Solid Waste Material Reuse Analysis: Filling the Road Subgrade with Riverway Silt and Sediment

Qingzhou Wang
Hebei University of Technology
Liying Kong
Hebei University of Technology
Ming-Lang Tseng (tsengminglang@gmail.com)
Asia University https://orcid.org/0000-0002-2702-3590
Yang Song
Hebei university of water resources and electric engineering
Hongyu Wang
Hebei University of Technology

Research Article

Keywords: reuse of solid waste material (SWM), subgrade filling material, riverway silt and sediment, improved mechanical properties, sensitivity analysis

Posted Date: October 26th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-996317/v1

Abstract

This study proposes to explore solid waste material (SWM) reuse with the riverway silt and sediment, and examines the impacts of chemical composition on the road construction through sensitivity analysis. Considering the characteristics of silt mixture, it is necessary to investigate the modified materials to improve the mechanical feasibility for subgrade filling. In this study, modification schemes for construction waste and garbage slag presented well mechanical properties and environmental benefits in sensitivity analysis, especially for the high-water content silt modified by the garbage slag and lime mixture. The results indicate the lime-improved silt with medium water content is a cheap and high-performance material compared to the original silt. Moreover, modified silt demonstrated superior features in particle size, permeability and bearing capacity. Among six lime-improving schemes, the California bearer ratio ($CBR_{2.5}$) increased from 7.1 to 19.6, while the minimum $CBR_{2.5}$ was 2.45 times to the original silt. At last, this study proposes the engineering measures to improve the silt mixture subgrade to prevent heavy metals from polluting the water and soil environment. Further implications were also discussed.

1. Introduction

Solid waste material (SWM) recycling pays more attention to resource utilization and harmlessness in the whole recycling process (Mohammad et al., 2020; Soliman and Moustafa, 2020; Tsai et al., 2021). In addition, a number of legal regulations ensure further reduction of environmental and ecological damage (Khodier et al., 2021; Peng et al., 2020; Vijayan and Parthiban, 2020). Higher environmental protection requirements are put forward for reuse of riverway silt and sediment, as the traditional reuse methods for farmland composting and dredging fill soil is hard to follow the recycling, reuse, and reduction (3Rs) concept (Razzaq et al., 2021; Vsevolod et al.,2017; Wu et al., 2021). This brings unprecedented challenges to the reuse of silt and sediment. This study proposes a novel approach to utilize riverway silt and sediment to fill roads and subgrades, which is believed to achieve the resource conservation and harmless silt treatment.

Riverway silt and sediment is a typical SWM, containing a large amount of toxic heavy metals and non-degradable substances (Abdulnaser et al., 2020; Ahmed et al.,2020; Chu and Yao., 2020; Aneeta, 2020). Solutions for river silt and sediment waste treatment must be sustainable. Hence, the mining of non-renewable natural resources has always been considered as an environmental protection issue (Razzaq et al., 2021; Tang et al., 2020; Wu et al., 2021). The waste generated by industrial activities and urban expansion has aggravated environmental load and toxic pollution to be social and environmental problems. According to statistics of Global Waste Generation released in 2019, 8 billion people in the world have made about 2.5 billion tons of waste (Wang, 2019). Assuming the apparent proportion of the landfill is 1 and the average height of the pile is 30m, over 200 thousand of acre of land will be occupied if these solid wastes are buried and piled up (Neha et al., 2019; Vijayan and Parthiban, 2020). Moreover, groundwater and soil polluted by toxic solid waste are cytotoxic, genotoxic, and mutagenic.

In the literature, Teoh and Li (2019) claimed that the riverway silt and sediment waste production had increased significantly, despite the policy to prevent and manage riverway silt and sediment waste was released. According to the statistics, annual silt production of China is 5,500 tons, while annual silt production of Europe and United State are 4,400 tons and 3,800 tons (Abdulgazi, 2020; Chad et al., 2020; Zhang et al., 2019). 137 million tons of silt has been produced by the world’s three largest economies on 2020, and silt production is believed to grow with 4–6% annually (Silt research China, 2018; Vipin et al., 2020). As restricted approaches, incineration and landfill are still the main treatment methods of silt. For instance, more than 70% of the silt in Europe is burned and heat-treated before used for agricultural land compost. In 2016, Japan and China burned nearly 70% and 59% of silt (Timothy et al., 2017). Almost half of the silt produced in the United States is incinerated and landfilled, while the other half is handled through anaerobic digestion or aerobic fermentation to form bio-solids for farmland fertilizers (Tarpani et al.,2019). Therefore, the purpose of this study is summarized as follows.

- To identify the composition of riverway silt, and evaluate its impact on the environment during construction.
- To investigate the mechanical properties and environmental benefits of lime, construction waste and lime + garbage slag silt modification schemes.

Contributing to the existing literature, this study proposed an efficient and harmless approach to reuse the riverway silt mixture as road subgrade. Additionally, the riverway silt mixed with construction waste, garbage slag and lime were found to illustrate well mechanical performance and environmental benefits.

The remainder of this paper is organized as follows. Section 2 introduces the literature of solid waste and silt reuse. Section 3 addresses the application of riverway silt and sediment on roads and the methodology for the test. Section 4 provide the results of mechanical indicators of riverway silt. Section 5 discusses the feasibility of the silt soil improvement plan and the heavy metal leaching test. Section 6 summarize the findings and implications for further study.

2. Literature Review

The recycling and reuse of SWM are meaningful to alleviate resource shortages and promote the sustainable economic development. Including municipal solid waste (MSW) and industrial solid waste (ISW), MSW is commonly produced during human activities (Aneeta, 2020; Mohammad et al., 2020; Razzaq et al., 2021; Soroudi et al.,2018). ISW, containing residue, dust, sludge and etc., is always generated during the industrial production (Soliman and Moustafa, 2020; Tsai et al., 2021; Vsevolod et al.,2017). Generally, traditional incineration and landfilling are considered as the unsustainable way to reuse the non-degradable MSW, such as domestic refuse and plastics. For instance, Huang et al. (2018) compared recycling, incineration, and landfill treatment methods. And recycling was found to be the most environmentally friendly way to reduce greenhouse effect.

Additionally, there is not enough land for waste disposal in landfills owing to the rising land-use with housing, business and planting purpose. Wesley et al. (2015) and Chad et al., (2020) claimed that 80–90% are municipal solid waste incineration bottom ash (MSWI-BA) through the waste incineration process, which is an appropriate method to deal with the harmful elements within the SWM and MSW. Aneeta (2020) presented the SWM was found to be the granular and dense material with similar performance to natural aggregate. Therefore, it is used as a subgrade filling material and a modified material for subgrade filling. However, few studies have been conducted to mix MSWI-BA and silt to fill roads and subgrades, except to deal with the high-water content riverway silt deposits (Abdulnaser et al., 2020; Razzaq et al., 2021; Tseng et al., 2021). Waste incineration is involved to be unsustainable and harmful for environment. Prior studies stated that the improper recycling of waste was caused by the lacking of waste classification management, commercial reuse method and low recycling benefits. Thus, the economical and environment-friendly reuse methods for MSW, such as the production of bio-butanol, the production of clean hydrogen, power generation and the production of microbial fuel cells were explored (Khodier et al., 2021; Sara et al., 2020; Tsai et al., 2021). In addition, Japan, USA, Germany and China have successively issued national laws on the classification of household waste to promote the reuse of MSW.

Instead, the ISW contains construction solid waste (CSW), industrial slag waste, stones and tailings from the mining industry, cement dust, and ceramic waste (Tang et al., 2020; Wu et al., 2021). Therefore, civil construction is the major industry to reuse the ISW. For instance, Cristina et al. (2017) employed bottom ash, crushed slag and silica fume as the auxiliary materials for the production of cement, which is a traditional method to reuse ISW with finer particle size. Yao et al. (2019) stated that the directly waste conversion at the waste disposal site, reducing the transportation and storage costs, is an environment friendly and economical reuse method. The coarse aggregates in ISW, including tailings, waste rock, damaged asphalt pavements and construction waste aggregates, are mainly used to build civil structures or roads after mixed with concrete (Abdulnaser et al., 2020; Zhang et al., 2019).

Recently, reuse of riverway silt and sediment as the building material has attracted increasing attention in various countries. Riverway silt was previously used to replace clay as building materials. For example, instead of clay, incinerated sewage sludge ash (ISSA) was mixed with silt to produce ceramic floor tiles, and the silt was mixed with zeolite and clay to produce ceramsite (Xu et al.,2017; Wang et al.,2020). In addition, riverway silt and sediment were utilized to produce new blended cement and mix cement concrete (Abdulgazi, 2020; Chu and Yao., 2020; Du and pang, 2018). Although a few studies have investigated the reuse of riverway silt, the environmental hazards of heavy metal sludge have been neglected due to the lack of the chemical composition analysis of riverway silt.

Moreover, aforementioned approach is insufficient for the rapid and large-amount recycle of silt, while the engineering filler shows great potential in reuse of riverway silt. The rapid development of infrastructure construction and restrictions on excavation of mountains or cultivated land has caused the imbalance of supply-demand of engineering filler. Thus, the riverway silt waste has become a possible substitute for clay filler. Several existing literatures presented the use of riverway silt and sediment to the foundation layer of roads, land reclamation, embankment filling material, green grass planting soil on river and lake embankments (Ahmed et al., 2020). This reuse method can effectively deal with final disposal of riverway silt and sediment, specifically for the land damage.

