonate and lime slurry is the existing wall finishes used for the primer in Sri Lanka. Therefore, the performance of the developed wall putty was tested and compared with existing wall finishes. Therefore, the most commonly used three putty products and lime were selected to test properties along with the developed sludge putty.

7.3.1. Material selection

In the research, commercially available primers were collected from the market. As the research study was conducted at the University of Moratuwa, hardware stores located around the university premises were selected to purchase wall putty products. An area with a 1.5km distance around the university was identified using Google Maps as shown in Figure 7.14; the locations of hardware stores within the area were collected. Therefore, fifteen hardware stores were identified and after contacting those, details were collected regarding available wall putty products and their sales record for one year time period. According to the collected data, nine commercial putty products were identified which are commercially available around the area where the research study is conducted. And the properties of each product were collected from material specifications (Appendix – VI). Those three putty products with the highest sales records were selected for the study as shown in Table 7.4. And lime was also selected for the study as it is a widely used traditional material applied as a primer in Sri Lanka. Selected materials are shown in Figure 7.15.

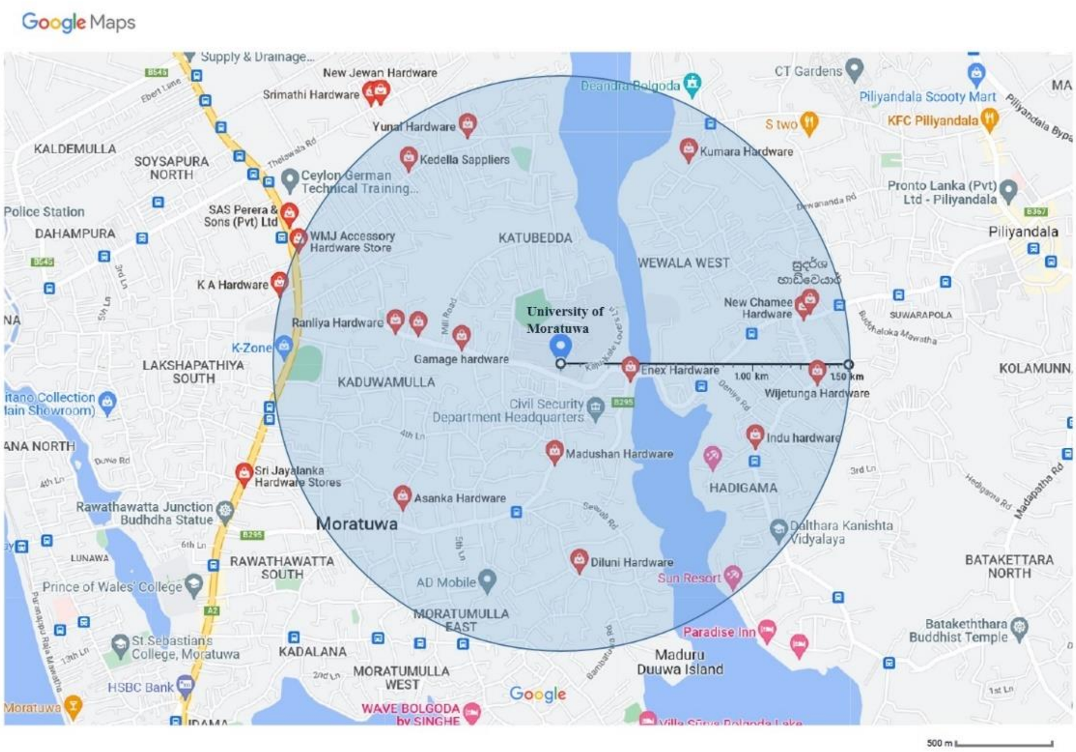


Figure 7.14: Hardware stores selected to purchase commercially available wall putty products

Table 7.4: Properties of selected commercial putty products

Putty	Putty form	Raw Materials Used	Water Demand by Volume	Maximum Thickness	Coverage
P1	Powder	White cement, re-dispersible polymer, functional additives	36 - 40 %	1.5 mm (2 Coats)	20 - 25 sqfeets/kg on Single Coat (Varies with Surface Quality)
P2	Powder	White cement, Dolomite	30 - 35%	3 mm (2 Coats)	16 sqfeets/kg on Single Coat (Varies with Surface Quality)
P3	Powder	$CaCO_3$, white cement	35 - 40%	3 mm	12.5 sqfeets/kg on single Coat (Varies with Surface Quality)

Five mixtures were prepared for the study by mixing materials according to the mix design shown in Table 7.5. Mix 1 was prepared by mixing lime with water. Selected three putty products were mixed with 10% cement by weight and sludge putty mix was prepared by mixing with 25% styrene acrylic binder by weight. The mixtures were mixed in the mechanical mixer. Experiments were conducted to test the bonding strength, bio receptivity and durability of mixtures; and three replicates from each mixture were used for the experiments.

Figure 7.15: Wall finishes selected for the comparison

Table 7.5: Mix design for preparation of putty mixtures

Mix	Lime (%)	P1 (%)	P2 (%)	P3 (%)	Sludge Putty (%)	Cement (%)	Binder (%)
1	100	-	-	-	-	-	-
2	-	90	-	-	-	10	-
3	-	-	90	-	-	10	-
4	-	-	-	90	-	10	-
5	-	-	-	-	75	-	25

7.3.2. Bonding strength comparison of different wall finishes

To test the bonding strength of the mixtures, the lap shear strength test was conducted according to the ASTM D5868-014 test standards [116]. Plaster panels were prepared with the dimensions of 15cm×5cm×2.5cm (Figure 7.16 (a)) and mixtures were applied on one surface with 1mm thickness as shown in Figure 7.16 (b). After drying the samples wall filler was applied on mix2, mix3 and mix4, and sealer was applied on mix5 as the top coat. After completion of sample preparation, a high solid epoxy adhesive was applied on the surface and two samples with the same mix were bonded together as shown in Figure 7.16 (c). Samples were cured and after the adhesive dried completely the lapse shear test was conducted using a universal testing machine (Figure 7.17 (a)). A force is applied to the directions as shown in Figure 7.17 (b), and increased until the bond fails until the materials separate and highest possible joint strength is identified and also the bond breaking pattern was observed. There are four possible crack patterns identified according to the literature as shown in Figure 7.17 (c) [116]. By identifying the bond-breaking crack patterns adhesiveness of the putty mix can be critically analyzed as shown in Table 7.2 [177].

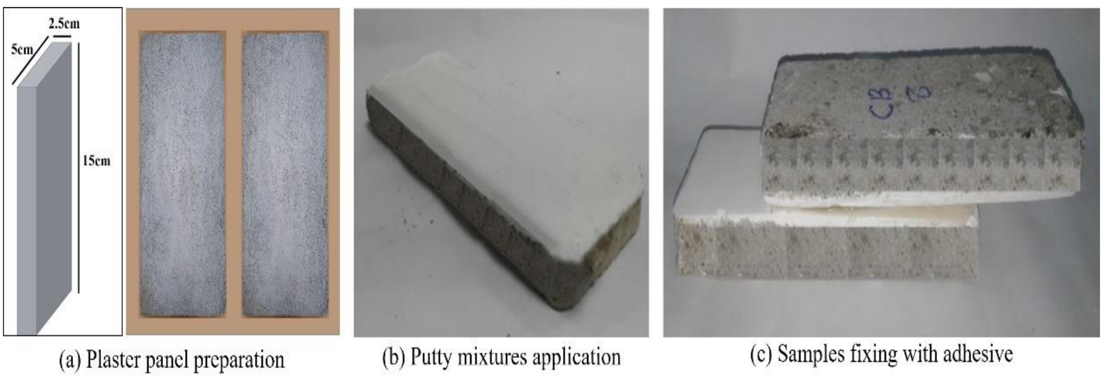


Figure 7.16: Sample preparation for bonding strength comparison of different wall finishes

Figure 7.17: Bonding strength test conducted for comparison of different wall finishes

Three replicates of each mix were tested and the average bonding strength value was calculated. Results of the test were statistically analyzed (Appendix – VII) and the variation is shown in Figure 7.18. According to the test results, mix 1 (lime mix) has the highest strength value and mix 3 (P2 putty mix stabilized with 10% cement) has the lowest strength value. The bonding strength of mix1 and mix2 is not significantly different from each other and significantly different from the other three mixtures. The bonding strength of mix2 and mix5 is not significantly different from each other and significantly different from the other three mixtures. The bonding strength of mix3, mix4 and mix5 is not significantly different from each other and significantly different from the other two mixtures. Therefore, the bonding strength of sludge putty stabilized with 25% styrene acrylic binder by weight is not significantly different from commercial putty products and it is significantly different from lime. In the test cohesive failure is the only crack pattern observed among the samples. So, there is a high bonding strength between all mixtures and plaster panels. Therefore, all the selected wall finishes were tightly bound to the plaster surface.

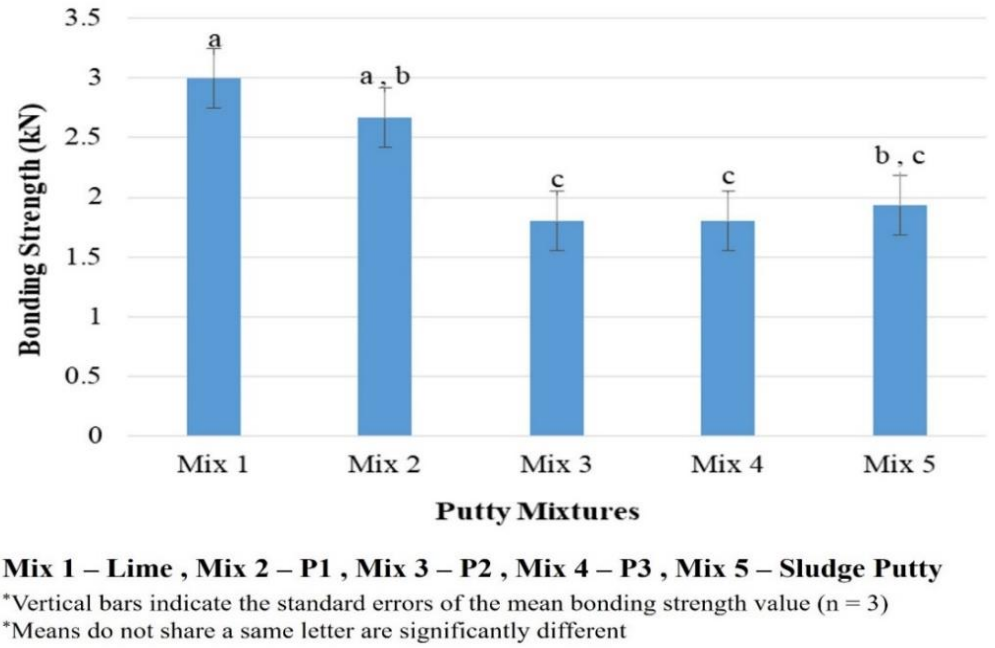


Figure 7.18: Bonding strength variation of different wall finishes

7.3.3. Bio receptivity comparison of different wall finishes

Bio receptivity of the mixtures was tested by conducting a fungus growth test according to the ASTM D3273-94 test standards. Cement plaster panels were cast according to the size of 5cmx15cmx2.5cm as shown in Figure 7.19 (a). Mixtures were applied on one surface of each sample with 1mm thickness and cured until completely dry. Wall filler was applied on the samples of mix2, mix3 and mix4 and a sealer was applied on samples of mix5 as the top coat. After the preparation of samples, the surface appearance of each sample was captured before being hung in the fungus test chamber. Samples were hanged in the chamber (Figure 7.19 (b)) for four weeks (one month) duration and after that samples were taken out from the chamber and the surfaces were captured. Surfaces were compared before and after to identify fungus growth on the samples. The results of the fungus growth test are shown in Figure 7.20. According to the observations, fungus growth is not observed on any sample surface as all the selected wall finishes do not support fungus growth.

