Enhancing the environmental sustainability of water treatment sludge (WTS) disposal through blended binder solidification/stabilisation

Nurshamimie Muhammad Fauzi[1*], *Mohd Fadzil* Arshad[1], *Ramadhansyah* Putra Jaya[2], *Mazidah* Mukri[1], and *Nor Hanim* Khiyon[1]

[1]School of Civil Engineering, College of Engineering, Engineering Complex, Tunku Abdul Halim Muadzam Shah, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
[2]Department of Geotechnics and Infrastructure, Faculty of Civil Engineering & Earth Resources, Universiti Malaysia Pahang, 23600 Gambang, Pahang, Malaysia

Abstract. Managing water treatment sludge (WTS) is challenging due to its continuous production and environmental impact. Traditional disposal in landfills is standard but risky for groundwater contamination. Researchers are exploring a more environmentally friendly method using a blend of binders, partially replacing Ordinary Portland Cement (OPC) with waste materials like Waste Paper Sludge Ash (WPSA), Palm Oil Fuel Ash (POFA) and Fly Ash (FA). These materials not only help reduce environmental waste but also decrease cement usage. The study assesses the Atterberg Limits of the treated sludge to design the appropriate solidification/stabilisation (S/S) method, providing essential data on its physical and mechanical properties Using waste materials as binders effectively stabilises the sludge, reducing reliance on cement, cutting disposal costs, and minimizing environmental pollution. The study identifies WPSA as the most suitable replacement, offering self-cementing properties, and demonstrates that combining WPSA OPC, and WTS creates a stable mix with liquefaction resistance. This approach presents a promising, cost-effective, and environmentally solution for WTS management.

1 Introduction

Water treatment sludge (WTS) refers to the semi-solid slurry generated as a byproduct during water treatment at water treatment plants. This sludge contains solid and liquid materials and is typically considered waste. Currently, the most common method of disposing of WTS is through landfilling, which is widely practised due to its ease and cost-effectiveness [1]. A study conducted by Lohani et al. in 2021 confirms that landfilling is the simplest and most economical technology available for WTS disposal [2]. However, this method has significant drawbacks, primarily related to its environmental impact. One of the major concerns associated with landfilling WTS is the significant strain it puts on available disposal areas, considering the ever-increasing amount of sludge produced. Moreover, landfilling requires specific environmental reduction measures, such as leachate collection systems and lining materials, to prevent harmful substances from seeping into the surrounding soil and groundwater [1].

WTS contains various contaminants, including bacteria, aluminium, nitrates, metals, trace quantities of toxic materials, and salts. The presence of these pollutants makes proper disposal essential to avoid any potential adverse effects on the environment and public health. A critical environmental consequence of WTS disposal is the generation of leachate, a hazardous liquid formed when rainwater comes into contact with the disposed sludge and carries dissolved contaminants. If not effectively managed, this leachate can contribute to soil and groundwater pollution, posing a significant risk to ecosystems and human well-being [1]. Given the evident environmental challenges associated with the current disposal practices, exploring and implementing alternative, more sustainable methods for handling WTS is imperative. Developing improved disposal technologies that minimize environmental impacts, such as advanced treatment processes or resource recovery techniques, is essential for the sustainable management of WTS. By addressing these challenges, we can effectively reduce the environmental footprint of WTS disposal and contribute to a cleaner and healthier environment.

Solidification is a widely used technique for remediating sludge before its disposal in landfills. The main objective of this approach is to reduce the leaching of pollutants from the sludge, which can be achieved through physical or chemical processes [3]. This is accomplished by mixing the sludge with a specified binder. The ultimate goal of this process is to transform the sludge into a safe and environmentally friendly form, thus ensuring its proper and responsible disposal. According to Zhang et al. (2021), solidification has

---

* Corresponding author: nurshamimie87@gmail.com

found extensive application in the disposal of various types of hazardous waste and the reclamation of contaminated disposal sites. The process has been recognised as an effective means of addressing the environmental challenges posed by hazardous waste, offering a practical and efficient approach to managing and mitigating potential risks associated with improperly handling such waste materials. Solidifying hazardous sludge makes it more stable and less prone to leaching, rendering it suitable for secure disposal and contributing to environmental protection. Solidification is a proven and valuable method in waste management, particularly in treating sludge and hazardous waste materials. Its implementation helps to safeguard the environment by minimising the release of pollutants, ensuring the safe disposal of waste, and facilitating the reclamation of contaminated sites.