Although riverway silt and sediments have high plasticity, the cohesiveness, compressibility and bearing capacity are low, which presents the poor properties as fillers. In most engineering scenarios, they need to be modified by adding lime, cement, and a curing agent to obtain good mechanical properties and ensure the successful utilization. However, the silt sediments are not allowed to be directly used as subgrade fillers and the technical application still need to be further explored. It is meaningful to evaluate the type and composition of improved materials, especially for the ability of construction waste and garbage slag to improve the mechanical properties of sludge sediment. Moreover, from the perspective of harmless reuse, there is few chemical composition and content analysis of riverway silt and sediment, as well as the analysis of the environmental impact of road subgrade filling.

3. Methods

3.1 Reduce, reuse, and recycle (3Rs) concept

This study needs to apply the 3Rs concept for the reuse of riverway silt and sediment waste (Chu and Yao., 2020; Wu et al., 2021). For example, discharge standards for industrial wastewater are proposed to reduce the pollution of heavy metals to sludge deposits. There are various ways to reuse the unpolluted sludge. The principle of Reuse and Recycle requires to abandon the traditional end-of-use methods of sludge, such as incineration and landfilling, and to actively use it in building materials, raw materials and subgrade filling for recycling. These principles can not only improve the efficiency of resource utilization, but also generate additional benefits from multiple life cycles. In order to promote the “reduction, recycling, and pollution minimization” of solid waste, many governments have formulated SWM recycling plans to improve the management and reuse (Tsai et al., 2021; Wu et al., 2021). Thus, appropriate waste management and recycling policies can promote the effectively use of natural resources and reduce the mining impact on environment.

In this study, riverway silt and sediment was defined as low-, medium-, and high-water content silt (Zhang et al., 2019). The mechanical properties of silt were explored through tests with different mixing ratios and different water contents. In particular, this study examined the feasibility of adding two types of SWM, construction waste and garbage slag, to modify riverway silt and sediment in subgrade filling modification programs. Additionally, the subgrade anti-heavy metal leaching scenario was proposed and evaluated. To contribute the existing literature, this study provides practical application for the reuse of riverway silt and sediment, and supports the decision-making of policymaker, academician and government.

3.2 Technical requirements for subgrade filler

Roads are important carriers of human activities and interconnection, and they are multi-layered systems that carry traffic and transfer loads to the subgrade. The subgrade is the layer between the pavement and the original foundation (Abdulnaser et al., 2020). Gravel-like soil and sand-like coarse-grained materials with fine gradation and easy compaction are selected and constructed in multiple overlapping layers to obtain well load-bearing and anti-deformation capabilities. These high-quality fillers mainly come from the excavation of cultivated land and mountain mining. The shortage of these natural materials has resulted in governmental restrictions on the unsustainable methods to taking soil. Local authorities have begun to formulate effective strategies to implement attractive waste in large-scale road construction projects, especially for filling subgrade applications (Boguniewicz-Zablocka et al., 2021). It is expected that these incentives can not only ensure the sustainability of road construction, but also preserve natural primitive resources, reduce landfills, protect arable land and mountain ecosystems and prevent incineration-driven carbon emissions. "*Technical Specifications for Construction of Highway Subgrades*" in China (2019) introduces that the silt needs to be treated with technical measures and can be used for road construction after inspection. Table 1 specifies the technical indicators of subgrade filling. In addition, the liquid limit, plasticity index and other indicators are the key factors to evaluate the engineering properties of river silt and sediment.

Table 1

Minimum load-bearing ratio and maximum particle size requirements of subgrade filler

Filling application part (depth below the bottom of the road surface) (m)				California bearing ratio (CBR) (%)			Maxi-mum particle diameter size of filler (mm)
				High-speed, first-class highway	Second-class highway	Third- and fourth-class highway	
Fill roadbed	Road bed		0–0.30	8	6	5	100
	Off road bed	Light, medium, and heavy traffic	0.30–0.80	5	4	3	100
		Heavy traffic	0.30–1.20				
	On embankment	Light, medium, and heavy traffic	0.8–1.5	4	3	3	150
		Heavy traffic	1.2–1.9				
	Lower embankment	Light, medium, and heavy traffic	>1.5	3	2	2	150
		Heavy traffic	>1.9				
Zero fill and excavation subgrade	Road bed		0–0.30	8	6	5	100
	Off road bed	Light, medium, and heavy traffic	0.30–0.80	5	4	3	100
		Heavy traffic	0.30–1.20				

3.3 Engineering characteristics of silt and sediments

There are two technical difficulties to prompt the riverway silt meet the technical regulations mentioned in the "Technical Specifications for Construction of Highway Subgrades". Firstly, the type of improved material and the mixing ratio should be determined to meet the mechanical properties in the specification, which affects the silt-improved soil mechanics, improvement cost and improvement time. Soil solidification with lime is a common technique in soil subgrade engineering, which can improve the material's mechanical properties and bearing capacity (Mendes et al.,2021). Lime is mainly used to dehydrate the soil and change the geotechnical properties, such as plastic limit, shear strength and soil compaction properties. The mechanism is that the minerals and lime in the soil undergo a pozzolanic reaction with water to form secondary cementation products. Consequently, the cohesion and shear strength of the soil are increased. The effect of the volcanic ash reaction is long-term. Additionally, to solidify sludge, the cement can improve the mechanical properties of the material rapidly. However, the treatment performance is greatly affected by the uniformity of mixing when cement improves sludge with high water content. In addition, fly ash, garbage slag, soil solidification agent, steel slag, construction waste and other ISWs can also improve the mechanical properties of silt soil (Aldaood et al., 2014). The improved and solidified silt soil can meet the technical requirements of road subgrade filling and be used in subgrade filling engineering (Li et al., 2020; Xiao et al., 2021).

Secondly, secondary contamination of pollutants and heavy metals in sludge must be avoided. Industrial wastewater contains heavy metals, toxic substances and dyestuff, which would settle in the river to form river silt and sediment. Inappropriate way of silt reuse can result in heavy metals entering the human body through groundwater and food, which is dangerous (Nihal et al., 2021a, 2021b; Qi et al., 2011). The reuse of silt and sediments for filling subgrades requires assessment of its toxicity to the environment and corresponding engineering methods to prevent heavy metal leaching.

3.4 Materials

Tianjin is located at the estuary of the Bohai Sea, China. There are many rivers and the annual dredging volume of the main river channels is as high as 6 million m^3. The riverway silt and sediment used in the experiment was taken from the Dagu section of the sewage drainage river in Tianjin, China. Wastewater from factories along the river is discharged into the river, which contains heavy metals and other pollutants.

3.4.1 Physical and chemical properties of riverway silt and sediment

(1) Physical properties

When silt is dredged from the river, the water content is as high as 100%. In order to sieve the harmful substances in the silt, the silt is transported to the landfill for temporary storage. After 2-3 months of natural evaporation and infiltration, the water content of silt can be reduced to 40-60%, which basically reaches the minimum tolerance of roadbed filling construction. In this paper, the silt placed in the landfill was selected as the test material and mixed with the modified material for roadbed filling. Therefore, the river silt is divided into two categories based on water content. The silt with medium water content is less than 40%, While the silt with high water content is more than 40%.

The riverway silt and sediment is an heterogeneous clay composed of organic debris, inorganic particles, bacterial cells and colloids. 80% of the particles size ranges from 0.005 mm to 0.075 mm, which is named silt loam. The saturation is 98.9–100%, which is close to the saturation state, and the porosity ratio is 3.2–3.7. It also presents low-density and loose soil with high compressibility. Silt was obtained from the Qingninghou landfill along the Dagu River in Tianjin. Five soil pits were randomly selected for sampling at the landfill with number from 1 to 5. Figure 1 shows the physical properties of riverway silt. Natural moisture content of the silt samples ranged from 37.1–45.6% and the permeability coefficient was 10^{-5}–10^{-8}cm/s, which showed poor permeability. The organic matter content ranged from 7.2–10.4%, which indicated that it was organic soil (Castorina and Paulo,2015; Wang, 2019). The high organic matter content made the wet soil acidic. Additionally, the organic matter was easily oxidized and affected the long-term stability of the soil. The liquid limit ranged from 50.1–57.6%, which presented the high liquid plastic limit. Besides, the plasticity index, ranging from 18.7 to 26.1, had an average value of 23.12, which presented poor engineering quality with the state of flow plasticity. Therefore, the silt liquid limit did not meet the requirements for subgrade filling and must be improved before the construction.

(2) Chemical properties

Scanning electron microscopy and energy spectrum analyses were used to determine the elemental composition of each dry mud sample. Three sampling areas were randomly selected in the upstream, midstream and downstream section of the Dagu River, which were numbered as U#, M# and D#. Left, middle and right points were tested for each section with depth of 0-20cm and 20-40cm through the element composition inspection. The results are shown in Figure 2. Among them, the Carbon and Oxygen contents were the highest followed by the Silicon content, which the Magnesium content was the lowest (Tomei and Carozza,2015).

Table 2 lists the heavy metal content for the three silt sampling sections U#, M# and D#, which were tested every quarter of year. The results show that oxygen is the most abundant element in U #, M # and D #. Even in the same section, there were uneven distributions in different mud layers and locations. The extreme value of pollutant content is relatively large.