(a) Sample preparation (b) Samples hang in fungus test chamber

Figure 7.19: Sample preparation for comparison of fungus growth of different wall finishes

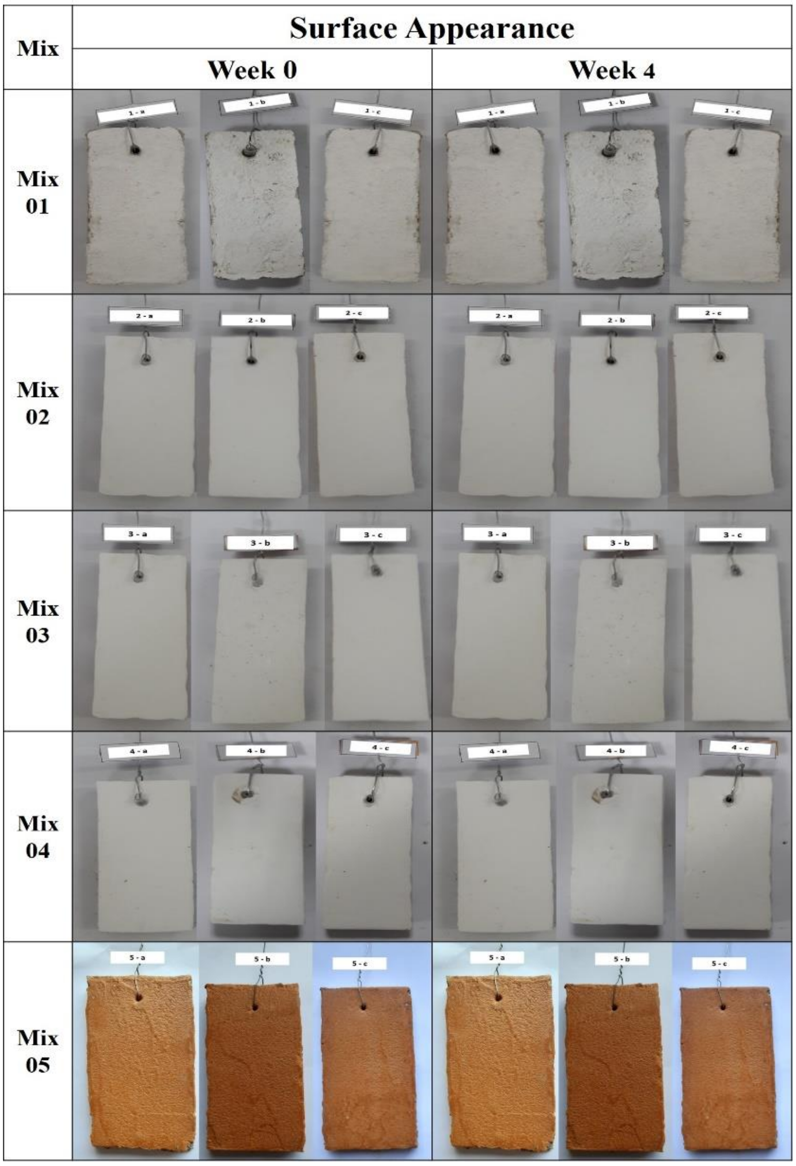


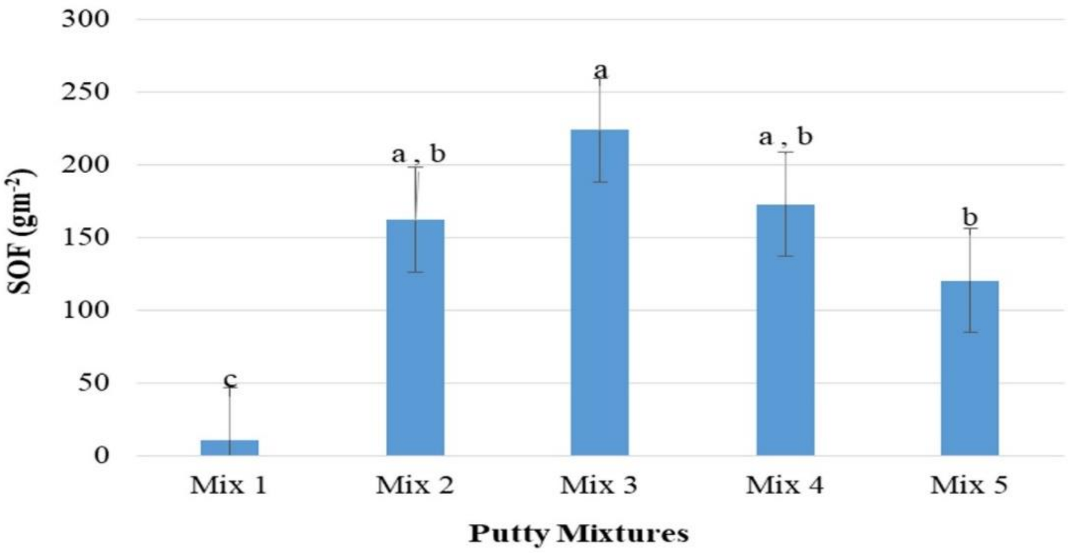
Figure 7.20: Surface appearance of different wall finishes before and after the fungus test

7.3.4. Durability comparison of different wall finishes

The durability of the mixtures was tested considering the rain impact on the material. An accelerated erosion test was conducted and samples were prepared as shown in Figure 7.21. Cement plaster panels were prepared with the dimensions of 1feetx1feetx1inch and mixtures were applied on one surface of the panel. Three replicates from each mix were applied and cured until the putty surface was completely dry. Wall filler was applied on the samples of mix2, mix3 and mix4 and sealer was applied on samples of mix5 as the top coat. After completion of the test, samples were weighed to record the dry weight of the sample before exposure for the spray erosion test. Once the samples were weighted, a spray erosion test was conducted as shown in Figure 7.12. After completion of the test, the sample was dried completely and the weight of the dry sample was recorded. SOF was calculated to determine the number of particles that are scaled off from the surface using equation 7-1.

Figure 7.21: Sample preparation and spray erosion test for comparison of different wall finishes

Three replicates of each mix were tested and the average SOF value was calculated for each mix. Results of the test were statistically analyzed (Appendix – VIII) and the variation is shown in Figure 7.22. According to the test results, mix 1 (lime mix) has the lowest SOF value and mix 3 (P2 putty mix stabilized with 10% cement) has the highest SOF value. SOF of mix2, mix3 and mix4 is not significantly different from each other and significantly different from the other two mixtures. SOF of mix2, Mix4 and mix5 is not significantly different from each other and significantly different from the other two mixtures. SOF of mix1 is significantly different from the other four mixtures. Therefore, the SOF of sludge putty stabilized with 25% styrene acrylic binder by weight is not significantly different from P2 and P4 commercial putty products and it is significantly different from lime and P3.



Mix 1 – Lime , Mix 2 – P1 , Mix 3 – P2 , Mix 4 – P3 , Mix 5 – Sludge Putty

*Vertical bars indicate the standard errors of the mean SOF value (n = 3)

*Means do not share a same letter are significantly different

Figure 7.22: SOF variation of different wall finishes

7.4. Real Scale Application

After a series of experiments, a wall putty was developed from DWTP waste sludge. A dry powder was developed from the wet sludge and a workable wall putty mix was developed. The developed wall putty mix was tested under laboratory conditions and acquired results. To analyze the real scale behavior of the developed wall putty mix it was applied on a few building walls including both interior and exterior surfaces as shown in Figure 7.23. Sludge putty was produced in large amounts and provided to skilled laborers and applied to walls following the procedure mentioned in Figure 7.24. During the real-scale application comments and suggestions were collected from skilled laborers for further improvements to the product. And also, the putty surface variation, when exposed to real environmental conditions, was observed for a one-year time duration.

Figure 7.23: Real-scale applications of the sludge putty

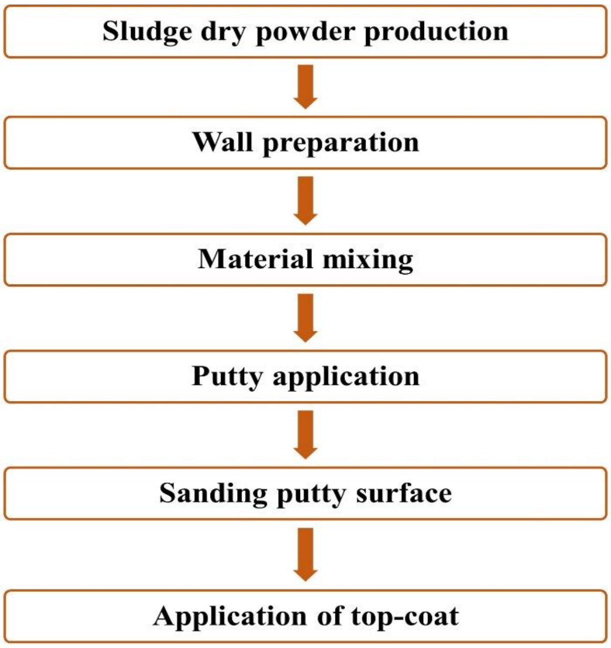


Figure 7.24: Sludge putty application procedure

7.4.1. Sludge dry powder production

To apply the putty on a real scale large amount of sludge dry powder was required. So 10kg of sludge dry powder was produced following the dry powder production steps as shown in Figure 7.25.