Sludge solidification extensively utilizes Ordinary Portland Cement (OPC) as a binding material. However, OPC is known to be expensive due to its high energy consumption during production, its cost, and its adverse impact on the environment. Furthermore, studies have consistently shown that the cement industry is one of the significant contributors to greenhouse gas (GHG) emissions, especially in terms of CO2 emissions [5][6][7]. To address these challenges, researchers have explored the use of replacement materials in Portland cement. Prior studies have already demonstrated the successful solidification of WTS using industrial waste materials, highlighting their efficacy in mitigating adverse environmental impacts. Additives such as Fly Ash (FA) and Palm Oil Fuel Ash (POFA) have gained prominence due to their pozzolanic nature, making them suitable as partial cement replacements in various construction applications, including foamed concrete. Studies by Siti et al. (2005) have highlighted the viability of such supplementary cementing materials, paving the way for more sustainable and cost-effective approaches to sludge treatment. Industrial waste materials, such as FA, POFA, and Waste Paper Sludge Ash (WPSA), have shown promising potential as substitute binders for OPC in solidifying WTS. By incorporating these waste materials into the process, it becomes possible to reduce the reliance on OPC when solidifying WTS [8][9][10][11][12]. These waste materials are cost-effective and exhibit long-term stability, making them attractive options for environmentally responsible practices. This approach addresses the environmental concerns associated with OPC and presents a cost-effective and sustainable means of managing sludge.

This study aims to introduce a sludge treatment approach that uses a combination of binders to minimise the dependency on cement during solidification of WTS. By incorporating these alternative materials as additives, the research seeks to enhance sludge treatment's overall efficiency and eco-friendliness. The primary focus of this investigation is to determine the Liquidity Index (LI) of the sludge after treatment with the blended binder. The significance of these parameters lies in their ability to establish crucial geotechnical properties of the blended cement, especially concerning silt-clay materials. The strength of the mixture significantly influences the compatibility of the blended cement, where higher LI values contribute to better compaction characteristics. Despite the promising potential of blended binders, the information regarding their impact on Plastic Limit (PL) and Liquid Limit (LL) still needs to be improved. As such, this study aims to bridge this knowledge gap, shedding light on the effects of blended binders on these specific properties of the solidified sludge. This comprehensive research initiative is crucial to sustainable and environmentally responsible sludge management practices. By reducing the reliance on OPC and exploring supplementary cementing materials, this study offers insights into a more efficient, cost-effective, and environmentally friendly approach to treating WTS, contributing to waste management and ecological preservation efforts.

2 Material

The study focuses on using various materials for solidification purposes, with a particular interest in sustainable alternatives. The materials chosen for investigation include OPC, FA, WPSA, POFA, and WTS. OPC is a widely used binder in construction and has been sourced from reputable local manufacturers, ensuring it meets the quality standards outlined in MS522: Part 1:1989. FA, a by-product of coal-fired power plants, has been obtained from Stesen Janakuasa Elektrik, Sultan Salahuddin Abdul Aziz Shah, Kapar. The utilization of FA in solidification techniques is of great interest due to its pozzolanic properties, which can enhance the strength and durability of the solidified material. WPSA is another industrial waste material used in the study, sourced from Malaysian Newsprint Industries (MNI) in Mentakab, Pahang. Incorporating WPSA in the solidification process offers potential benefits, such as reducing waste and utilizing a resource that would otherwise be discarded. POFA, obtained directly from Kilang Sawit Jengka 21, Bandar Jengka, Pahang, is a waste product generated while burning palm oil fuel. This material has shown promising in solidification applications due to its pozzolanic nature, similar to FA, and can contribute to the improved properties of the solidified matrix. WTS sourced from the Perak Gunung Semanggol Water Treatment Plant is also included in the study. WTS contains various mineral residues and has the potential to be utilized in solidification processes to minimize environmental impact and manage water treatment by-products effectively.