Table 2

Test results for heavy metals in silt at test site (mg/kg)

Sampling section	Cu	Zn	Cd	Cr	Pb
U#	48.4–1132.3	281.9–1430.8	0.8–10.7	27.5–278.9	29.6–205.3
M#	20.5–218.7	226.6–2458.2	1.2–11.4	37.0–229.7	4.4–71.6
D#	36.4–567.7	535.9–3708.9	0–6.7	0–21.6	2.2–122.8

3.4.2 Properties of modified materials

As water content of riverway silt and sediment is usually high, two problems need to be solved before the use for subgrade filling. Firstly, reduce the water content of river silt to less than 50% in terms of the requirement of road engineering. Subsequently, add modified materials to obtain the homogeneous mixture of the two materials. The mixture has the best compaction effect with the optimal water content (about 20%). Secondly, the riverway silt and sediment, with high liquid limit and high plasticity index, must be modified to meet the standard of subgrade filling. Therefore, the modification of the riverway silt and sediment is indispensable for road subgrade filling. In order control the silt reuse costs, an experiment was conducted with building material lime and two types of SWM, construction waste and garbage slag, to enhance the particle size distribution and reduce the water content and organic content. The parameters of the main materials used in the modification are described as follows.

(1) Lime(L)

The lime used in this test was Yixian grade III calcium quicklime powder. The activity of lime depends on the CaO and MgO contents. The CaO content is 68.3% and MgO content is 4.1%. The higher content of active ingredients could effectively reduce the liquid limit water content and plasticity index of the silt, enhance the cementing ability and promote fundamental changes in the properties of the soil. To fully mix the lime and silt during the test, the lump lime was ground and passed through a 2 mm sieve before use.

(2) Construction waste(CW)

Construction waste (CW) has the advantages of large pores and well water absorption. It is suitable for solidifying silt with a medium water content. The CW selected for this study was taken from a construction waste crushing yard in Bazhou City, Hebei Province, China. It was crushed concrete and demolished brick wall materials. The chemical composition of CW contains silicate, oxide, hydroxide, carbonate, sulfide and sulfate, etc. The ratio of coarse to fine aggregates was 3:7. The particle size of the construction waste was 5–25 mm, the water absorption rate was 8.59% and the loose density was 1.030 $kg{\cdot}m^3$.

(3) Garbage slag(GS)

Garbage slag is the slag produced through the incineration of municipal solid waste in a garbage power plant (Vsevolod et al.,2017). It contains active ingredients and the carrying capacity can be increased after interaction with silt. The waste slag in this test was taken from the Tangshan Power Plant. The major active ingredients were SiO_2 (51.96%), Al_2O_3 (12.14%), Fe_2O_3 (5.87%), CaO (14.05%) and MgO (1.11%). The sum of the SiO_2 and Al_2O_3 contents was as high as 64.1%, which met the requirement of the 70% active ingredient content standard. Approximately, 60% of the garbage slag had a size ranging from 0.6 mm to1.18 mm, while minority was ranged from 0.15 mm to 0.3 mm. Additionally, the apparent density was 2.24 g/cm^3, the loose bulk density was 0.87 g/cm^3, the water content was 7.2%, the firmness was 27.4% and the loss on ignition was 6.82% (Castorina and Paulo,2015).

3.5 Proposed Method

3.5.1 Tests and indicators

(1) Heavy compaction test

In terms of the T0131-2007 heavy compaction test method in China's "Test Methods of Soils for Highway Engineering"(JTG E40-2007), the test was designed. Before the test, different proportions of curing agent mixed with silt samples were prepared and moistened. The soil samples were loaded into the test model in three layers, and each layer was given 98 hits by a compaction hammer with 4.5 kg weight and 45 cm drop distance, which can determine the optimal water content and dry density of riverway silt and sediment. The optimum moisture content of the original silt was 23.7%, while the optimum dry density was 1.712 g/cm^3.

(2) Liquid plastic limit test

The liquid limit, plastic limit and plasticity index reflect the dryness or wetness of a mixture. Especially for the plasticity index, which directly illustrates the plasticity of the mixture. In terms of China's "Test Methods of Soils for Highway Engineering"(JTG E40-2007), the liquid plastic limit test method was utilized to determine the liquid plastic limit and plasticity index of the silt mixture. According to the requirements for subgrade filling indicators in China's "Specification for Design of Highway Subgrade " (JTGD30-2015), liquid limit are lower than 50% and plasticity index is lower than 26. The measured liquid limit of the original silt was 54.7%, the plastic limit was 30.9% and the plasticity index was 23.8.

(3) California bearing ratio (CBR) test

In terms of the T0134-1993 California load-bearing ratio test, the molded specimen was compacted with 96% compaction under the condition of the optimum water content measured in the compaction test (Arul et al.,2014). The $CBR_{2.5}$ value and expansion of the specimen were determined after 3 days of health maintenance and 4 days of soaking in water. The test process is shown in Figure 3. The $CBR_{2.5}$ value of the original silt was 2.9%, while the expansion was 2.7%.

3.5.2 Modification scheme design

Different disposal methods were proposed for the medium water content and high-water content silt. Besides water content, the high liquid limit, high plasticity index of riverway silt and sediment and carrying capacity are also the properties to be concerned for low-medium water content silt. The effect of lime and construction waste on the mechanical properties of silt mixtures with medium water content needs to be investigated. On the other hand, the disposal approach for high-water content silt should decrease the water content and increase its bearing capacity. Considering the small particle size, large surface area and well water absorption, garbage slag is combined with lime to improve the engineering properties of the silt mixture (Lang et al.,2020). Table 3 presents the details of the test protocols. SD represents the proportion of silt in each test, L4 stands for a lime (L) mixing ratio of 4%, CW25 represents 25% construction waste (CW), L6GS12 represents a lime mixing ratio of 6% plus a garbage slag (GS) mixing ratio of 12%.

Table 3

Test plan and designations

Modification material	SD (%)	Mix ratio (%,dry weight)	Designation
Lime	96	4	L4
	95	5	L5
	94	6	L6
	92	8	L8
	90	10	L10
	85	15	L15
Construction waste	75	25	CW25
	65	35	CW35
	50	50	CW50
	35	65	CW65
Lime + garbage slag	82	6 + 12	L6GS12
	70	6 + 24	L6GS24
	46	6 + 48	L6GS48

The mixture was configured according to the mixing ratio in test. In the standard test method, the optimum dry density, optimum moisture content, liquid–plastic limit, plasticity index, $CBR_{2.5}$ value, and swelling capacity of each mixture were determined through the heavy proctor compaction test, liquid–plastic limit test, and California bearing ratio test. The mechanical performance of silt mixture with different blending materials and mixing ratios were examined.

4. Results

4.1 Mechanical properties of silt with mediummedium water content improved by lime

Figure 4 shows the mechanical properties using the six lime-improvement schemes. In the heavy compaction test, the optimum dry density of the silt mixture ranged from 1.678 to 1.698 g/cm^3 with a downtrend, while the optimum moisture content showed an uptrend. Compared to the original silt (which had an optimum dry density of 1.712 g/cm^3), the optimum dry density decreased and the optimum moisture content increased to 23.7%. This was mainly caused by the hydration reaction between the lime and silt soil particles. The reaction released a large amount of reaction heat, and partial water evaporated from the mixture, which generated the $Ca(OH)_2$. Cohesion and cementation occurred between the fine particles, which produced an agglomeration effect and forming larger particles. This resulted in the original structure change of the soil. For instance, space between soil particles reduced and water holding capacity increased, which modified the compaction performance of the soil and improved the permeability of the silt mixture (Lang et al.,2020). In addition, the high lime mixing ratio leaded to high liquid plastic limit and low plasticity index for the silt. This was mainly caused by the low-valent cation exchange reaction between K^+ and Ca^{2+} in the silt surface. Consequently, particle agglomeration and aggregation changed the content of clay particles in the silt and the adsorption water film around the clay. Although the liquid–plastic limit showed an uptrend, it still satisfied the requirements of China's "Technical Specifications for Construction of Highway Subgrades". Specifically, lime can significantly increase the carrying capacity of the silt mixture. While the lime mixing ratio increased from 4–15%, the $CBR_{2.5}$ value increased by 2.76 times and the minimum $CBR_{2.5}$ value also increased by 2.45 times compared to the original silt. Additionally, the expansion with the L6 and above schemes was 0.8%, which was 3.375 times lower than that of the original silt.

Therefore, the lime could absorb and react with partial water to increase the optimal water content of the silt mixture, which improved the compactness of the mixture. The mechanical properties were found to increase significantly over time, which made lime-modified silt a cheap and effective method. However, lime cracking due to water loss should be concerned. The lime silt should be mixed evenly during the construction process.

4.2 Mechanical properties of silt with medium water content improved by construction waste

Figure 5 presents the test of the four blending schemes, CW25, CW35, CW50, and CW65, using construction waste. Under the conditions of the heavy compaction test, the added construction waste coarse aggregate caused the optimum dry density of the silt mixture to greatly increase from 1.716 g/cm^3 to 1.765 g/cm^3 and then decrease to 1.736 g/cm^3, when compared to the original mud. Simultaneously, the optimum moisture content slowly decreased from 18–15%. Moreover, construction waste improved the liquid–plastic limit of the silt. When the ratio of construction waste was increased, the liquid limit of the silt mixture was gradually decreased, the plastic limit was increased and the plastic index was decreased. Liquid–plastic limit and plasticity index of the silt mixture among four blending schemes were satisfied with the requirements of China's "Specification for Design of Highway Subgrade" for subgrade filling.