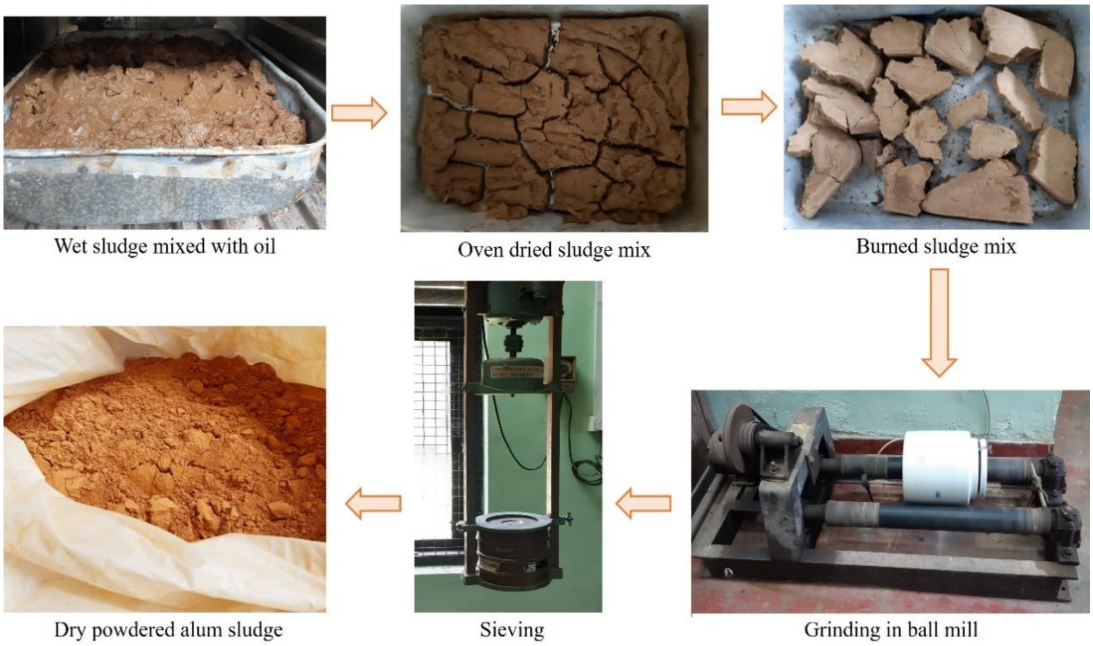


Figure 7.25: Sludge dry powder production for real-scale application

7.4.2. Wall preparation

The Block wall should be plastered before applying sludge putty. So, the selected block walls were plastered with sand cement plaster as shown in Figure 7.26. Plaster mix was prepared by mixing cement and sand with a ratio of 1:5. Plastered wall was cured for 24 hours to completely dry and sludge putty was applied.

Figure 7.26: Wall preparation for putty application

7.4.3. Material mixing

Putty mix was prepared by mixing sludge dry powder and styrene acrylic binder with a ratio of 3:1 adding water. The natural soil color gradient of the developed powder is the unique property of the product; therefore, styrene acrylic binder was selected as the stabilizer. Styrene acrylic binder is white but colorless when dry, and there is no influence on the natural color of the product. Putty mixtures were prepared by mixing by hand and using a putty mixer as shown in Figure 7.27. According to the skilled labor feedback mixing using a putty mixer is the most effective mixing option.

Figure 7.27: Mixing the sludge putty mixture

7.4.4. Putty application

The sludge putty mix was applied to the wall plaster as shown in Figure 7.28. For the putty application putty trowel and putty scrapers (Figure 7.29) were used. Sludge putty was applied with a 1mm thickness. After application, the putty surface was cured for two days until completely dry after that the first putty coating can be sanded, and apply the second putty coating where necessary.

Figure 7.28: Sludge putty application on wall plaster

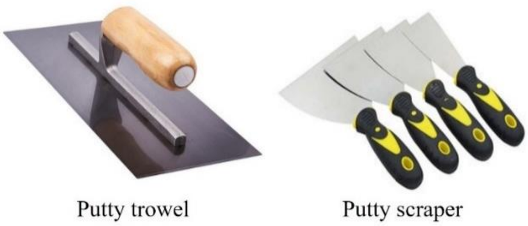


Figure 7.29: Putty application tools

7.4.5. Sanding putty surface

After complete drying of the sludge putty coating, the surface can be sanded with sandpaper as shown in Figure 7.30. Sandpapers with 180 and 200 grit numbers were used in the sanding process. The putty surface should be sanded to obtain a smooth finish surface.

Figure 7.30: Sanding the putty surface with sandpapers

7.4.6. Application of top coat

After sanding the sludge putty surface, a sealer was applied as the finishing top coat as shown in Figure 7.31. The sealer is applied as a protective coating for the sludge putty; which is act as a moisture barrier and increases the durability of the putty surface. And also, the sealer with transparent color was used to preserve the natural color of the sludge putty. The sealer was applied using a sponge to obtain a smooth surface finish avoiding brush marks. The total putty application was done by skilled laborers and at the end of each step, their feedback and comments were recorded. At the end of the process, suggestions were made as shown in Table 7.6

Figure 7.31: Applying sealer on sludge putty surface as a top coat

Table 7.6: Product details developed with skilled labor feedback and observations

Putty form	Powder - 300µm
Best mixing option	Mix using a putty mixer
Best mixing ratio	Dry powder 3: Binder 1
Coverage	10-15ft^2/kg on single coat(vary with surface quality)
Maximum thickness	1mm
Water demand by volume	35 – 40%
Colour	Natural soil color
Recommended applications	For both interior and exterior walls

7.4.7. Real-scale performance analysis

After the application of the sludge putty in real-scale building walls, three walls were selected to analyze the real-scale performance of the putty. Three walls, which were exposed to different conditions were selected for the study. One interior wall and two exterior walls were selected as shown in Figure 7.32. One of the exterior walls (Figure 7.32 (b)) is completely exposed to the exterior environment and the other one (Figure 7.32 (c)) is under shade.

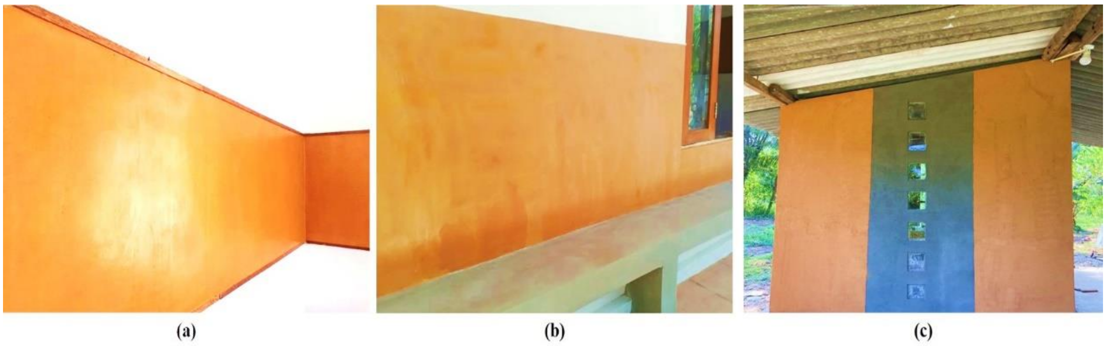


Figure 7.32: Selected sludge putty applied walls to analyze performances; (a) Interior wall (b) exterior wall (c) Exterior wall with shade

Putty surfaces of the selected walls were observed for one year time period. Data were recorded after analyzing the surface monthly. Color variation, scaling off, fungus growth and other variations were observed monthly. Scale off and fungus growth was not observed for the first one-year time duration after putty application. Photos of the putty surface were taken monthly and compared the images to identify the color variation with the time. Color variation of sludge putty applied on the interior wall is shown in Figure 7.33 and a considerable color deterioration was not observed during the first one-year duration. Color variation of sludge putty applied on the exterior wall is shown in Figure 7.34 and a considerable color deterioration was observed after eight months. The exterior wall was directly exposed to sunlight, solar radiations and rainy conditions; but scale-off or fungus growth was not observed. Color variation of sludge putty applied on the exterior wall with shade is shown in Figure 7.35 and a considerable color deterioration was not observed during the first one-year duration.

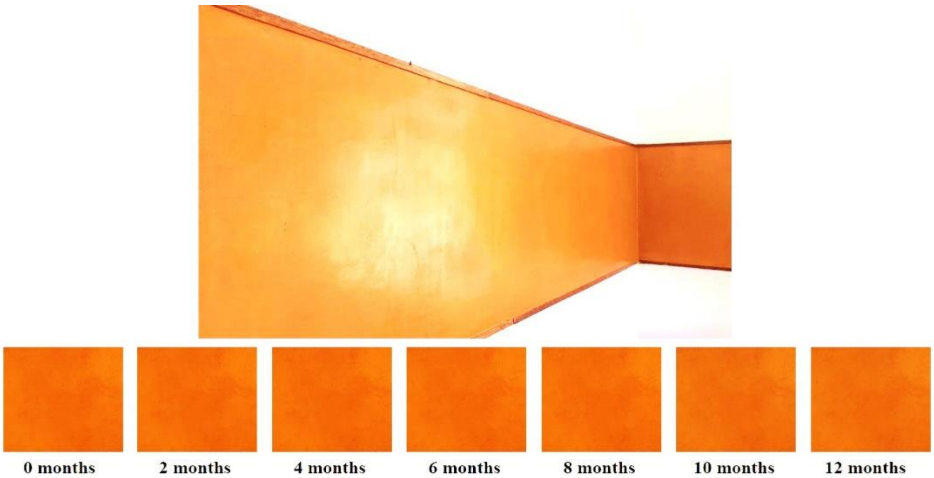


Figure 7.33: Colour variation of the sludge putty applied to an interior wall

Figure 7.34: Colour variation of sludge putty applied on exterior wall

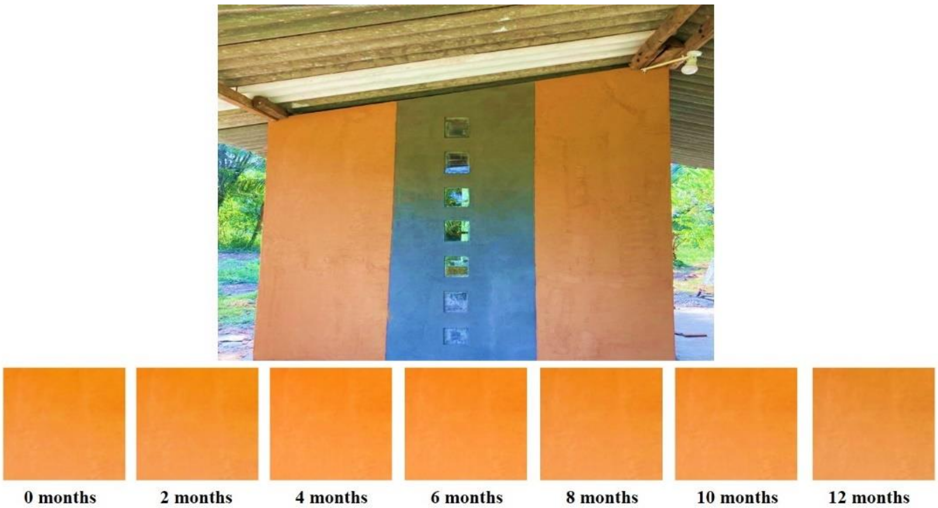


Figure 7.35: Colour variation of sludge putty applied on exterior wall with shade