3 Method

This study evaluated and compared three additives, namely WPSA, POFA, and FA, regarding their impact on the Plasticity Index (PI) and LI of treated Water Treatment Sludge. The PL and Liquid Limit (LL) characteristics of WPSA and POFA were found to be different. The LI was used to measure the water-plasticity ratio in the water treatment sludge and was also determined in this research. The Atterberg limits test, based on the well-established BS1377 (1990) standard, was employed to assess the plasticity characteristics of the WTS, determining the PL and LL as percentages of water content. Additionally, the LI value was obtained through this test. By analysing the collected data, correlations were drawn between the PI and LI of the WTS and blended binders, following the BS1377 (1990) standard. In conclusion, this research aimed to compare WPSA, POFA, and FA as additives for treating WTS, focusing on their PI and LI. The Atterberg limits test, utilising the BS1377 (1990) standard, was employed to determine these characteristics, and data analysis allowed for exploring the interrelation between the two indexes of WTS and blended binders.

The Atterberg limits are a standardised testing method to assess the plasticity of soils and similar materials. This study conducted Atterberg limits tests following the British Standard BS1377 (1990) to determine different blended binders' Plastic Limits and Liquid Limits. The Liquid Limit Test is a crucial part of this testing, involving plotting data on a semilog graph to find the Liquid Limit value. Three trials were performed for each blended binder with varying amounts of water represented by the number of drops added. The water content in the soil increased incrementally during the trials, causing a decrease in the number of drops required to reach a liquid consistency state. The liquid consistency state refers to when the soil loses its cohesive strength and starts to deform and flow, and the water content responsible for this state is defined as the liquid limit. In simpler terms, the liquid limit is the minimum water content at which the soil behaves like a liquid, losing its ability to hold its shape and exhibiting minimal shearing strength. Understanding the liquid limit is crucial for various engineering and construction applications, including water treatment and soil stabilisation.

The Hand Rolling Method is a technique used to identify the Plastic Limit of a binder material, which is a crucial parameter in assessing the properties of cohesive soils and sludges. During the process, a mass of the binder is taken and rolled between the palm or fingers and a ground-glass plate, forming a long, slender thread. The rolling continues until the thread reaches a diameter of 3mm, transferring the mass into a container. The Plastic Limit is considered to be reached when the thread formed during the Hand Rolling Method starts to deform or crumble upon reaching the 3mm diameter. Multiple trials are conducted with the binder material to ensure accuracy, and the weight of the thread formed at the crumbling point is recorded in each trial. The Plastic Limit of the binder material is determined by averaging the moisture content from these multiple trials. This value indicates the transition point at which the treated sludge or binder material behaves more like a plastic solid than a pliable material. The material's stiffness near the Plastic Limit is such that the thread formed during the Hand Rolling Method crumbles when it reaches a diameter of 3mm. Understanding the Plastic Limit is essential as it provides valuable information about how treated sludge or cohesive soils will behave in various applications. This knowledge allows engineers and scientists to make informed decisions when working with these materials and ensures their proper utilisation in different projects.

3.1 Chemical composition

X-Ray Fluorescence (XRF) analysis was employed to ascertain the chemical compositions of each substance under investigation. The study required a thorough understanding of the chemical composition of the materials involved, detailed in Table 1. The XRF analysis is a non-destructive technique commonly used in scientific research to determine the elemental composition of various substances. It allows researchers to identify the presence of different elements and quantify their proportions accurately. By utilizing this analytical method, the study aimed to gain valuable insights into the elemental makeup of the materials, facilitating a comprehensive understanding of their properties and potential applications.

Table 1. Chemical composition of materials.

Compound	OPC (%)	WTS (%)	FA (%)	WPSA (%)	POFA (%)
Cao	61.43	0.17	6.9	30.52	4.92
SiO_2	18.62	26.74	59	28.15	59.62
Al_2O_3	4.75	20.72	21	15.77	2.54
MgO	3.21	-	1.4	1.94	4.52
Fe_2O_3	3.02	-	3.7	1.05	5.02
SO_3	2.29	-	1	0.57	1.28
Na_2O	1.51	-	-	0.67	0.76
K_2O	1.42	0.74	0.9	0.45	7.52
LOI	3.55	-	4.62	17.23	8.25
Others	-	9	-	-	-

3.2 Mix proportion

The specific proportions for each binder are organized and presented in Table 2 and Table 3.