On the other hand, the silt mixture mixed with construction waste had an excellent carrying capacity. When the proportion of construction waste increased from 25–65%, $CBR_{2.5}$ increased firstly and then decreased. When the proportion was 35%, the load ratio reached the optimal dosage. Thus, various blending ratio can result in fluctuated $CBR_{2.5}$. Moreover, amount of expansion decreased from 1.8% to the minimum value of 1.2% as the proportion of construction waste increased. CW35 scheme had the smallest expansion, which indicated this modification scheme had better water sensitivity and stability of subgrade structure (Gideon et al.,2020). Specifically, $CBR_{2.5}$ of the CW35 scheme was 3.1 times to the minimum load-bearing ratio required for high-speed and first-class highway subgrade fillers, and 4.3 times to the original silt load-bearing ratio. As a subgrade filler, it presented excellent mechanical properties and bearing capacity.

Additionally, silt mixed with a low proportion of construction waste was found to be beneficial for engineering applications. The results indicate high proportion of construction waste presented poor mechanical properties, which supports the optimization of mixing ratio of construction waste. At the same time, the load-bearing ratio of the CW25 scheme was 2.56 times to the minimum load-bearing ratio required for high-speed and first-class highway subgrade filling, and 3.55 times to the original silt load-bearing ratio. These excellent mechanical indicators also support the CW25 to be the road base layer filler. Thus, low proportion of construction waste would consume more silt and reuse the silt with low cost.

4.3 Mechanical properties of silt with high water content improved by lime and garbage slag

The results for three schemes L6GS12, L6GS24 and L6GS48 are shown in Figure 6. In the heavy compaction test, when the proportion of garbage slag increased, the optimum dry density of the silt mixture decreased. Specifically, the optimum moisture content reached the minimum value when the slag was added to 24%. It was mainly caused by the low strength of garbage slag. The lightweight porous material was easily broken into fine particles after being hammered. As silt with high-water content has a high liquid limit, it is hard to reduce the liquid and plastic limits through mixing with garbage slag only. In order to reduce the liquid–plastic limit of silt, lime and garbage slag were mixed with the fixed 6% lime mixing ratio. The surface of the garbage slag has large pores and strong water absorption, which is beneficial to improve high-water content silt.

In the liquid–plastic limit test, as the mixing ratio increased, the liquid limit and plastic limit of the silt mixture decreased. However, the liquid limit of the L6GS12 scheme did not meet the requirements of subgrade filling, while the liquid–plastic limit and plasticity index of L6GS24 and L6GS48 were qualified. In addition, lime and garbage slag were found to improve the carrying capacity of the silt significantly. With the continuous increase in waste slag content, the load-bearing ratio increased from 9.9 to 17.8, which increased the load-bearing ratio of the mixture. The swelling amount after being saturated with water fluctuated. The maximum swelling amount was 1.3%, which met the requirements for subgrade material. The load-bearing ratio, liquid–plastic limit and other indicators of the L6GS24 scheme also showed better engineering characteristics. In order to implement the large-amount use of riverway silt and sediment, L6GS24 scheme is recommended. Further study are needed for the technology and feasibility of adding lime and garbage slag to silt with a high-water content in engineering practice.

5. Discussion

5.1 Feasibility of silt mixture improvement schemes

Water content is a key factor for the rapid use of riverway silt and sediment as subgrade filling material. Generally, it takes more than 10 months for high-water content silt to become low-water content silt through the natural evaporation of the water (Wang et al., 2020). Alternatively, the high-water content silt is placed for 2 months to dehydrate naturally, and then exposed to the sun for about 30 days. The moisture requirements of the subgrade can be met after being turned over every 7-8 days (Lin et al., 2020). However, aforementioned dewater method might occupy large areas of landfills. Therefore, it is necessary to accelerate the dewater and reuse of silt. In engineering applications, dewater method of silt should be determined according to the actual situation and improvement plan for the subgrade fill.

Three improvement schemes were analyzed from the perspective of mechanical performance and silt utilization. The CBR index of each scheme is shown in Figure 7. Firstly, when the lime mixing ratio was 6–8%, the water content decreased significantly. While the $CBR_{2.5}$ reached 10.4 to14.6 and the proportion of silt utilization in the mixture was 92–94%, the requirements for the water content, liquid plastic limit, plasticity index, $CBR_{2.5}$ value, and other indicators in the treatment of various content silts can be satisfied. Therefore, it is feasible to use 6–8% lime-improved riverway silt and sediment for subgrade filling. Secondly, in the improvement plan with construction waste, the $CBR_{2.5}$ of the CW25 plan reached 10.3 and the amount of silt that could be processed was 75%. The mechanical properties were inferior to the improvement plan with lime, especially for the low doping ratio scheme with 25–35%.

Finally, mixed with lime and garbage slag, the utilization efficiency of high-water content silt could be increased. The $CBR_{2.5}$ of the L6GS24 scheme reached 12.1. The increasing water content indicated that more waste slag was added on the basis of 24% to consume more water. Thus, a better subgrade bearing capacity could be obtained. It should be emphasized that construction waste and garbage slag are both SWM. The modified schemes employ novel technology for harmless treatment and apply the sustainable use of resources.

5.2 Environmental impact assessment of improved silt mixture

As the heavy metals might be involved within the river silt, environmental impact of the proposed road material was investigated (Ding et al., 2019; Xu et al., 2017; Daniela et al., 2006). Considering the subgrade filling with silt in this study and secondary pollution to the environment, a leaching test analysis was utilized to evaluate the leaching capacity of the toxic metals. According to the test standards "Identification Standard of Hazardous Wastes-Identification for Extraction Toxicity" and "Solid Waste-Extraction Procedure for Leaching-Sulfuric Acid & Nitric Acid Method", 14 samples, including the raw mud, were tested to identify the contents of eight heavy metals. Table 4 presents the results.

Table 4

Experimental of heavy metal leaching results for raw mud and combined mud

Content(mg/L) Number	Cd	Cr	Zn	Hg		Cu	Mn	Pb	Ni
SD1#	<LOD	0.024	0.066	<LOD	0.04	0.022	<LOD	<LOD	
SD 2#	<LOD	<LOD	0.037	<LOD	0.026	0.64	<LOD	<LOD	
SD 3#	<LOD	<LOD	0.026	<LOD	0.02	0.15	<LOD	<LOD	
SD 4#	<LOD	<LOD	<LOD	<LOD	0.017	0.035	<LOD	<LOD	
SD 5#	<LOD	<LOD	0.034	<LOD	0.057	0.071	<LOD	<LOD	
SD 6#	<LOD	0.03	0.019	<LOD	0.053	0.049	<LOD	<LOD	
L5	<LOD	<LOD	0.012	<LOD	0.14	<LOD	<LOD	<LOD	
L10	<LOD	<LOD	<LOD	<LOD	0.084	<LOD	0.0007	<LOD	
L15	<LOD	<LOD	<LOD	<LOD	0.085	<LOD	0.0002	<LOD	
L20	<LOD	<LOD	<LOD	0.0002	0.07	<LOD	0.0004	<LOD	
CW5	<LOD	<LOD	<LOD	0.0002	0.068	<LOD	<LOD	<LOD	
CW10	<LOD	<LOD	<LOD	0.0016	0.055	<LOD	<LOD	<LOD	
CW15	<LOD	<LOD	<LOD	<LOD	0.045	<LOD	0.0003	<LOD	
CW20	<LOD	<LOD	<LOD	0.0004	0.048	<LOD	0.0007	<LOD	
Limit	1	15	100	0.1		100	—	5	5

LOD: limit of detection = 0.001 mg/L

It can be seen that the heavy metal content of the leaching solution of the raw mud leaching liquid, lime and construction waste-modified silt mixture was far less than the standard. Therefore, the mixture could be classified as non-hazardous waste and the solidified riverway silt and sediment could be used as a subgrade filler.

This study proposed the approaches to modify the silt mixture subgrade to prevent heavy metals from polluting the water and soil. One of the measures is designing a waterproof geomembrane between the silt mixture and the underlying soil to solve the issues of groundwater and wide-spread areas in Tianjin. This waterproof geomembrane can effectively prevent the contact between the silt mixture and the groundwater and soil and prevent harmful substances from infiltrating into the groundwater. When the subgrade reaches its service life, it can not only be used as the boundary between the silt mixture and other soil samples, but also as a sign to distinguish the silt mixture from non-silt. Another measure is to use clay edging to prevent contact between the silt mixture and the soil on both sides and upper part of the subgrade. The silt mixture would be placed in the center of the subgrade to prevent secondary environmental pollution through rain erosion and wind erosion.

These engineering measures are shown in Figure 8. The width of the edging soil is generally controlled at approximately 1.5 m to 2.0m and the thickness of the top edging soil should be over 30 cm, which is convenient for mechanized construction. The waterproof geomembrane is spreading on the soil interface under the silt mixture layer and back at least 1m from the boundary between the edging soil and the silt mixture. The roller compacts the edging soil layer by layer, before the roller compacted silt mixture is filled.

5.3 The application potential of SWM in road construction

Tremendous of soil, natural aggregate, asphalt and other materials are consumed in SWM road construction application. Total length of highway in China is 4,866,500 kilometers, while the length in U.S. and Europe are 6.6 million and 5 million kilometers (Abdulgazi, 2020). Therefore, it is difficult to fulfill the huge demand for road construction materials in the complex environment across mountains, deep valleys, rivers, plains and railways. In the near future, the huge demand of building materials is generated with the construction and maintenance of highways.