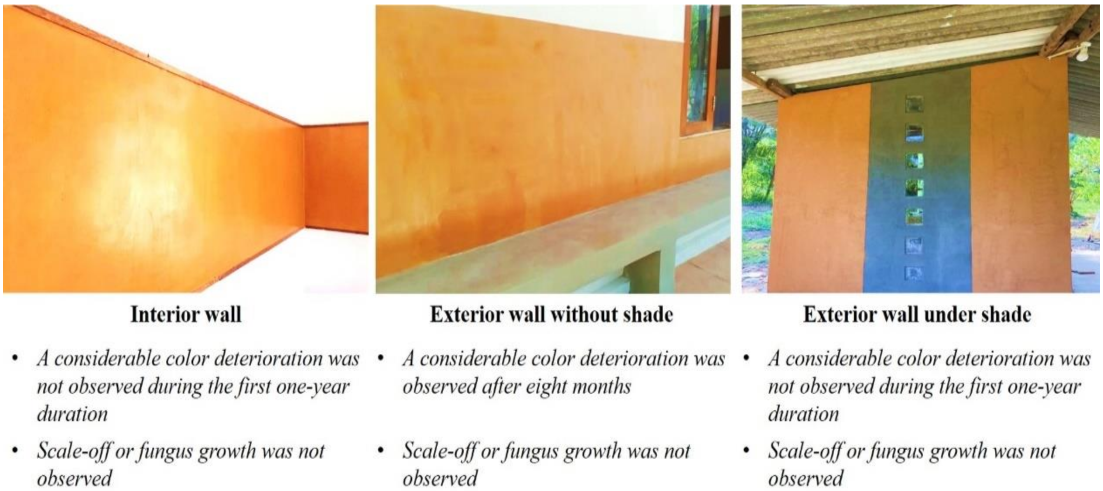


Figure 7.36: Observations of real-scale performances of the developed wall putty

7.5. Summary

In the previous chapter, experiments were conducted to develop a dry powdered sludge with putty properties. DWTP wet alum sludge is harder when dry, due to the activation of alum and it is difficult to powder. However, an effective method was developed and optimum conditions were identified to produce dry powdered sludge. The putty properties should be compared with existing wall finishes and the real-scale performances of the developed putty mix should be studied. In this chapter, experiments were conducted to identify the properties including physical properties and durability performances of the developed wall putty and the existing wall finishes, and analyzed the real-scale behavior of the developed wall putty.

As discussed in the previous chapter, a stabilizer should be added to improve the putty properties of the mix. Therefore, as the first step of this chapter experiments were conducted to identify a workable stabilizer and the optimum mixing ratio for the sludge wall putty. To that three stabilizers were selected; cement, lime and styrene acrylic binder, and performances were tested. Ten different putty mixtures were prepared by mixing sludge putty and stabilizers according to the mix design and bonding strength test, fungus growth test and spray erosion tests were conducted. Sludge putty without mixing stabilizer was remain as the controller for all experiments.

To test the bonding strength of the mixtures, a lap shear strength test was conducted according to the ASTM D5868-014 test standards. All the mixtures mixed with stabilizer have a higher bonding strength value than the sludge putty mix without stabilizer; also, the bonding strength value increase with the increase of stabilizer proportion in each mixture. When comparing the three stabilizers, a significant increase in bonding strength value is observed in the mixtures stabilized with styrene acrylic binder compared to other mixtures. According to the observations fiber-tear failure, cohesive failure and adhesive failure are observed within the samples and stoke-break failure is not observed. Therefore, the putty mixtures observed cohesive failure is tightly bound to the plaster panel and the most workable stabilizers are included also the sludge putty mix do not tightly bound to the plaster panel without a stabilizer. All the putty mixtures prepared by mixing styrene acrylic binder are tightly bound to the plaster panel and other mixtures are tightly bound with the highest percentages only (cement 15% and lime 50%). Therefore, cement and lime should be added in high amounts to increase the bonding strength of the putty mixture while the bonding strength can be increased with a lower amount of styrene acrylic binder; styrene acrylic binder is the most workable stabilizer for sludge putty compared to cement and lime.

Bio receptivity of putty mixtures was tested by conducting a fungus growth test according to the ASTM D3273-94 test standards. According to the observations, fungus growth is not observed on any putty surface. Therefore, it can be concluded that sludge putty mixtures do not support fungus growth and it is not affected by selected stabilizers. The durability of the putty mixtures was tested considering the rain impact on the surface. An accelerated erosion test was conducted. All the mixtures mixed with stabilizer have lower SOF values than the sludge putty mix without stabilizer; also, the SOF value increase with the increase of stabilizer proportion in each mixture. When comparing the three stabilizers, a significant decrease in SOF value with a higher rate is observed in the mixtures stabilized with styrene acrylic binder compared to other mixtures. However, it can be concluded that stabilizers improve the durability of sludge putty mixtures against rain surfaces and styrene acrylic binder is the most workable stabilizer for that.

The next experiments of this chapter were conducted to compare the properties of the sludge putty mix with existing wall finishes. The most commonly used three putty products and lime was selected to test properties along with the developed sludge putty. Five mixtures were prepared according to the mix design and bonding strength test, fungus growth test and spray erosion tests were conducted. According to the test results, the bonding strength of sludge putty stabilized with 25% styrene acrylic binder by weight is not significantly different from commercial putty products and it is significantly different from lime. In the test cohesive failure is the only crack pattern observed among the samples. So, there is a high bonding strength between all mixtures and plaster panels. Therefore, all the selected wall finishes were tightly bound to the plaster surface. According to the observations of the fungus growth test, there is no fungus growth observed on any sample surface as all the selected wall finishes do not support fungus growth. According to the spray erosion test results, SOF of sludge putty stabilized with 25% styrene acrylic binder by weight is not significantly different from P2 and P4 commercial putty products and it is significantly different from lime and P3.

Up to the previous section, the developed wall putty mix was tested under laboratory conditions only and acquired results. Therefore, the next step of this chapter was conducted to analyze the real-scale behavior of the developed wall putty mix. To that, the sludge putty mix was applied on a few building walls including both interior and exterior surfaces with skilled labor. After the application of sludge, putty feedback was taken from skilled laborers. According to the feedback 300μm is identified as the effective fineness for the sludge putty powder and dry powder 3: binder 1 is the best mixing ratio for the putty mixture. And also, it was found that there is no considerable color deterioration, scale off or fungus growth observed in the sludge putty for one-year time duration and the putty can be recommended for both interior walls and exterior walls. All the findings of this research will be concluded in the next chapter including recommendations for further research studies.

CHAPTER 08: CONCLUSIONS AND RECOMMENDATIONS

8.1. Conclusions and Recommendations

- This research was conducted with the main aim of the development of wall putty for the tropics using DWTP waste alum sludge. As the first step DWTP was selected to collect sludge samples for the study. DWTPs practice different sludge removal processes and removing sludge has different properties identical to the sludge removal process. Sludge samples were collected from Ambathale, Biyagama and Kandana DWTPs; as each plant practice different sludge removal methods.

- Laboratory experiments were conducted to identify the properties of each sludge sample to select a DWTP to collect sludge for the study. According to the test results, the Ambathale DWTP sludge sample has the highest moisture content and the lowest solid content. Biyagama DWTP sludge; which was collected from the sludge treatment plant of the Biyagama DWTP, has the lowest moisture content, highest solid content and lowest volumetric shrinkage values; and Biyagama DWTP was selected to collect sludge for the study.

- The chemical composition of Biyagama DWTP sludge was identified by conducting an XRF analysis and according to the analysis, Si (42.23%) is identified as the main chemical element includes in DWTP sludge.

- According to the XRD analysis test results, DWTP sludge chemical composition consists of kaolinite, quartz, calcite and ettringite. And also, the chemical composition is significant to the findings in the literature.

- According to the heavy metal analysis test results Cadmium (Cd) (<0.1ppm), Lead (Pb) (4.3ppm), Mercury (Hg) (<0.1ppm) and Arsenic (As) (0.9ppm) were identified in the sludge sample as heavy metals; but the available quantities are lower than the maximum permissible level define for wall top coatings in Sri Lanka. Therefore, there is no harmful impact on human health or the environment when developing a wall putty with the sludge

- Laboratory tests were conducted to identify the shrinkage and moisture content of DWTP sludge. Volumetric shrinkage of DWTP sludge varies between the values of 59.82% and 93.62% with an average of 83.91%. Observational shrinkage is not affected by the applied area and the DWTP sludge layer is completely cracked and detached from the surface. DWTP sludge moisture content varies between the values of 62.31% and 84.72% with an average of 76.26%. Humidity is the significant climatic factor that affects on shrinkage of DWTP sludge with a positive correlation.

- Wall putty cannot be developed with DWTP wet sludge according to the high shrinkage. Therefore, experiments were conducted to optimize the putty properties of wet sludge. To develop wall putty using wet sludge, adhesiveness should be increased while reducing the drying shrinkage of the mix and additives can be used to improve the putty properties of wet sludge.