Table 2. Mix proportion of binder without WTS.

Types of mixes	Material	Percentages (%)	Weight (g)
M1	WPSA	40	20
	OPC	60	30
M2	POFA	40	20
	OPC	60	30
M3	FA	50	25
	OPC	50	25
M4	OPC	100	50

Table 3. Mix proportion of binder with WTS.

Types of mixes	Material	Percentages (%)	Weight (g)
M5	WPSA	40	20
	OPC	60	30
	WTS	100	50
M6	POFA	40	20
	OPC	60	30
	WTS	100	50
M7	FA	50	25
	OPC	50	25
	WTS	100	50
M8	OPC	100	50
	WTS	100	50
WTS	WTS	100	100

The mixing ratios vary depending on the type of binder used and whether it is combined with sludge or independently. These varying proportions are detailed in a tabular format for reference and analysis.

4 Result and discussion

Multiple tests were carried out: Plastic Limit (PL), Liquid Limit (LL), and Liquidity Index (LI) under two different conditions: one involving binders without WTS and the other involving binders with the presence of WTS.

4.1 Plastic limit

The Plastic Limit (PL) Test was performed on binders with and without WTS using three types of waste material: WPSA, POFA, and FA. Each binder underwent three trial readings, resulting in different moisture content values for each trial. The PL value was determined by taking the average moisture content from these trials. Subsequently, the obtained PL values were plotted in Figure 1 and Figure 2 for analysis.

4.1.1 Without water treatment sludge (WTS)

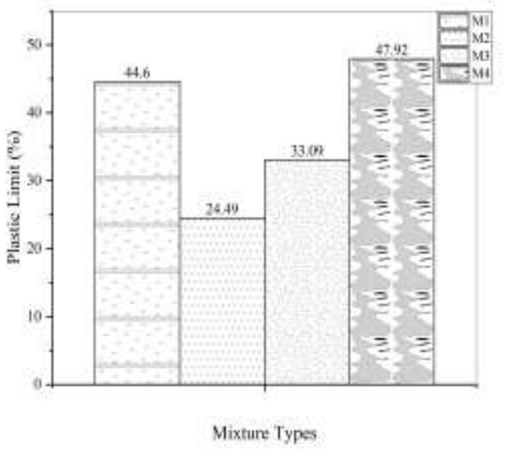

Fig. 1. Plastic limit of binder mix without WTS

According to the data presented in Figure 1, the PL values for Mix 1, Mix 2, Mix 3, and Mix 4 are 39.30%, 23.52%, 29.30%, and 22.30%, respectively. Notably, Mix 1, which comprises a blend of WPSA and OPC, exhibits the highest PL among all the binder mixes investigated. The other binder mixes have lower PL values in comparison. This study categorised the WPSA used as Class-C fly ash following ASTM C618 and AASHTO M295 standards. This classification is attributed to the WPSA's lime (CaO) content exceeding 20%. Class-C fly ash, known for its self-cementing properties due to its high calcium oxide content and pozzolanic characteristics [13]. Notably, the self-cementing action of Class-C fly ash has the advantage of modifying the engineering properties of subgrade soil without requiring additional activators. This makes it an economically viable option for soil stabilisation applications. Moreover, research conducted by Sharipudin et al. (2011) reinforces the significance of the pozzolanic content in Class-C fly ash, as excessive pozzolanic content can adversely affect compressive strength at all stages of development [14]. Based on the PL range of 35% to 50%, Mix 1 is appropriately classified as "CLAY of intermediate plasticity" in the study.

In summary, the study highlights the superior PL of Mix 1, attributed to its composition of WPSA and OPC. The use of Class-C fly ash in this mix demonstrates its potential for economically efficient soil stabilisation without the need for additional activators. However, it also emphasises avoiding excessive pozzolanic content to maintain adequate compressive strength. Consequently, Mix 1 is suitably categorised as "CLAY of intermediate plasticity" within the defined PL range. The elevated PL of WPSA can be attributed to its high carbon content [15]. This carbon content has the unique property of being absorbed by water, reducing the overall water demand during the hydration process. Additionally, the carbon present in WPSA contributes to its high porosity and significant specific surface area, further enhancing its water-absorbing capabilities. However, incorporating WPSA as a cement replacement in specific percentages is essential because it can impact the material's compressive strength. Careful consideration and optimisation of WPSA content are essential to ensure the desired performance of the cementitious mixtures.