In the road construction project, various of solid wastes can be recycled. As the major raw materials for road construction, clay, sand, gravel aggregates, cement, asphalt and steel can be replaced or modified by solid waste, except for the steel. For instance, silt, bottom ash, fly ash, aluminum slag, slag and construction waste can replace clay or sand to build roads (Ahmed et al., 2020; Zhang et al., 2019). Waste tires, steel slag and glass waste can serve as the modifier of cement concrete or asphalt concrete (Wang et al., 2020). Bio-oil, as an alternative material of cement concrete, can be paved on the upper layer of the road to reduce the paving cost and extend the service life (Abdulnaser et al., 2020). Moreover, the utilization of SWM, including waste rubber tires, glass waste and fly ash, in the pavement and subgrade structure can also achieve better durability (David et al., 2018).

The benefits of applying SWM in road construction are significant. Most of these SWM are renewable resources with low cost. SWM is environmental friendly material with low energy consumption and low greenhouse gas emission. Moreover, SWM utilization reduces the land occupation for landfills and improve the mechanical performance of materials. In terms of the production costs, the economic benefits of SWM to replace building materials in road construction are also meaningful. The recycled of CSW are 70%~80% cheaper than natural materials considering the same transportation cost. For instance, the rubber waste modified asphalt produced by waste tires can save over 59% of cost, when compared to adding styrene-butadiene-benzene Ethylene. The use of a supplementary material mixed with fly ash and foundry sand for the pavement base layer can save up to 21% of the cost compared with the traditional mixture (Ding et al., 2019; Li et al., 2019).

In the future, it is still challenging to promote the reuse of SWM on the road construction. First of all, the availability of waste resources, the performance degradation and eco-toxicity caused by these wastes should be concerned. Therefore, fixed detection approach should be developed to examine the composition and performance of SWM to ensure the utilize of SWM meet the requirements of the construction. Secondly, performance improvement of waste products and new products development should be promoted to make up for the reduced mechanical properties of recycled materials and poor interfacial adhesion. Finally, the government can formulate binding legislation or introduce incentives to encourage the designers, waste recycling companies and construction contractors. In particular, the promulgation and improvement of the rules and standards of SWM application in road construction can ensure the replacement of traditional building materials by SWM legally.

6. Concluding Remarks

This study proposes to replace traditional building material by riverway silt and sediment mixture for subgrade filling with sensitivity analysis. Through a series of indoor test, the mechanical characteristics and heavy metal leaching with three modification schemes, involving lime, construction waste, and lime-garbage slag, were investigated. The results are summarized as follows.

- The lime-modified silt mixture was found to be a cheap and effective method for enhancing the carrying capacity of the riverway silt and sediment. While lime increased from 4–15%, the $CBR_{2.5}$ increased by 2.76 times and the expansion with the L6 and above schemes was 0.8%, which was 3.375 times to the original silt. All the mechanical indicators were satisfied with the requirements for subgrade fillers in China’s "Technical Specifications for Construction of Highway Subgrades."
- The improvement scheme, utilizing construction waste and lime-garbage slag, was found to improve the silt mixture and obtain higher environmental benefits. In the improvement schemes of CW25 and L6GS24, the low mixing ratio ensure more consumption of silt and excellent mechanical properties. The $CBR_{2.5}$ values of improvement scheme were 3.55 and 4.17 times to the original mud. Additionally, reducing the silt water content is still the primary problem for engineering applications.

- Through the total metal content analysis and heavy metal leaching test, the raw mud was found to contain a variety of heavy metals with low content, which met the requirements for soil use in China's "Identification Standard of Hazardous Wastes–Identification for Extraction Toxicity"(GB5085.3-2007). In engineering applications, to prevent the secondary pollution to the water and soil, the edging soil and waterproof geomembranes were proposed. These measures can cut off the contact between the raw mud and the environment.
- The application of most SWM, such as riverway silt, steel slag, waste tires and demolished construction wastes, to replace traditional materials can obtain significant environmental and economic benefits.
- Further study can be conducted to explore the changes in the mechanical properties of the products produced using different modification schemes over time. Besides, the physical properties of a silt mixture, including the direct shear, compression test and other test indicators, can also be examined. The result is believed to support and promote the large-scale application of riverway silt and sediment in road subgrade filling.

Declarations

Author Contributions

Qingzhou Wang - Conceptualize, original version and finalized the final version; Liying Kong-Conceptualize, original version and finalized the final version; Ming-Lang Tseng- Conceptualize, original version and finalized the final version; Yang Song- original version and finalized the final version; and Hongyu Wang-original version and finalized the final version

Availability of data and materials

No authorized

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Competing Interests

Not applicable

Ethical Approval

Not applicable

Funding Declaration

This study is partially supported from MOST 110-2222-E-468-002-, Ministry of Science and Technology, Taiwan

References

1. Abdulgazi, G(2020) A review on the evaluation of the potential utilization of construction and demolition waste in hot mix asphalt pavements. Resources, Conservation and Recycling. 161 104956.
2. Abdulnaser, M. A.S., Madzlan, B. N., Muslich, H. S., Wesam, S. A., Aliyu, U(2020) A systematic review of bio-asphalt for flexible pavement applications: Coherent taxonomy, motivations, challenges and future directions. Journal of Cleaner Production. 249, 119357.
3. Ahmed, L., Mounsif, I., Omar, W., Ali L., Oksana, T(2020) Valorisation of dredged marine sediments for use as road material. Case Studies in Construction Materials. 13, e00455.
4. Aldaood, A., Bouasker, M., Al-Mukhtar, M(2014) Impact of wetting–drying cycles on the microstructure and mechanical properties of lime-stabilized gypseous soils. Engineering Geology.174,11-21.
5. Aneeta, M. J., Ruben, S., Peter, N., Stijn, M., Nele, D.B(2020) Pre-treatment and utilisation of municipal solid waste incineration bottom ashes towards a circular economy. Construction and Building Materials.260,120485.
6. Arul A., Mahdi M. D., Suksun H., Cherdsak S., Nutthachai P(2014) Physical properties and shear strength responses of recycled construction and demolition materials in unbound pavement base/subbase applications,Construction and Building Materials,Volume 58 ,245-257.
7. Boguniewicz-Zablocka, J., Klosok-Bazan, I. & Capodaglio, A.G (2021)Sustainable management of biological solids in small treatment plants: overview of strategies and reuse options for a solar drying facility in Poland. Environ Sci Pollut Res 28, 24680–24693.
8. Castorina, S.V., Paulo, M.P(2015)Use of recycled construction and demolition materials in geotechnical applications: A review. Resources, Conservation & Recycling 103,192-204.
9. Chad, J. S., Michael, M.V., Steven J. L., Timothy G. T(2020)A field-scale evaluation of municipal solid waste incineration bottom ash as a road base material: Considerations for reuse practices. Resources, Conservation &Recycling. 105264.
10. Chu, S.H., Yao, J.J., 2020. A strength model for concrete made with marine dredged sediment. Journal of Cleaner Production.274, 122673.
11. Cristina, A., Amparo, M., Esperanza, M(2018)Use of ground coal bottom ash as cement constituent in concretes exposed to chloride environments. Journal of Cleaner Production.170,25-33.
12. Daniela, B., Dino, M., Sergio, B., Lorenzo, F., Alessandro, B., Stefano, M(2006)Possible production of ceramic tiles from marine dredging spoils alone and mixed with other waste materials. Journal of Hazardous Materials. 134, 202-210.

13. David, S.M., Álvaro, R.E., Enrique, F.L., José, M.F., José, R. J(2019)Feasible use of colliery spoils as subbase layer for low-traffic roads. Construction and Building Materials. 229, 116910.
14. Ding, G.Y., Xu, J., Wei, Y., Chen, R., Li, X(2019)Engineered reclamation fill material created from excavated soft material and granulated blast furnace slag. Resources, Conservation & Recycling. 150, 104428.
15. Du, H.J., Pang,S.D(2018)Value-added utilization of marine clay as cement replacement for sustainable concrete production. Journal of Cleaner Production.198, 867-873.
16. Gideon, O. B., Daniel, E. B., David, O. O., Ben, U. N., Dunmininu, A., Abimbola, O. O., Mutiu, A. K., David, O. E., Austin, T. N(2020) Waste materials in highway applications: An overview on generation and utilization implications on sustainability, Journal of Cleaner Production. 283,124581.
17. Hargreaves, J.C., Adl, M.S., Warman, P.R(2007)A review of the use of composted municipal solid waste in agriculture. Agriculture, Ecosystems & Environment. 123, 1-14.
18. Ho, N.L., Hiroto, T., Teppei, K., Amirhomayoun, S., Takayuki, S(2020)Simulating the impact of heavy rain on leaching behavior of municipal solid waste incineration bottom ash (MSWI BA) in semi-aerobic landfill. Waste Management.113,280-293.
19. Huang, B.J., Wang, X.Y., Harnwei, K., Geng, Y., Raimund, B., Ren, J.Z(2018)Construction and demolition waste management in China through the 3R principle. Resources, Conservation & Recycling.129,36-44.
20. Khodier, K., Feyerer, C., Möllnitz, S., Curtis, A., Sarc, R(2021)Efficient derivation of significant results from mechanical processing experiments with mixed solid waste: Coarse-shredding of commercial waste. Waste Management. 121,164-174.
21. Lang, L., Liu, N., Chen, B(2020)Strength development of solidified dredged sludge containing humic acid with cement, lime and nano-SiO2.Construction and Building Materials. 230, 116971.
22. Li, J.S., Zhou, Y.F., Chen, X., Wang, Q.M., Xue, Q., Daniel, C.W. T., Chi S. P(2020) Engineering and microstructure properties of contaminated marine sediments solidified by high content of incinerated sewage sludge ash. Journal of Rock Mechanics and Geotechnical Engineering. 1674-7755.
23. Li, J.W., Shen, W.G., Zhang, B.L., Ji, X.L., Chen, X., Ma, W., Hu, J.Q., Zhou, M.K., Li, Y.X(2019) Investigation on the preparation and performance of clinker-fly ash-gypsum road base course binder. Construction and Building Materials. 212, 39-48.
24. Lin, N.X., Zhu, W., Fan, X.H., Wang, C.Y., Chen, C., Zhang, H., Le, C., Silin, W., Yan, C(2020) Key factor on improving secondary advanced dewatering performance of municipal dewatered sludge: Selective oxidative decomposition of polysaccharides. Chemosphere. 249,126108.
25. Liu, E.G., Ghanim, K., Li, L(2020)Transformation of industrial solid wastes into carbon-infused infrastructure materials. Journal of Cleaner Production.260,120890.
26. Mendes, R.F., Viana, Q.S., Eugênio, T.M.C. et al(2021) Study of the use of polymeric waste as reinforcement for extruded fiber-cement. Environ Sci Pollut Res 28, 42737–42749.
27. Mohammad, A. A.G., Mariam, K., Mustafa, S. N., Khalid, A.S., Oon E. H(2020)Recent advances and applications of municipal solid wastes bottom and fly ashes: Insights into sustainable management