- The addition of sand reduced the volumetric shrinkage and the shrinkage becomes zero at 70% sand percentage, but it is not practically applicable in developing a putty mixture. According to the ball drop test results, it was identified that wet sludge mixtures with a sand percentage of between 30% to 60% have optimum clay and sand contents to develop wall putty mix. Although the mix has optimum shrinkage performances, the adhesiveness of the mix should be developed.

- Three natural fibers; banana fiber, coir fiber and sugarcane fiber, were selected for the study, and mixtures were prepared by mixing fiber with wet sludge and a volumetric shrinkage test was conducted. According to the test results addition of fiber reduced the volumetric shrinkage and banana fiber is the most effective natural fiber type to reduce volumetric shrinkage of wet sludge compared to coir fiber and sugarcane fiber.

- The effectiveness of binders was tested. Three plant-based natural binders and a synthetic binder were selected. Crack patterns of wet sludge mixture vary with the binder type and the moisture content of the mix increased with the addition of binders. But fungus growth in the mix increase with natural binders. Therefore, natural binders are not effective as an additive to develop wall putty with DWTP sludge. Addition of synthesized binder; styrene acrylic binder reduces volumetric shrinkage and observational shrinkage without facilitating fungus growth.

- Physical additives reduced drying shrinkage while binders increase the adhesiveness of wet sludge mixtures. According to that the most effective method to enhance the putty properties of wet sludge is adding both synthetic binder and physical additives. The optimum wet sludge mix was identified as 57% wet sludge, 30% sand, 3% sugarcane fiber and 10% styrene acrylic binder. The wet sludge mixture consists of low volumetric shrinkage, low drying cracks and high adhesiveness; but the mix has few defects as the presence of small surface cracks and fibers pop up from the surface when apply as a wall putty.

- DWTP wet alum sludge is harder when dry, due to the activation of alum and it is difficult to powder. As wall putty cannot be developed with wet sludge, experiments were conducted to develop a process to produce dry powdered sludge. Therefore, the thermal properties of DWTP sludge were studied. The Colour of the sludge is variants with the temperature, and from 100°C to 400°C the color becomes darker in both dry and wet conditions. Beyond 400°C color become lighter up to 700°C and become constant up to 1000°C.

- The highest density was achieved at the temperature of 900°C and the lowest density was achieved at 500°C. Density values of the heated sludge samples are gradually reduced from 100°C up to 500°C and beyond the 500°C, density again gradually increases up to 900°C temperature. Density increased when applying heat to sludge and the lowest density was recorded at 500°C temperature.

- To overcome alum activation coconut oil was selected as the lubricant; Coconut oil has the potential to overcome alum activation without effect on the color of the sample.

- The density values of heated sludge samples with oil are significantly lower than the density values of heated sludge samples without oil. The lowest density was recorded at 700°C temperature and the optimum coconut oil mixing percentage was identified as 8% by weight, for a productive dry powder production process.

- Drying cracks were observed on the samples burned at temperatures from 200°C to 600°C, and no drying cracks were observed on the samples burned at 700°C and 800°C. Therefore, the dry sludge powder sample burned at 700°C temperature was the optimum dry sludge powder sample to develop wall putty.

- A stabilizer was added to improve the putty properties of the dry powdered sludge mix. A lap shear strength test was conducted according to the ASTM D5868-014 test standards Bonding strength increase with the increase of stabilizer proportion in each mixture. When comparing the three stabilizers, a significant increase in bonding strength value is observed in the mixtures stabilized with styrene acrylic binder compared to other mixtures. All the putty mixtures prepared by mixing styrene acrylic binder are tightly bound to the plaster panel and other mixtures are tightly bound with the highest percentages only (cement 15% and lime 50%). Therefore, cement and lime should be added in high amounts to increase the bonding strength of the putty mixture while the bonding strength can be increased with a lower amount of styrene acrylic binder; styrene acrylic binder is the most workable stabilizer for sludge putty compared to cement and lime.

- Bio receptivity of putty mixtures was tested by conducting a fungus growth test according to the ASTM D3273-94 test standards. According to the observations, fungus growth is not observed on any putty surface. Therefore, it can be concluded that sludge putty mixtures do not supportive of fungus growth and it is not affected by selected stabilizers. The durability of the putty mixtures was tested considering the rain impact on the surface. An accelerated erosion test was conducted. All the mixtures mixed with stabilizer have lower SOF values than the sludge putty mix without stabilizer; also, the SOF value increase with the increase of stabilizer proportion in each mixture. When comparing the three stabilizers, a significant decrease in SOF value with a higher rate is observed in the mixtures stabilized with styrene acrylic binder compared to other mixtures. However, it can be concluded that stabilizers improve the durability of sludge putty mixtures against rain surfaces and styrene acrylic binder is the most workable stabilizer for that.

- Experiments were conducted to compare the properties of the sludge putty mix with existing wall finishes. The most commonly used three putty products and lime was selected to test properties along with the developed sludge putty. Five mixtures were prepared and bonding strength tests, fungus growth tests and spray erosion tests were conducted. According to the test results, the bonding strength of sludge putty stabilized with 25% styrene acrylic binder by weight is not significantly different from commercial putty products and it is significantly different from lime. In the test cohesive failure is the only crack pattern observed among the samples. So, there is a high bonding strength between all mixtures and plaster panels.

- According to the observations of the fungus growth test, there is no fungus growth observed on any sample surface as all the selected wall finishes do not supportive of fungus growth. According to the spray erosion test results, SOF of sludge putty stabilized with 25% styrene acrylic binder by weight is not significantly different from P2 and P4 commercial putty products and it is significantly different from lime and P3.

- After testing the developed sludge putty under laboratory conditions, the putty mix was applied on a few building walls including both interior and exterior surfaces with skilled labor to analyze real-scale behavior. After the application of sludge, putty feedback was taken from skilled laborers. According to the feedback 300µm is identified as the effective fineness for the sludge putty powder and dry powder 3: binder 1 is the best mixing ratio for the putty mixture. And also, it was found that there is no considerable color deterioration, scale, or fungus growth observed in the sludge putty for one-year time duration and the putty can be recommended for both interior walls and exterior walls.

- Finally, a dry powder was developed from dewatered alum sludge collected from Biyagama DWTP. Wall putty mix can be developed by mixing the dry powder with a styrene acrylic binder. The sludge putty is applicable on both exterior and interior wall surfaces and a sealer is applied on the putty surface as a protective coating.

8.2. Future Research

- Development of a standard for soil-base wall finishes
- Lifecycle costing of newly invented sludge putty compared to existing wall finishes
- Development of a natural binder to use as the stabilizer for the sludge putty mix
- Development of a natural polymer as a protective top coating for the sludge putty mix.
- Investigation of possible technologies to develop white color sludge putty powder.
- Analyzing the potential of alternative applications of dry powdered alum sludge.
- Investigating the potential to develop, a useful dry powder from other industrial wastes.

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APPENDIX – I: Recorded data of physical properties, chemicals and climatic factors