4.1.2 With water treatment sludge (WTS)

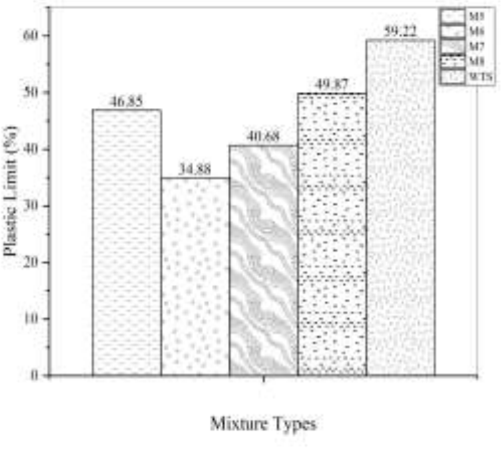

Fig. 2. Plastic limit of binder mix with WTS

The data presented in Figure 2 indicates the PL values for various mixes, with Mix 5 having 46.85% of the PL, Mix 6 at 34.88%, Mix 7 at 40.68%, Mix 8 at 49.87%, and the WTS with the highest value at 59.22% of the PL. It is observed that the PL values for Mix 1, Mix 2, Mix 3, and Mix 4 have increased by 2.25%, 10.39%, 7.59%, and 1.95%, respectively, when compared to the data shown in Figure 4.1. The difference between Figure 4.1 and Figure 2 suggests that WTS significantly influenced the PL increment in each binder mix. This influence is likely due to the clay content in the mixes, which tends to render the binders more plastic. Interestingly, the WTS demonstrates a notably high PL of about 59.22% compared to the other mixes.

However, it should be noted that there were some challenges during the testing process. The inability to roll the thread into 3mm at specific moisture contents suggests some mixes might be non-plastic. This is further supported by the fact that the threads quickly broke before reaching a 1/8-inch length during the test. Consequently, these mixes can be classified as non-plastic materials, according to the findings from the study. The research conducted by Simpson et al. (2013) also reinforces that certain silt and sandy soils lack PL and cannot be rolled into 3mm threads at specific moisture contents [15]. In summary, the study's results show variations in PL values across different mixes, with WTS having a considerable impact on the PL increment in each binder. Moreover, the challenges faced during the testing process indicate that some mixes are non-plastic materials, primarily influenced by their clay content.

4.2 Liquid limit

A Liquid Limit (LL) Test was carried out using WPSA, POFA, and FA waste materials. During the test, three different ranges of drops were measured, and the data obtained from these measurements were used to create a semi-logarithmic graph with a straight line. The focus of the study was to compare the results obtained with and without the presence of WTS to determine its impact on the LL value. The graph presented below illustrates the findings from this comparative analysis.

4.2.1 Without water treatment sludge (WTS)

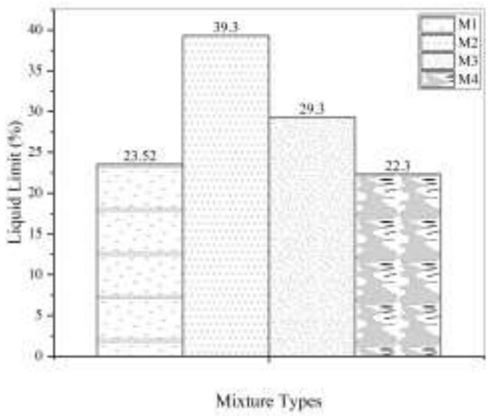

Fig. 3. Liquid limit of binder mix without WTS

Figure 3 illustrates the results of the LL tests conducted on four different binder mixes: Mix 1, Mix 2, Mix 3, and Mix 4. The LL values obtained for each mix are as follows: Mix 1 has a LL of 23.52%, Mix 2 has 39.30%, Mix 3 has 29.30%, and Mix 4 has 22.30%. Analyzing these values, it becomes evident that Mix 2, which comprises a combination of POFA and OPC, exhibits the highest LL among all the binder mixes. This suggests that POFA in the binder contributes to higher water content in the mix, resulting in an elevated liquid state. The significance of this finding lies in identifying that POFA, as a component of Mix 2, possesses greater water-holding capacity than the other binder constituents. This elevated water content impacts the LL, a critical parameter in determining the plasticity and workability of the binder mix. Thus, the study highlights the importance of considering the water content contributed by POFA in designing and formulating binder mixes for various applications.