and conservation of resources. Environmental Technology & Innovation.101267.

28. Neha, M., Tatiana, C., Sabrina, C., Elio, P., Giovanna, A.D., Franco, A.M., Siobhan, F.C., Frederic, C., Domenico, A.D.L(2019)Linking oral bioaccessibility and solid phase distribution of potentially toxic elements in extractive waste and soil from an abandoned mine site: Case study in Campello Monti, NW Italy. Science of The Total Environment.651,2799-2810.
29. Nihal, G., Latha, R., Sudip, M(2021) Occurrence, geochemical fraction, ecological and health risk assessment of cadmium, copper and nickel in soils contaminated with municipal solid wastes. Chemosphere.271,129573.
30. Nihal, G., Sudip, M., Ankit, S., Richa, A., Latha, R., Eldon, R.R., Mahaveer, P. S(2021) Speciation, contamination, ecological and human health risks assessment of heavy metals in soils dumped with municipal solid wastes. Chemosphere.262,128013. https://doi.org/10.1016/j.chemosphere.2020.128013.
31. Oldham, D.J., Fini, E.H., Chailleux, E(2015) Application of a bio-binder as a rejuvenator for wet processed asphalt shingles in pavement construction. Construction and Building Materials.86,75-84.
32. Peng, Y.Z., Peng, X., Yang, M., Shi, H.L., Wang, W.C., Tang, X.C., Wu, Y(2020)The performances of the baking-free bricks of non-sintered wrap-shell lightweight aggregates from dredged sediments. Construction and Building Materials. 238, 117587.
33. Qi, Y., Daniel, S., Ronny T.W.Y., Andrew, F.A. H., Gavin, M(2011) Application of sludge dewatered products to soil and its effects on the leaching behaviour of heavy metals. Chemical Engineering Journal. 166, 586-595.
34. Razzaq, A., Sharif, A., Najmi, A., Tseng, ML., Lim, MK. (2021) Dynamic and causality interrelationships from municipal solid waste recycling to economic growth, carbon emissions, and energy efficiency using a novel bootstrapping autoregressive distributed lag. Resources, Conservation & Recycling166, 105372
35. Sara, F., Hamid, A., Keikhosro, K(2020)S ynergy of municipal solid waste co-processing with lignocellulosic waste for improved biobutanol production. Waste Management.118,45-54.
36. Silt research China,2018. Status analysis and prospect forecast of China's silt treatment and disposal in 2018. https://www.qianzhan.com/analyst/detail/220/180224-b4a1ce29.html (accessed14 February 2018).
37. Soliman, N.K., Moustafa, A.F(2020) Industrial solid waste for heavy metals adsorption features and challenges; a review. Journal of Materials Research and Technology.9,10235-10253.
38. Soroudi, M., Omrani, G., Moataar, F. et al(2018)A comprehensive multi-criteria decision making-based land capability assessment for municipal solid waste landfill sitting. Environ Sci Pollut Res 25, 27877–27889.
39. Tang, Z., Li, W.G., Vivian W.Y. T., Xue, C.H(2020)Advanced progress in recycling municipal and construction solid wastes for manufacturing sustainable construction materials. Resources, Conservation & Recycling: X.6,100036.

40. Tarpani, R.R.Z., Carolina, A., Almudena, H., Azapagic A(2019) Life cycle environmental impacts of sewage sludge treatment methods for resource recovery considering ecotoxicity of heavy metals and pharmaceutical and personal care products. Journal of Environmental management 260, 109643
41. Teoh, S.K., Li, L.Y., 2019. Feasibility of alternative sewage sludge treatment methods from a lifecycle assessment (LCA) perspective. Journal of Cleaner Production.247,119495.
42. Timothy, E. S., André, M. C., Richard, L. S(2017) Municipal wastewater sludge as a sustainable bioresource in the United States. Journal of Environmental Management.197, 673-680.
43. Tomei, M.C., Carozza, N.A(2015)Sequential anaerobic/anaerobic digestion for enhanced sludge stabilization: comparison of the process performance for mixed and waste sludge. Environ Sci Pollut Res 22, 7271–7279.
44. Tsai, F.M., Bui, DT., Tseng, M.L.*, Lim, MK., Mashud, AHM(2021) Assessing hierarchical sustainable solid waste management structure in qualitative information: policy and regulations drive social impacts and stakeholder participation. Resources, Conservation & Recycling 168,105285
45. Tseng, M.L., Tran, T.P.T., Ha, H.M., Bui, TD & Lim, M.K. (2021). Sustainable industrial and operation engineering trends and challenges Toward Industry 4.0: a data driven analysis, Journal of Industrial and Production Engineering, DOI: 10.1080/21681015.2021.1950227
46. Vijayan, D.S., Parthiban, D(2020) Effect of Solid waste based stabilizing material for strengthening of Expansive soil- A review. Environmental Technology & Innovation.20,101108.
47. Vipin, S., Harish, C. P., Munish, K. C(2020) Estimation of energy recovery potential of sewage sludge in India: Waste to watt approach. Journal of Cleaner Production. 276, 122538.
48. Vsevolod, M., Jacqueline, C. S., Cristofer, B. S., Roberto, C.Y. P., Filipe, G. S., Kirill, A., Daniela, E. P., Andrea, M., Otavio, M. F(2017) Utilization of sediments dredged from marine ports as a principal component of composite material. Journal of Cleaner Production.142, 4041-4049.
49. Wang, L.K., Shao, Y.L., Zhao, Z.L., Chen, S., Shao, X.H(2020)Optimized utilization studies of dredging sediment for making water treatment ceramsite based on an extreme vertex design. Journal of Water Process Engineering.38, 101603.
50. Wang, Q.Z., Wang, N.N., Tseng, M.L., Huang Y.M., Li, N.L(2020)Waste tire recycling assessment: Road application potential and carbon emissions reduction analysis of crumb rubber modified asphalt in China. Journal of Cleaner Production. 249, 119411.
51. Wang, T(2019) Global Waste Generation - Statistics & Facts source from Statista.
52. Wesley, N.O., Justin, G. R., Nawaf, I.B., Timothy, G.T(2015)Contemporary practices and findings essential to the development of effective MSWI ash reuse policy in the United States. Environmental Science & Policy.51,304-312.
53. Wu, KJ., Tseng, ML., Ali, M.H., Xue, B., Chiu, ASF, Fujii, M., Xu, M. Ren, M., Bin, Y(2021) Opportunities or threats in balancing social, economic and environmental impacts: the appearance of the Polar Silk Road. Environmental Impact Assessment Review. 88,10657
54. Xiao, J.Z., Shen, J.Y., Bai, M.Y., Gao, Q., Wu, Y.C(2021) Reuse of construction spoil in China: Current status and future opportunities. Journal of Cleaner Production.290,125742.

55. Xu, Y.,Zhang, C.Z.,Zhao, M.H., Rong, H.W., Zhang, K.F., Chen, Q.C. (2017)Comparison of bioleaching and elect rokin etic remediation processes for removal of heavy metals from wastewater treatment sludge.Chemosphere.168,1152-1157.
56. Yao, X.L., Wang, W.L., Liu, M., Yao, Y.G., Wu, S(2019) Synergistic use of industrial solid waste mixtures to prepare ready-to-use lightweight porous concrete. Journal of Cleaner Production. 211, 1034-1043.
57. Zhang, J.h., Gu, F., Zhang Y.Q(2019) Use of building-related construction and demolition wastes in highway embankment: Laboratory and field evaluations. Journal of Cleaner Production. 230, 1051-1060.