2020	Week	Day	Sludge			Plant Production																Weather condition					
			Moisture Content	Shrinkage	Dry Density	Water	Sludge to decanter	Alum		Lime				Chlorine				Polymer				Temp (High)		Temp (Low)		Humidity	
										Pre		Post		Pre		Post		Raw Water		Sludge Decanter							
			%	%	g/cm³	m³/day	m³/day	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	°C	°C	°C	°C	%	%
		1				186874	72	10.8		0		9.32		2.16		1.89		0.09		32.71		30		26		76	
		2				188312	84	11.8		0		7.77		2.11		1.73		0.1		33.8		31		25		78.5	
		3				192990	133	12.18		0		10.43		2.05		2.31		0.09		26.13		31		24		75	
		4				193618	88	11.4		0		11.08		2.05		2.36		0.08		30.37		31		26		76	
		5				193747	125	12.83		0		9.39		2.06		2.14		0.09		22.39		31		25		76	
		6				192430	63	12.15		0		9.48		2.07		2.12		0.09		37.65		32		25		71	
		7				191392	159	11.35		0		10.32		2.09		2.09		0.1		23.67		34		25		59	
	Week 01	8	68.48	69.48	1.27	191887	163	11.32	11.505714	0	0	10.97	9.777	1.99	2.01857	2.09	2.04429	0.09	0.087143	38.74	29.9243	32	32	26	24.71	58.5	65.5
		9				194306	158	11.37		0		9.29		1.97		2		0.09		24.46		32		24		60	
		10				193778	94	10.62		0		9.15		1.98		1.94		0.09		33.12		31		24		68	
		11				193109	118	10.9		0		9.84		1.97		1.93		0.06		29.44		32		24		66	
		12				195129	65	10.68		0		9.14		1.97		1.91		0.06		36.31		33		25		58	
		13				191334	170	10.83		0		8.41		1.98		1.75		0.06		16.71		32		25		50	
		14				189640	94	10.56		0		6.22		1.96		1.74		0.06		34.55		32		24		49.5	
	Week 02	15	75.66	78.38	1.32	193627	126	10.89	10.385714	0	0	6.73	7.813	1.94	1.95286	1.72	1.81	0.06	0.057143	24.11	31.18	31	31.43	22	24.57	60.5	60.357
Jan		16				193925	87	9.8		0		7.98		1.94		1.72		0.06		36.82		31		23		64	
		17				194238	118	9.82		0		7.3		1.94		1.87		0.05		43.8		30		27		72	
		18				194624	145	10.12		0		8.91		1.94		1.96		0.05		25.96		31		26		68.5	
		19				194135	109	10.34		0		9.5		1.96		2.18		0.05		40.43		32		26		71	
		20				193047	80	9.9		0		8.66		1.94		1.95		0.05		40.67		32		27		67	
		21				194708	132	9.67		0		7.39		1.93		2.04		0.05		24.83		33		27		66.5	
	Week 03	22	78.53	81.17	1.34	194558	83	9.34	9.27	0	0	8.28	8.454	1.94	1.94714	2.08	2.05143	0.05	0.05	38.57	35.7671	33	32.43	26	26	68	67.786
		23				192458	112	8.86		0		10.03		1.97		1.91		0.05		38.4		32		26		67	
		24				194981	174	8.32		0		7.96		1.93		2.18		0.05		32.21		32		25		67.5	
		25				195290	134	8.46		0		7.36		1.96		2.02		0.05		35.26		33		25		67.5	
		26				194275	85	8.59		0		7.14		1.95		2.17		0.05		40.25		33		25		54.5	
		27				194468	115	8.42		0		5.74		1.96		2.22		0.05		42.34		31		24		66.5	
	Week 04	28	78.32	84.8	1.32	194029	191	8.46	8.405	0	0	8.47	7.738	1.95	2.00167	2.27	2.18	0.05	0.05	31.72	38.0383	31	31.17	24	24.33	66.5	64.333
		29				194585	174	8.36		0		9.77		2.01		2.17		0.05		37.12		31		23		64	
		30				191288	157	8.51		0		8.16		2.11		2.15		0.05		41.22		31		25		66	
		31				193366	199	8.09		0		7.15		2.03		2.1		0.05		35.58		30		25		68.5	
		1				194243	139	8.02		0		8.63		2.05		2.11		0.05		32.45		33		25		65	
		2				194428	126	8.01		0		8.59		2.05		2.15		0.05		28.59		32		25		62.5	
		3				193603	79	8.05		0		7.69		2.04		2.16		0.05		34.28		33		25		66.5	
		4				194763	88	7.96		0		9.41		2.03		2.15		0.05		42.76		34		25		55	
		5				192510	78	8.18		0		7.04		2.11		2.19		0.05		44.84		33		26		63	
	Week 1	6	78.58	82	1.37	194977	130	8.96	8.75	0	0	7.91	8.296	2.16	2.13571	2.05	2.03143	0.04	0.045714	36.21	42.1471	33	32.43	25	24.86	61	63.786
		7				194120	107	9		0		8.44		2.2		1.87		0.04		44.62		31		25		67	
		8				193025	69	9.68		0		7.8		2.22		1.92		0.05		64.21		32		24		66	
		9				193747	158	9.42		0		9.78		2.19		1.88		0.04		28.11		31		24		68	
		10				194714	152	9.43		0		9.08		2.19		2.05		0.05		40.92		34		23		51.5	
		11				193885	129	9.66		0		9.13		2.19		2.14		0.06		31.32		32		24		61	
		12				194743	113	9.51		0		7.2		2.16		2.06		0.05		28.05		34		26		60	
	Week 2	13	80.9	80.62	1.32	185425	136	9.82	9.6885714	0	0	7.09	7.884	2.28	2.20571	1.94	2.1	0.06	0.052857	26.61	30.9743	36	33.29	26	25.43	56.5	62.643
		14				194610	111	9.87		0		7.73		2.2		2.18		0.05		22.01		33		26		67	
Feb		15				194969	250	9.93		0		7.99		2.21		2.19		0.05		28.6		31		27		72.5	
		16				194174	98	9.6		0		6.97		2.21		2.14		0.05		39.31		33		26		70	
		17				194647	96	9.49		0		8.07		2.28		2.29		0.05		37.69		34		26		65	
		18				180518	99	10.17		0		9.54		2.63		2.31		0.05		39.27		33		24		59	
		19				195855	232	9.68		0		7.59		2.6		1.83		0.05		17.47		32		24		60.5	
	Week 3	20	63.39	59.82	1.3	195445	155	9.21	9.4671429	0	0	7.9	8.167	2.6	2.58143	1.88	1.94714	0.05	0.05	29.03	29.8071	33	33.29	25	25.43	62	61.214
		21				182172	92	10.42		0		7.8		2.72		1.8		0.05		31.87		32		26		63	
		22				195236	129	9.25		0		8.19		2.62		1.76		0.05		28.63		34		27		59.5	
		23				194830	143	8.05		0		8.08		2.62		1.76		0.05		24.69		35		26		59.5	
		24				194031	105	9.11		0		5.5		2.53		2.05		0.04		29.69		33		26		61	
		25				195132	184	9.45		0		9.77		2.53		1.95		0.04		26.79		32		26		66	
	Week 4	26	70.98	70.71	1.39	194811	120	9.25	9.1	0	0	7.79	7.202	2.52	2.515	1.81	1.97333	0.04	0.04	25.44	27.4733	32	32.33	27	26.33	69.5	64.167
		27				194922	146	9.22		0		7.47		2.51		2.44		0.04		27.21		33		27		62	
		28				195179	183	8.41		0		6.58		2.5		1.81		0.04		26.44		32		26		66.5	
		29				195216	133	9.16		0		6.1		2.5		1.78		0.04		29.27		32		26		60	
		1				194980	95	8.97		0		6.2		2.5		1.8		0.05		42.91		32		25		66	
		2				194573	124	11.04		0		7.37		2.57		1.98		0.06		30.62		31		26		70.5	
		3				194695	121	9.69		0		10.9		2.62		2.02		0.05		27.23		31		26		69.5	
		4				195579	121	9.09		0		6.93		2.62		2		0.05		31.48		31		25		67	
	Week 1	5	76.46	77.24	1.37	197654	147	9.62	10.354286	0.01	0.0029	8.44	8.641	2.59	2.61714	2.05	2.08	0.05	0.055714	26.29	30.01	32	31.71	26	25.71	71	67
		6				196795	150	9.92		0.01		8.49		2.59		2.04		0.06		25.51		32		27		68	
		7				195575	135	12.33		0		9.07		2.62		2.3		0.07		25.95		33		26		60.5	
		8				196008	117	10.79		0		9.29		2.71		2.17		0.05		42.99		32		24		62.5	
		9				196303	116	10.05		0		8.63		2.62		1.99		0.05		22.61		32		26		69.5	
		10				148934	177	10.23		0.01		9.68		2.91		2.12		0.05		22.85		32		27		67	
		11				196804	176	10.09		0.01		7.23		2.58		2.04		0.06		27.58		31		27		72.5	
	Week 2	12	80.12	88.02	2.01	197482	127	11.08	10.718571	0	0.0029	8.91	7.989	2.58	2.63143	2.19	2.09714	0.06	0.058571	26.19	23.6557	32	32	27	27	68.5	69.143
		13				197299	254	12.07		0		6.34		2.54		1.98		0.06		14.61		32		27		67.5	
		14				196760	141	11.01		0		7.35		2.59		2.03		0.07		25.89		33		28		67.5	
		15				196861	140	10.5		0		7.78		2.6		2.33		0.06		25.86		32		27		71.5	
Mar		16				186111	89	11.77		0		6.87		2.7		2.6		0.07		24.35		33		27		65.5	
		17				190954	142	12.21		0		9.76		2.6		2.99		0.06		24.28		34		26		68	
		18				196802	224	11.98		0		8.85		2.61		2.61		0.06		23.73		33		26		62.5	
	Week 3	19	78.61	80.21	1.43	194658	142	11.36	11.402857	0	0	8.88	8.464	2.61	2.59143	2.23	2.45857	0.06	0.064286	23.24	24.2157	32	32.71	26	25.71	73	66.286
		20				195161	200	10.75		0		8.96		2.42		1.87		0.07		23.4		32		25		72	
		21				193501	191	10.77		0		6.98		2.58		2.46		0.07		26.01		33		25		58.5	
		22				195122	78	10.98		0		8.95		2.62		2.45		0.06		24.5		32		25		64.5	
		23				195146	133	10.89		0		12.89		2.6		2.37		0.06		16.36		32		26		66	
		24				195062	128	10.75		0		10.44		2.06		2.45		0.06		23.15		32		27		70.5	
		25				192830	110	10.8		0		8.23		1.81		2.44		0.06		22.58		32		27		65	
	Week 4	26	82.18	83.29	1.45	194798	132	10.62	10.682857	0	0.0029	7.34	9.046	1.72	1.89429	1.83	2.12286	0.06	0.06	22.07	24.6329	32	32.29	25	26.43	67.5	67.571
		27				195627	131	10.77		0		8.68		1.69		1.87		0.06		38.34		32		26		74	
		28				195930	252	10.65		0.01		8.46		1.7		1.96		0.06		21.74		33		26		67	
		29				196888	139	10.3		0.01		7.28		1.68		1.94		0.06		28.19		33		28		63	
		30				195440	214	11.17		0.01		7.45		1.67		1.92		0.05		27.94		33		26		69	
		31				197011	224	11.72		0.01		5.77		1.67		1.95		0.04		28.05		32		26		69	