4.2.2 With water treatment sludge (WTS)

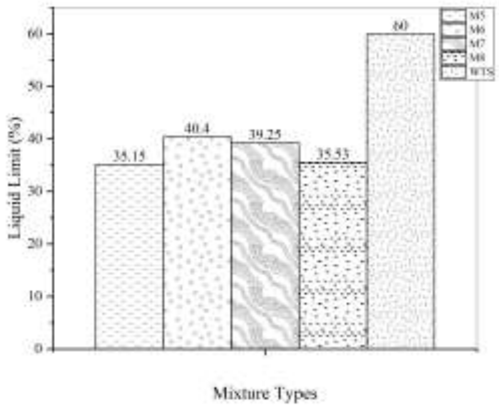

Fig. 4. Liquid limit of binder mix with WTS

Figure 4 displays the effects of WTS on various binder mixes: Mix 5, Mix 6, Mix 7, and Mix 8. The results show that the LL of these mixes has been influenced by the presence of WTS, with different degrees of impact. Specifically, Mix 5 has seen an increase of approximately 11.63% in its Liquid Limit, Mix 6 increased by 1.10%, Mix 7 by 9.95%, and Mix 8 by 13.23%. It is noteworthy that Mix 5, which contains WPSA, OPC, and WTS, exhibits a LL comparable to Mix 8, containing only OPC and WTS. This suggests that WPSA possesses stabilising characteristics similar to OPC when dealing with sludge. Such findings can be valuable for practical applications in sludge stabilisation processes.

The analysis of the LL values also indicates that WTS has a relatively high LL of approximately 60%. In geotechnical terms, a LL falling from 50% to 70% is classified as CLAY with high plasticity. This implies that the high-water content plays a significant role in achieving this consistency in the sludge. This observation aligns with the insights of Al-Bared (2017), who emphasized that high liquid limits indicate soils with substantial clay content and generally low load-carrying capacity [17]. Therefore, understanding the impact of water content on the LL of binder mixes, especially when incorporating WTS, can aid in designing more effective and suitable stabilisation strategies for various engineering applications.

4.3 Liquidity index

The Liquidity Index is a crucial parameter used to assess the flow characteristics and consistency of the mixtures, providing valuable information about their handling and processing properties. According to the research findings, the Liquidity Index (LI) data has been compiled and presented in Figure 5. Based on the data presented in this figure, a graphical representation has been created to visualize the comparison effectively. The comparison revolves around the LI values, which indicate the ease with which a substance flows. By evaluating the data in the graph, valuable insights into the overall Liquidity Index can be gained about the impact of adding the WTS into the mixtures.

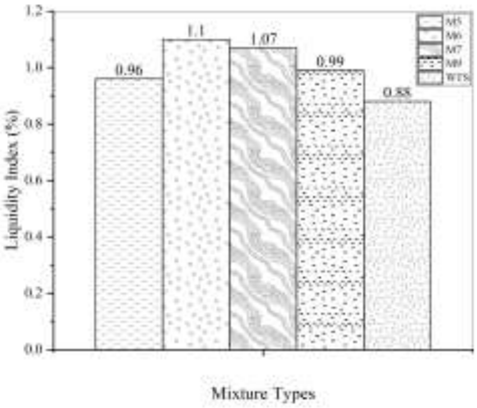

Fig. 5. Liquidity index of each type of binder mix

As depicted in Figure 5, the LI values for different mixtures are as follows: Mix 5 has a LI of 0.93%, Mix 6 exhibits a value of 1.10%, Mix 7 demonstrates a value of 1.07%, and Mix 8 presents a value of 0.99%. Furthermore, the LI of the WTS stands at 0.88%. The data presented in Figure 5 offers an insight into the relative liquidity levels of the different mixes, with Mix 6 showing the highest liquidity at 1.10% and Mix 5 having the lowest at 0.93%. Additionally, the WTS measurement of 0.88% indicates the fluidity of the WTS, aiding in its treatment and disposal considerations. The LI values for Mix 5, Mix 8, and WTS are in the range of 0 to 1, indicating that they have a relatively low sensitivity to changes in water content. This suggests that these mixes have a more stable behaviour and can withstand sudden shocks without transforming into a liquid state. They fall under the category of plastic solid, meaning that when sheared, the current state of the mix contains a significant amount of clay and is classified as stiff [17]. Such mixes are well-suited for stabilisation processes where stability is crucial.