Figures

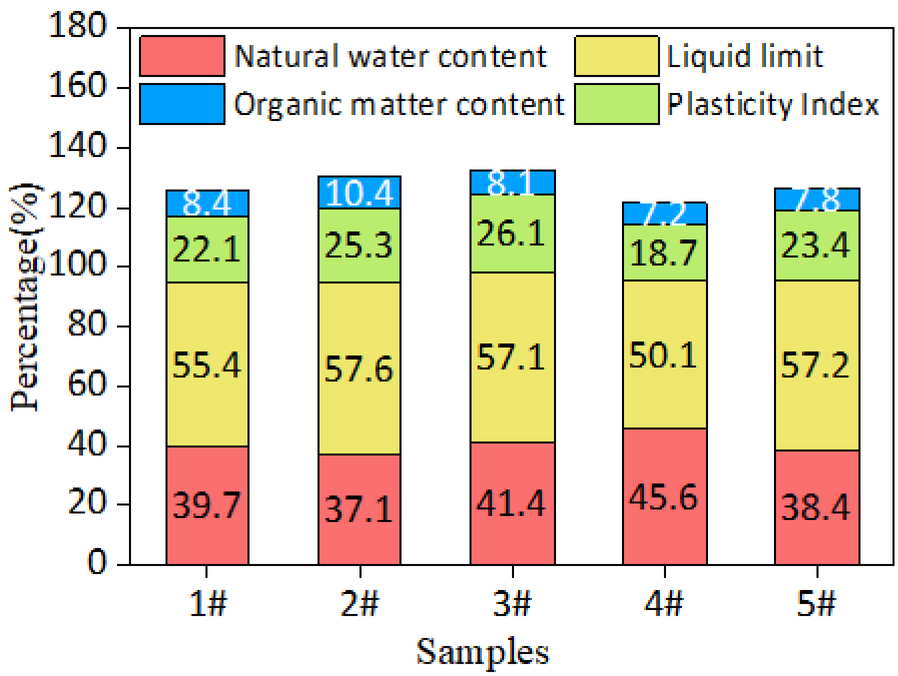

Figure 1

Basic physical properties of silt in Qingninghou landfill

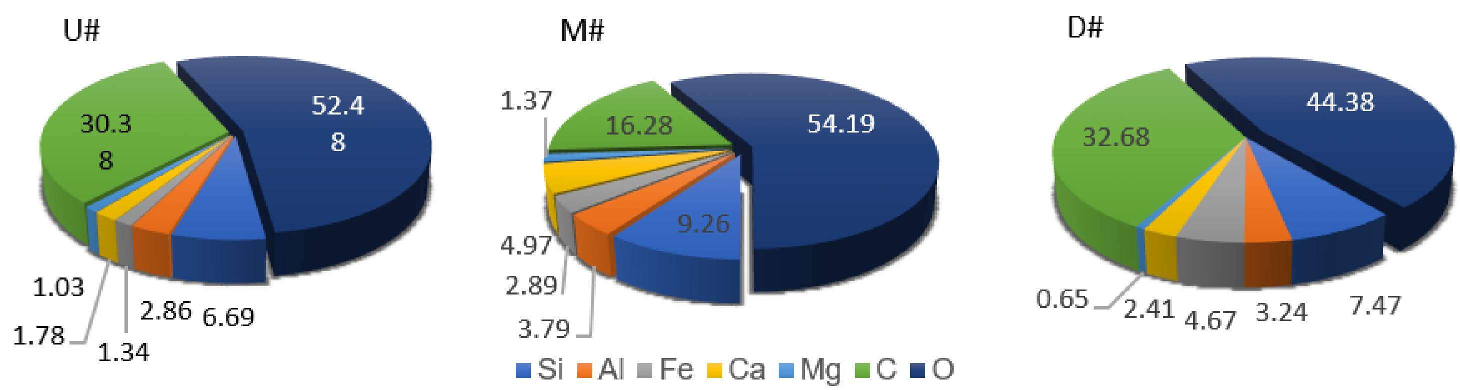

Figure 2

Elemental composition of Dagu Riverway silt (%)