2020	Week	Day	Sludge: Moisture Content (%)	Sludge: Shrinkage (%)	Sludge: Dry Density (g/cm³)	Plant Production: Water (m³/day)	Plant Production: Sludge to decanter (m³/day)	Alum (g/m³)	Alum (g/m³)	Lime Pre (g/m³)	Lime Pre (g/m³)	Lime Post (g/m³)	Lime Post (g/m³)	Chlorine Pre (g/m³)	Chlorine Pre (g/m³)	Chlorine Post (g/m³)	Chlorine Post (g/m³)	Polymer Raw Water (g/m³)	Polymer Raw Water (g/m³)	Polymer Sludge Decanter (g/m³)	Polymer Sludge Decanter (g/m³)	Weather condition: Temp (High) (°C)	Temp (High) (°C)	Temp (Low) (°C)	Temp (Low) (°C)	Humidity (%)	Humidity (%)
		1																				32		26		73	
		2																				33		26		67	
	Week 1	3	84.72	85.09	1.53	194976	137	12.58	12.886667	0	0.01	7.74	8.223	1.68	1.66667	2.64	2.63667	0.04	0.04	25.54	21.74	32	32.6	26	25.8	64.5	68.3
		4				194449	203	13.04		0.01		8.07		1.65		2.67		0.04		25.77		33		26		68	
		5				193599	239	13.04		0.02		8.86		1.67		2.6		0.04		13.91		33		25		69	
		6				193698	125	11.29		0.01		8.09		1.66		2.97		0.04		23.22		33		27		68	
		7				194841	118	12.43		0.02		7.85		1.68		3.15		0.05		25.28		32		27		67.5	
		8				193650	134	11.6		0.02		10.06		1.64		3.22		0.06		22.03		33		26		70	
	Week 2	9	84.57	84.14	1.53	195774	132	10.99	11.511429	0	0.0071	8.67	8.929	1.61	1.68	3.18	3.02714	0.05	0.051429	22.2	23.99	31	32.14	25	25.71	75	69.857
		10				195170	167	10.82		0		9		1.63		2.93		0.06		23.44		32		25		66	
		11				158967	170	11.75		0		9.41		1.91		3.07		0.05		25.59		32		25		68	
		12				194754	121	11.7		0		9.42		1.63		2.67		0.05		26.17		32		25		74.5	
		13				193858	150	11.89		0		9.38		1.65		2.46		0.05		25.26		32		25		69	
		14				193750	106	12.87		0		10.18		1.65		2.73		0.07		26.03		33		26		70.5	
		15				192767	101	11.63		0		9.95		1.69		2.76		0.07		42.51		32		25		69.5	
Apr	Week 3	16	83.6	83.51	1.46	192589	129	11.16	12.254286	0	0	8.62	9.454	1.69	1.66571	2.65	2.65	0.07	0.067143	40.32	32.4129	32	32.14	25	25.14	67	72
		17				193704	98	12.55		0		9.82		1.66		2.67		0.07		40.65		31		25		79	
		18				194264	128	12.71		0		8.98		1.65		2.69		0.07		26.1		33		25		73.5	
		19				194224	81	12.97		0		9.25		1.67		2.59		0.07		26.02		32		25		75.5	
		20				193491	137	14.38		0.04		9.69		1.72		2.79		0.06		23.24		32		25		78	
		21				193595	160	13.52		0.04		12.1		1.72		2.98		0.06		26.84		33		25		76	
		22				193468	124	11.55		0.01		9.96		1.7		2.92		0.06		25.79		31		25		82.5	
	Week 4	23	76.47	93.31	4.44	189760	139	13.28	12.751429	0	0.0129	10.9	10.52	1.75	1.70429	2.52	2.71571	0.06	0.062857	25.67	25.3643	32	32	25	25	79	80.429
		24				193980	114	12.7		0		10.95		1.67		2.6		0.07		24.37		31		24		84.5	
		25				193906	225	11.89		0		9.95		1.68		2.34		0.06		25.32		33		26		82.5	
		26				192320	141	11.94		0		10.08		1.69		2.86		0.07		26.32		32		25		80.5	
		27				194498	145	12.47		0.01		9.68		1.67		2.55		0.07		23.15		33		27		80	
	Week 5	28	77.97	92.63	4.23	194268	118	12.75	12.67	0.02	0.0175	8.75	8.645	1.69	1.67	2.51	2.445	0.06	0.0625	25.68	25.78	33	33	27	27	78.5	78.875
		29				195669	85	12.79		0.02		7.66		1.66		2.37		0.06		27		33		27		78.5	
		30				195743	139	12.67		0.02		8.49		1.66		2.35		0.06		27.29		33		27		78.5	
		1				195398	93	12.59		0.02		7.67		1.67		1.45		0.06		27.29		33		27		75	
		2				194285	114	12.65		0.02		8.19		1.69		1.1		0.06		27.57		33		27		73	
		3				195681	164	12.29		0.02		7.86		1.69		2.41		0.06		13.89		33		27		73	
		4				196245	98	11.97		0		12.81		1.69		2.45		0.06		27.34		32		27		72	
		5				194327	140	12.36		0		9.48		1.69		2.42		0.06		27.68		34		27		72	
		6				193346	114	12.11		0		8.57		1.69		2.49		0.06		26.93		30		26		80	
	Week 1	7	80.7	93.62	4.39	191270	142	11.87	12.165714	0	0	9.78	9.821	1.68		2.49	2.46	0.06	0.06	27.33	27.41	31	31.86	26	26.43	72.5	74.929
		8				195745	101	12.34		0		9.65		1.67		2.47		0.06		27.45		31		26		76	
		9				193806	113	12.35		0		9.62		1.68		2.46		0.06		27.47		32		27		78	
		10				195108	106	12.16		0		8.84		1.67		2.44		0.06		27.67		33		26		74	
		11				193965	109	12.7		0.01		8.67		1.7		2.35		0.05		26.91		29		26		86	
		12				195474	107	12.76		0.01		12.16		1.66		2.7		0.07		26.76		32		26		74	
		13				194366	106	13.01		0		10.9		1.7		2.8		0.08		27.07		31		25		61	
	Week 2	14	69.17	88.8	3.77	193171	146	11.93	13.182857	0	0.9729	13.58	11.17	1.64	1.66143	2.77	2.68714	0.08	0.081429	26.23	26.4929	32	30.71	27	26.86	72	77.929
		15				194246	152	11.77		0		12.64		1.6		2.73		0.08		25.9		29		26		91	
May		16				196159	123	16.29		2.82		11.19		1.63		2.77		0.1		26.87		31		29		79	
		17				190979	121	13.82		3.97		9.08		1.7		2.69		0.11		25.71		31		29		82.5	
		18				195668	106	13.15		3.79		11.01		1.65		2.89		0.08		26.3		31		29		58	
		19				196461	127	13.58		4.1		9.83		1.64		2.72		0.08		29.39		31		29		76	
		20				195633	171	13.2		5.09		10.94		1.78		2.32		0.1		25.09		32		29		71	
	Week 3	21	62.31	86.34	4.06	192601	135	13.28	13.197143	5.03	4.2343	11.93	13.39	1.88	1.86	2.44	2.51286	0.08	0.082857	24.84	25.8114	32	31.43	28	28	76	73.857
		22				194983	128	12.89		3.37		13.69		1.83		2.17		0.08		25.1		31		25		79	
		23				194357	143	13.42		3.71		23.12		2.07		2.83		0.08		25.13		31		27		76	
		24				195899	200	12.86		4.55		13.19		2.17		2.22		0.08		24.83		32		29		81	
		25				193825	132	14.08		3.7		10.08		2.21		2.06		0.11		26.68		31		29		84	
		26				195123	134	12.95		3.41		16.45		2.16		2.06		0.1		27.67		31		28		80	
		27				196567	168	14.24		3.57		12.36		2.17		1.69		0.1		27.97		30		24		83.5	
	Week 4	28	75	90.95	4.05	192734	221	14.71	13.83	3.65	3.54	11.17	11.73	2.2	2.26571	2.05	1.86143	0.11	0.092857	9.1	24.4914	30	30.86	24	26.71	78.5	79.143
		29				195272	189	13.91		3.18		12.12		2.3		2.23		0.08		26.78		31		28		77	
		30				193302	244	13.64		3.62		10.82		2.43		1.59		0.07		27.3		31		27		76	
		31				194939	153	13.28		3.65		9.1		2.39		1.35		0.08		25.94		32		27		75	
		1				194603	228	11.78		4.74		7.54		2.41		1.18		0.08		25.06		31		27		74.5	
		2				194547	206	12.22		1.8		10.77		2.55		1.16		0.07		23.91		31		27		72.5	
		3				196241	221	11.06		0.04		11.45		2.52		1.27		0.07		24.88		32		27		69.5	
	Week 1	4	75.24	91.72	4.05	198277	163	10.67	11.58	0.03	0.9471	8.98	10.08	2.42	2.43	0.82	1.56286	0.07	0.075714	24.88	25.1157	32	31.43	26	26.57	69.5	74.5
		5				193168	191	9.94		0.02		11.17		2.44		1.24		0.08		25.58		32		28		70.5	
		6				192366	123	12.1		0		9.58		2.37		2.32		0.08		25.65		31		27		80	
		7				193710	141	13.29		0		11.05		2.3		2.95		0.08		25.85		31		24		85	
		8				193504	133	12.89		0		12.07		1.7		1.35		0.08		25.45		30		24		79.5	
		9				195723	122	12.98		0.05		11.08		1.72		1.59		0.08		25.6		32		28		77	
		10				193058	133	12.16		0.02		10.55		1.91		1.3		0.08		26.22		31		28		79.5	
	Week 2	11	79.45	93.47	4.24	192664	148	12.48	12.49	0.03	0.0329	9.73	12.95	2.02	1.87714	1.12	1.45857	0.08	0.082857	25.98	25.8557	31	31	28	27.43	77.5	77.071
		12				194158	166	12.56		0.02		10.48		1.92		0.77		0.09		26.08		31		27		80	
		13				193969	137	11.85		0.05		17.98		2.06		1.1		0.09		25.8		31		28		74	
		14				194745	130	12.51		0.06		18.77		1.81		2.98		0.08		25.86		31		29		72	
Jun		15				194934	215	11.57		0.08		20.41		2.31		1.22		0.08		26.19		32		28		73.5	
		16				195185	156	10.77		0		19.18		2.37		1.56		0.08		26.29		30		28		81	
		17				195724	116	10.4		0		17.12		2.28		1.45		0.08		25.71		31		28		78.5	
	Week 3	18	76.47	91.34	3.97	195239	136	11.35	11.392857	0	0.0114	12.88	13.35	2.13	2.27143	0.98	0.94571	0.08	0.08	25.84	25.7729	32	31.29	28	28.14	74	75.071
		19				195721	170	11.68		0		8.19		2.26		1		0.08		24.37		32		29		73.5	
		20				196046	130	11.97		0		8.16		2.29		0.18		0.08		26.02		31		28		73	
		21				196913	134	12.01		0		7.53		2.26		0.23		0.08		25.99		31		28		72	
		22				196017	148	11.01		0.07		9.15		2.23		1.07		0.08		25.88		32		28		70	
		23				197922	215	11.17		0.08		8.34		2.21		2		0.09		25.65		31		28		69	
		24				197036	121	10.45		0.09		7.96		2.29		1.88		0.09		24.1		31		27		78	
	Week 4	25	68.49	87.12	3.74	198222	134	10.07	11.461429	0.11	0.0829	7.44	8.136	2.16	2.14857	1.89	1.75	0.08	0.087143	24.21	25.4486	31	30.86	28	27.43	79	74.929
		26				196234	117	12.16		0.05		8.06		2.17		1.73		0.09		24.55		29		27		77	
		27				194318	136	13.38		0.11		7.58		2		1.83		0.09		27.13		31		27		72.5	
		28				194862	206	11.99		0.07		8.42		1.98		1.85		0.09		26.62		31		27		79	

APPENDIX – II: Regression analysis of shrinkage

Regression Analysis: Sludge Shrinkage versus Chemicals Apply in DWTP (Alum, Lime, Chlorine & Polymer), Highest Temperature of the day, Lowest Temperature of the day & Humidity

Regression Equation

Shrinkage = 62.7 - 0.31 Alum - 0.77 Lime - 2.90 Chlorine + 0.030 Polymer
- 1.26 Highest Temperature of the day + 0.07 Lowest Temperature of the day
+ 1.163 Humidity

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	62.7	86.9	0.72	0.480	
Alum	-0.31	1.80	-0.17	0.866	6.05
Lime	-0.77	1.08	-0.71	0.486	3.10
Chlorine	-2.90	2.37	-1.22	0.238	1.31
Polymer	0.030	0.420	0.07	0.944	3.37
Highest Temperature of the day	-1.26	1.86	-0.68	0.507	1.55
Lowest Temperature of the day	0.07	1.81	0.04	0.971	2.97
Humidity	1.163	0.374	3.11	0.006	4.17