On the other hand, the LI values for Mix 6 and Mix 7 exceed 1, suggesting a reduction in the clay's plasticity. This reduction implies that these mixes are less sensitive to water and are less likely to exhibit expansive properties. They can be considered sensitive binders, according to A. Mahamedi (2014), this reduced sensitivity makes them better suited for compaction, and they may not require excessive amounts of OPC for solidification of sludge [18]. As OPC can be costly due to its high price over time, Mix 6 and Mix 7 can serve as partial replacement materials for OPC in specific applications, offering cost-saving benefits.

The summarised data analysis reveals valuable insights regarding different binder mixes' stability and water sensitivity. Among the studied mixtures, namely Mix 5, Mix 6, Mix 7, Mix 8, and WTS, it has been observed that Mix 5, Mix 8, and WTS exhibit higher levels of stability and are less susceptible to variations in water content. Precisely, Mix 6 and Mix 7 have been identified as sensitive binders with a notable reduction in clay plasticity. This characteristic may affect their performance in specific applications where maintaining consistent water content is crucial for optimal results. By understanding these findings, professionals and researchers can make informed decisions when selecting binders for solidification and stabilisation projects. The selection process can now consider the particular properties of each binder, allowing for the identification of the most suitable binders based on their stability, water sensitivity, and overall performance.

Moreover, these findings also emphasise the significance of cost considerations. By factoring in the properties of the binders, project managers can make economically viable choices without compromising the effectiveness of the solidification and stabilisation processes. In conclusion, this comprehensive data analysis provides valuable guidance for selecting appropriate binders for various solidification and stabilisation applications. It highlights the importance of stability, water sensitivity, clay plasticity, and cost-effectiveness, enabling professionals to make well-informed decisions that will optimise the success of their projects.

5 Conclusion

The study indicates that waste materials can be used as a binder to stabilise sludge effectively. This has several advantages, including reducing the reliance on cement, lowering disposal expenses, freeing up land for other beneficial purposes, and decreasing environmental pollution. The moisture content influenced the Liquid Limit of the stabilising mix. Higher moisture content led to higher LL values, indicating that the mix becomes more fluid with increased moisture. On the other hand, the PL value plays a crucial role in determining the characteristics of the binder mix. Replacement material, like WPSA, was suitable for stabilisation because it possesses self-cementing properties. As the PL increases, the binder mix becomes stiffer. Furthermore, the classification of the binder mix was also affected by the value of the LI. This index helps to determine the flow properties of the mixture. The study demonstrates that combining WPSA, OPC, and WTS creates a stable mix to solidify the sludge. This mixture also exhibits resistance to transforming into a liquid state when subjected to sudden shocks, indicating its stability. The stiffness of the binder mix is attributed to the substantial amount of clay-like material present in the mixture. Overall, using waste materials as binders for sludge solidification is a promising approach that benefits the environment and provides a cost-effective and efficient solution for managing sludge waste.

The authors express their deep gratitude to the College of Engineering, Universiti Teknologi MARA of Malaysia, for permitting this study. Additionally, they extend their heartfelt appreciation to the Ministry of Education for the financial support provided through the grant 600-IRMI/FRGS 5/3 (0120/2016). Furthermore, the authors acknowledge with pleasure the valuable contribution of the Malaysian Newspaper Industry Sdn. Bhd. (MNI), Stesen Janakuasa Elektrik, Sultan Salahuddin Abdul Aziz Shah, Kapar, Kilang Sawit Jengka 21, Bandar Jengka, Pahang, and Perak Gunung Semanggol Water Treatment Plant for supplying WPSA, FA, POFA, and WTS which was essential for the successful execution of the research. Special recognition is also given to all those who directly or indirectly contributed to the completion of this project. Their support and assistance were instrumental in the realization of this study. In summary, the authors want to convey their profound appreciation to the mentioned entities and individuals for their support and collaboration, without which this research would not have been possible.

References

1. S. Nanda, F. Berruti, Municipal solid waste management and landfilling technologies: a review. Environ. Chem. Lett. **19**, 1433 (2021)
2. S. P. Lohani, M. Keitsch, S. Shakya, D. Fulford, Waste to energy in Kathmandu Nepal – A way toward achieving sustainable development goals. J. Sustain. Dev. **29**(5), 906 (2021)
3. A. Reza, S. Anzum, R. C Saha, S. Chakraborty, M. H. Rahman, Implementation of solidification/stabilization process to reduce hazardous impurities and stabilize soil matrices. E3S Web of Conferences. **96**, 01003 (2019)
4. Y. Zhang, L. Wang, L. Chen, B. Ma, Y. Zhang, W. Ni, D. C. Tsang, Treatment of municipal solid incineration fly ash: State-of-the-art technologies and future perspectives. J. Hazard. Mater. **411**, 125132 (2021)
5. W. F. Lamb, T. Wiedmann, J. Pongratz, R. Andrew, M. Crippa, J. G. Olivier, J. Minx, A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environ. Res. Lett. **16**, 073005 (2021)
6. A. Talaei, D. Pier, A. V. Iyer, M. Ahiduzzaman, A. Kumar, Assessment of long-term energy efficiency improvement and greenhouse gas emissions mitigation options for the cement industry. Energy. J. **170**, 1051 (2019)
7. E. Benhelal, E. Shamsaei, M. I. Rashid, Challenges against CO_2 abatement strategies in cement industry: A review. J. Environ. Sci. **104**, 84 (2021)
8. I. Nurliyana, M. A. Fadzil, H. M. Saman, W. K. Choong, Waste paper sludge ash (WPSA) as binder in solidifying water treatment plant sludge (WTPS), in Proceedings of the International Civil and Infrastructure Engineering Conference, Springer Singapore (2016)
9. I. Nurliyana, M. A. Fadzil, H. M. Saman, W. K. Choong, Water treatment sludge stabilizer binder by waste paper sludge ash for solidification/stabilisation technique. Int. J. Integr. Eng. **11**(1), 113 (2019)
10. I. Nurliyana, M. A. Fadzil, H. M. Saman, W. K . Choong, Palm oil fuel ash and ceramic sludge as partial cement replacement materials in cement paste” in Proceedings of the International Civil and Infrastructure Engineering Conference, 2015
11. N. Khalid, M. Mukri, F. Kamarudin, M. A. Fadzil, Clay soil stabilized using waste paper sludge ssh (WPSA) mixtures. Electron. J. Geotech. Eng. **17**, 1215 (2012)
12. N. Khalid, M. A. Fadzil, M. Mukri, F. Kamarudin, A. H. A. Ghani, The California bearing ratio (CBR) value for Banting soft soil subgrade stabilized using lime-pofa mixtures. Electron. J. Geotech. Eng. **19**(A), 155 (2014)
13. A. Misra, D. Biswas, S. Upadhyaya S, Physico-mechanical behavior of self-cementing class C fly ash-clay mixtures. J. Fuels. **84**, 1410 (2005)
14. S. Sharipudin, A. Ridzuan, Influence of waste paper sludge ash (WPSA) and fine recycled concrete aggregate (FRCA) on the compressive strength characteristic of foamed concrete. Adv. Mat. Res. **626**, 376 (2012)
15. P. Simpson, T. Zimmie, Waste paper sludge-An update on current technology and reuse. Recycled Materials in Geotechnics. 75-90, (2012)
16. M. A. M. Al-Bared, A. Marto, A review on the geotechnical and engineering characteristics of marine clay and the modern methods of improvements. Mal. J. Fund. Appl. Sci. **13**(4), 825 (2017)
17. J. P. Maliza, A. Shakoor, Effect of water content and density on strength and deformation behavior of clay soils. J. Eng. Geol. **244**, 125 (2018)
18. A. Mahamedi, M. Khemissa, Stabilization of an expansive over consolidated clay using hydraulic binders. HBRC Journal, **11**(1), 82 (2015)