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
5.44689	69.42%	56.83%	39.32%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	7	1145.13	163.590	5.51	0.002
Alum	1	0.87	0.875	0.03	0.866
Lime	1	15.05	15.053	0.51	0.486
Chlorine	1	44.35	44.346	1.49	0.238
Polymer	1	0.15	0.149	0.01	0.944
Highest Temperature of the day	1	13.65	13.646	0.46	0.507
Lowest Temperature of the day	1	0.04	0.042	0.00	0.971
Humidity	1	286.12	286.125	9.64	0.006
Error	17	504.37	29.669		
Total	24	1649.49			

Fits and Diagnostics for Unusual Observations

Obs	Shrinkage	Fit	Resid	Std Resid
7	59.82	72.10	-12.28	-2.60 R

R Large residual

Durbin-Watson Statistic

Durbin-Watson Statistic = 1.55653

APPENDIX – III: Regression analysis of moisture content

Regression Analysis: Sludge Moisture content versus Chemicals Apply in DWTP (Alum, Lime, Chlorine & Polymer), Highest Temperature of the day, Lowest Temperature of the day & Humidity

Regression Equation

Moisture content = 85 - 0.67 Alum - 0.78 Lime - 3.20 Chlorine - 0.316 Polymer
+ 1.88 Highest Temperature of the day - 2.38 Lowest Temperature of the day
+ 0.432 Humidity

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	85	101	0.84	0.411	
Alum	-0.67	2.09	-0.32	0.754	6.05
Lime	-0.78	1.26	-0.62	0.542	3.10
Chlorine	-3.20	2.75	-1.16	0.261	1.31
Polymer	-0.316	0.488	-0.65	0.526	3.37
Highest Temperature of the day	1.88	2.16	0.87	0.397	1.55
Lowest Temperature of the day	-2.38	2.10	-1.13	0.273	2.97
Humidity	0.432	0.435	0.99	0.334	4.17

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
6.32508	22.83%	0.00%	0.00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	7	201.217	28.745	0.72	0.658
Alum	1	4.065	4.065	0.10	0.754
Lime	1	15.481	15.481	0.39	0.542
Chlorine	1	54.023	54.023	1.35	0.261
Polymer	1	16.782	16.782	0.42	0.526
Highest Temperature of the day	1	30.242	30.242	0.76	0.397
Lowest Temperature of the day	1	51.322	51.322	1.28	0.273
Humidity	1	39.538	39.538	0.99	0.334
Error	17	680.112	40.007		
Total	24	881.329			

Fits and Diagnostics for Unusual Observations

Obs	Moisture content	Fit	Resid	Std Resid	
7	63.40	76.92	-13.52	-2.46	R

R Large residual

Durbin-Watson Statistic

Durbin-Watson Statistic = 1.25002

APPENDIX – IV: One-way ANOVA: Bonding strength of putty mixtures with stabilizers

One-way ANOVA: Bonding strength versus Mix

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix	10	Mix 1, Mix 10, Mix 2, Mix 3, Mix 4, Mix 5, Mix 6, Mix 7, Mix 8, Mix 9

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix	9	4.18800	0.465333	*	*
Error	20	0.00000	0.000000		
Total	29	4.18800			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0	100.00%	100.00%	100.00%

Means

Mix	N	Mean	StDev	95% CI
Mix 1	3	1.000	0.000	(1.000, 1.000)
Mix 10	3	2.300	0.000	(2.300, 2.300)
Mix 2	3	1.300	0.000	(1.300, 1.300)
Mix 3	3	1.500	0.000	(1.500, 1.500)
Mix 4	3	2.000	0.000	(2.000, 2.000)
Mix 5	3	1.200	0.000	(1.200, 1.200)
Mix 6	3	1.500	0.000	(1.500, 1.500)
Mix 7	3	1.800	0.000	(1.800, 1.800)
Mix 8	3	1.400	0.000	(1.400, 1.400)
Mix 9	3	1.800	0.000	(1.800, 1.800)

Pooled StDev = 0

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix	N	Mean	Grouping
Mix 10	3	2.300	A
Mix 4	3	2.000	B
Mix 9	3	1.800	C
Mix 7	3	1.800	D
Mix 6	3	1.500	E
Mix 3	3	1.500	F
Mix 8	3	1.400	G
Mix 2	3	1.300	H
Mix 5	3	1.200	I
Mix 1	3	1.000	J

Means that do not share a letter are significantly different.

APPENDIX – V: One-way ANOVA: SOF of putty mixtures with stabilizers

One-way ANOVA: Scale off versus Mix

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix	10	Mix 1, Mix 10, Mix 2, Mix 3, Mix 4, Mix 5, Mix 6, Mix 7, Mix 8, Mix 9

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix	9	83015.7	9223.97	*	*
Error	20	0.0	0.00		
Total	29	83015.7			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0	100.00%	100.00%	100.00%

Means

Mix	N	Mean	StDev	95% CI
Mix 1	3	265.1	0.0	(265.1, 265.1)
Mix 10	3	107.5	0.0	(107.5, 107.5)
Mix 2	3	257.7	0.0	(257.7, 257.7)
Mix 3	3	244.2	0.0	(244.2, 244.2)
Mix 4	3	232.4	0.0	(232.4, 232.4)
Mix 5	3	239.7	0.0	(239.7, 239.7)
Mix 6	3	184.4	0.0	(184.4, 184.4)
Mix 7	3	153.8	0.0	(153.8, 153.8)
Mix 8	3	243.2	0.0	(243.2, 243.2)
Mix 9	3	143.2	0.0	(143.2, 143.2)

Pooled StDev = 0

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix	N	Mean	Grouping
Mix 1	3	265.1	A
Mix 2	3	257.7	B
Mix 3	3	244.2	C
Mix 8	3	243.2	D
Mix 5	3	239.7	E
Mix 4	3	232.4	F
Mix 6	3	184.4	G
Mix 7	3	153.8	H
Mix 9	3	143.2	I
Mix 10	3	107.5	J

Means that do not share a letter are significantly different.

APPENDIX – VI: Properties of existing wall putty products

Wall care putty	Product Details		Properties									
	Raw Materials Used	Putty form	pH	Wet Density	Transverse Strength	Compressive Strength (28 days)	Whiteness Index	Pot Life	Water Demand By Volume	Surface Hardness	Maximum Thickness	Coverage
P1	White cement, redispersible pollymer, functional additives	Powder							36 - 40 %		1.5 mm (2 Coats)	20 - 25 sqfeets/kg On Single Coat (Varies with Surface Quality)
P2	White cement, Dolomite	Powder			1.98 N/mm	11 kg/cm	94%	180 min	30 - 35 %	2.8 N	3 mm (2 Coats)	16 sqfeets/kg On Single Coat (Varies with Surface Quality)
P3	$CaCO_3$, White cement	Powder							35 - 40%		3 mm	12.5 sqfeets/kg On Single Coat (Varies with Surface Quality)
P4	$CaCO_3$, White cement, CMG	Powder							35 - 40 %		3 mm	12.5 sqfeets/kg On Single Coat (Varies with Surface Quality)
P5	**Filler** - Graded silica sand, CaCO3 **Binder** - White cement, powder polymers **Additives** - Water soluble powder polymers to improvr workability, water retantion, adhesion and for more durability	Powder	7	1700 kg/m^3				90 - 120 min	40 -45 %		2 - 2.5 mm	16 - 21.5 sqfeets/kg On Single Coat (Varies with Surface Quality)
P6	White cement, redispersible pollymer, functional additives	Powder							40 - 50 %		1.5 mm (2 Coats)	10 - 15 sqfeets/kg On two Coats (Varies with Surface Quality)
P7	Birla White Cement, high quality extra HP polymers, specialty chemicals and mineral fillers etc.	Powder				3.5 - 7.5 N/mm^2			36 - 40 %		1.5 mm (2 Coats)	20 - 25 sqfeets/kg On Single Coat (Varies with Surface Quality)
P8	White cement	Powder									1.5 mm (1st coat) 1mm (2nd coat)	14 sqfeets/kg On two Coats (Varies with Surface Quality)
P9	**Filler** - White cement **Pigmentation** - Titanium Dioxide, Magnesium, Aluminium Silicate **Solvent** - Water, Ethylene Glycol	Paste							No need to dialute		1.5 mm	20 - 25 sqfeets/kg On Single Coat (Varies with Surface Quality)

***Commercial product name of the wall care putty is not mentioned**

APPENDIX – VII: One-way ANOVA: Bonding strength of putty mixtures

One-way ANOVA: Bonding strength versus Mix

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix	5	Mix 1, Mix 2, Mix 3, Mix 4, Mix 5

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix	4	3.7227	0.93067	11.44	0.001
Error	10	0.8133	0.08133		
Total	14	4.5360			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.285190	82.07%	74.90%	59.66%

Means

Mix	N	Mean	StDev	95% CI
Mix 1	3	3.000	0.000	(2.633, 3.367)
Mix 2	3	2.6667	0.1528	(2.2998, 3.0335)
Mix 3	3	1.800	0.500	(1.433, 2.167)
Mix 4	3	1.800	0.265	(1.433, 2.167)
Mix 5	3	1.933	0.252	(1.566, 2.300)

Pooled StDev = 0.285190

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix	N	Mean	Grouping		
Mix 1	3	3.000	A		
Mix 2	3	2.6667	A	B	
Mix 5	3	1.933		B	C
Mix 4	3	1.800			C
Mix 3	3	1.800			C

Means that do not share a letter are significantly different.

APPENDIX – VIII: One-way ANOVA: SOF of putty mixtures

One-way ANOVA: Scale off versus Mix

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix	5	Mix 1, Mix 2, Mix 3, Mix 4, Mix 5

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix	4	76834	19209	15.81	0.000
Error	10	12150	1215		
Total	14	88985			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
34.8574	86.35%	80.88%	69.28%

Means

Mix	N	Mean	StDev	95% CI
Mix 1	3	11.3110	0.0018	(-33.5300, 56.1521)
Mix 2	3	162.5	42.5	(117.7, 207.4)
Mix 3	3	224.19	14.45	(179.35, 269.03)
Mix 4	3	173.1	54.4	(128.2, 217.9)
Mix 5	3	120.7	33.1	(75.8, 165.5)

Pooled StDev = 34.8574

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix	N	Mean	Grouping		
Mix 3	3	224.19	A		
Mix 4	3	173.1	A	B	
Mix 2	3	162.5	A	B	
Mix 5	3	120.7		B	
Mix 1	3	11.3110			C

Means that do not share a letter are significantly different.