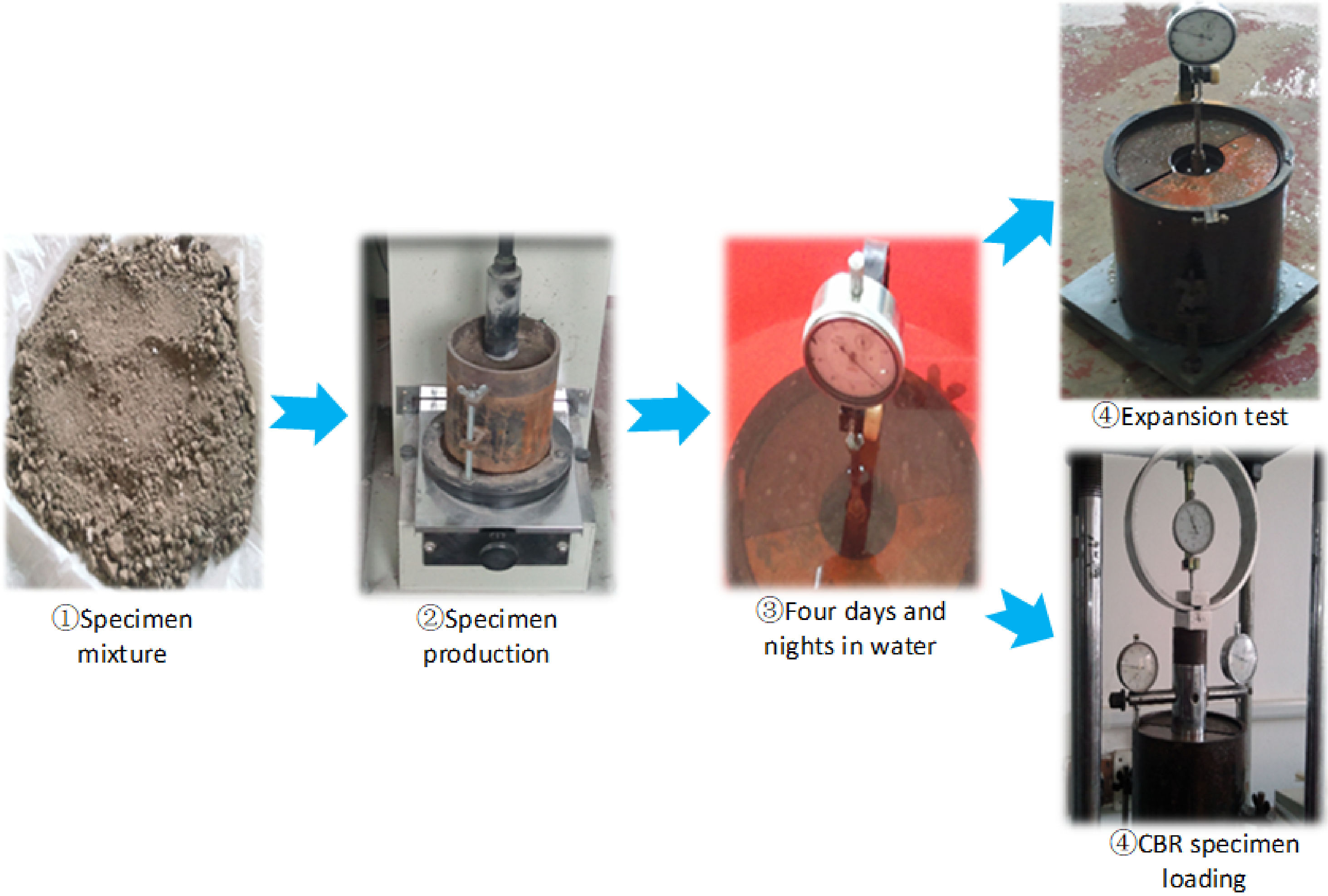

Figure 3

California bearing ratio test process

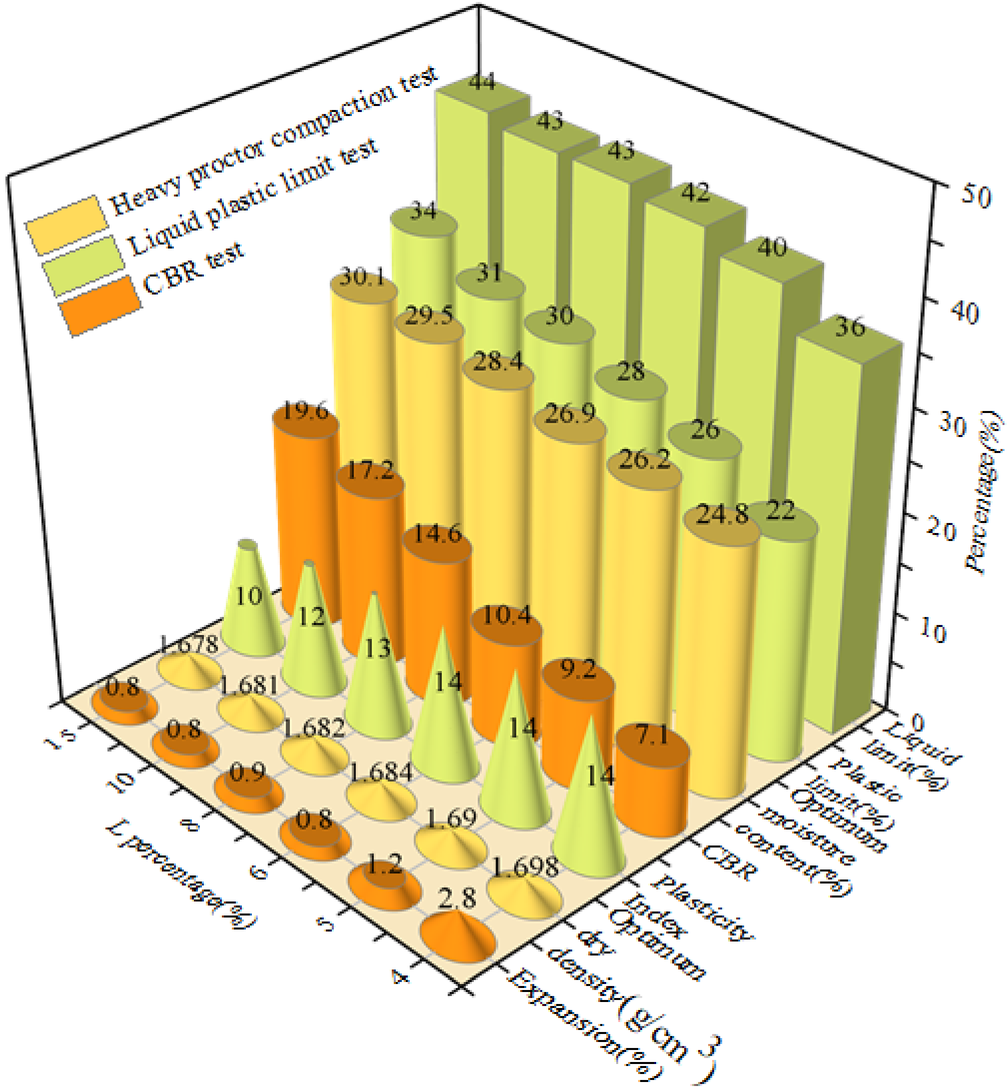

Figure 4

Mechanical index of L modified mixture

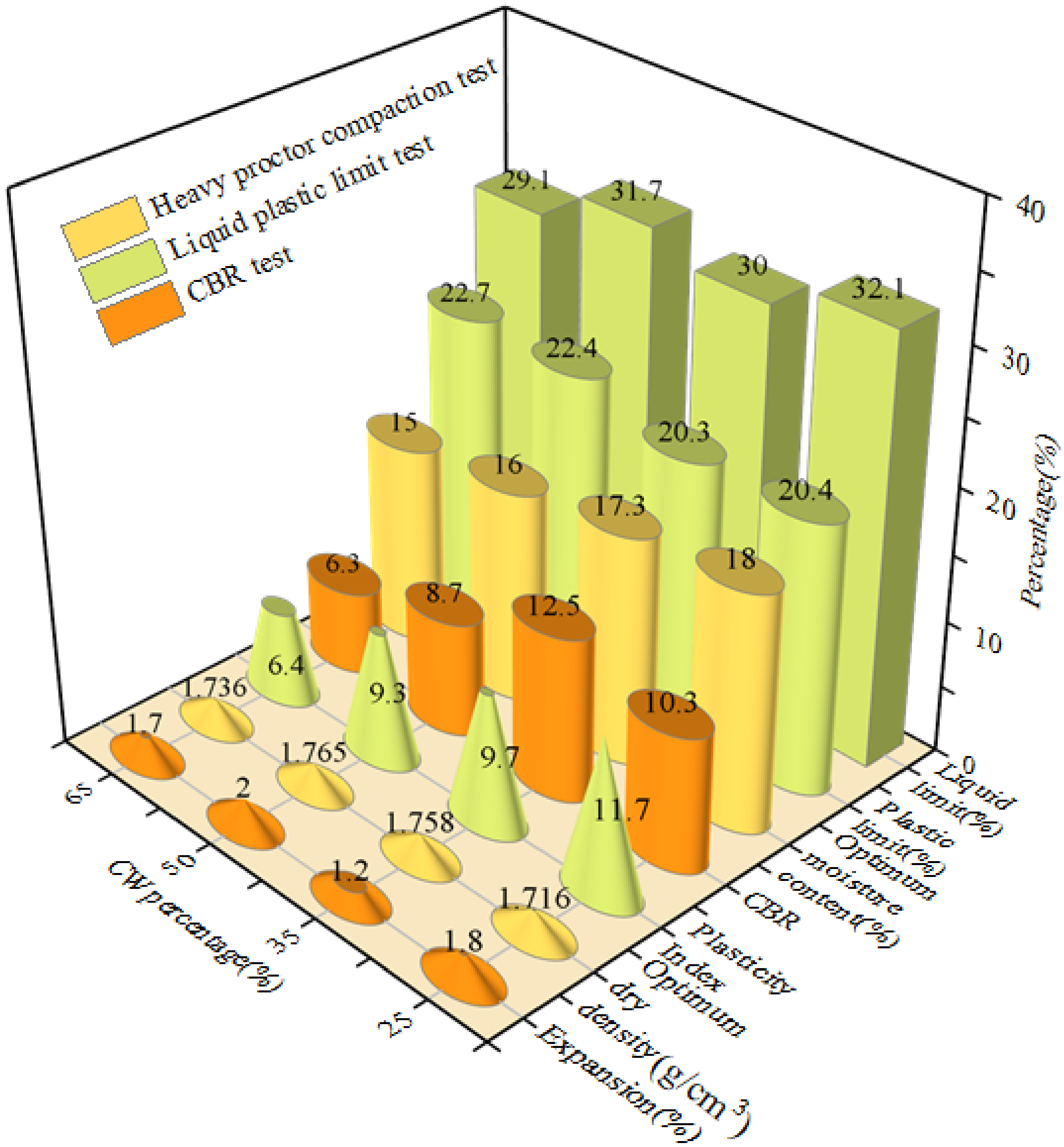

Figure 5

Mechanical index of CW modified mixture

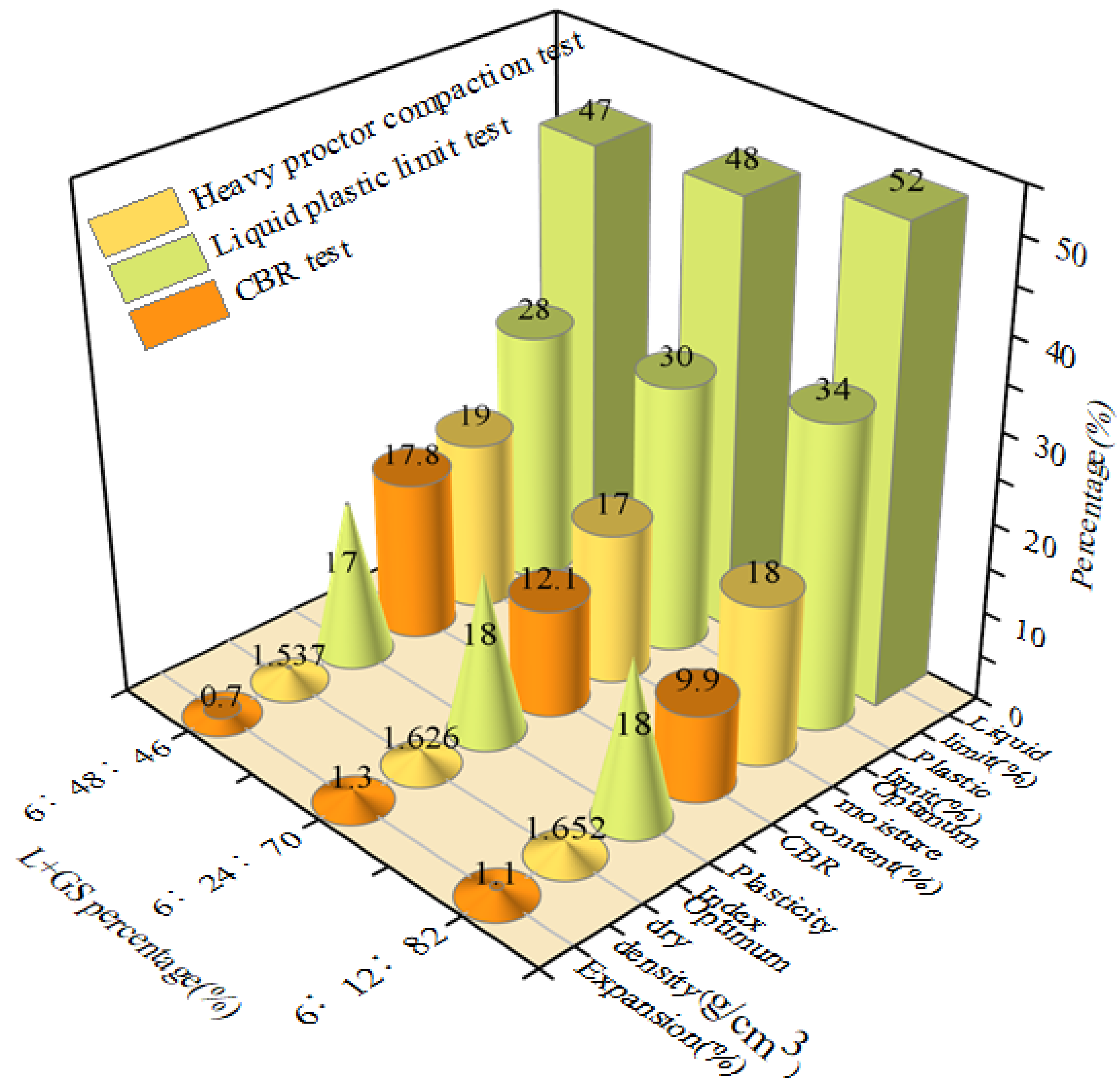

Figure 6

Mechanical index of L+GS modified mixture

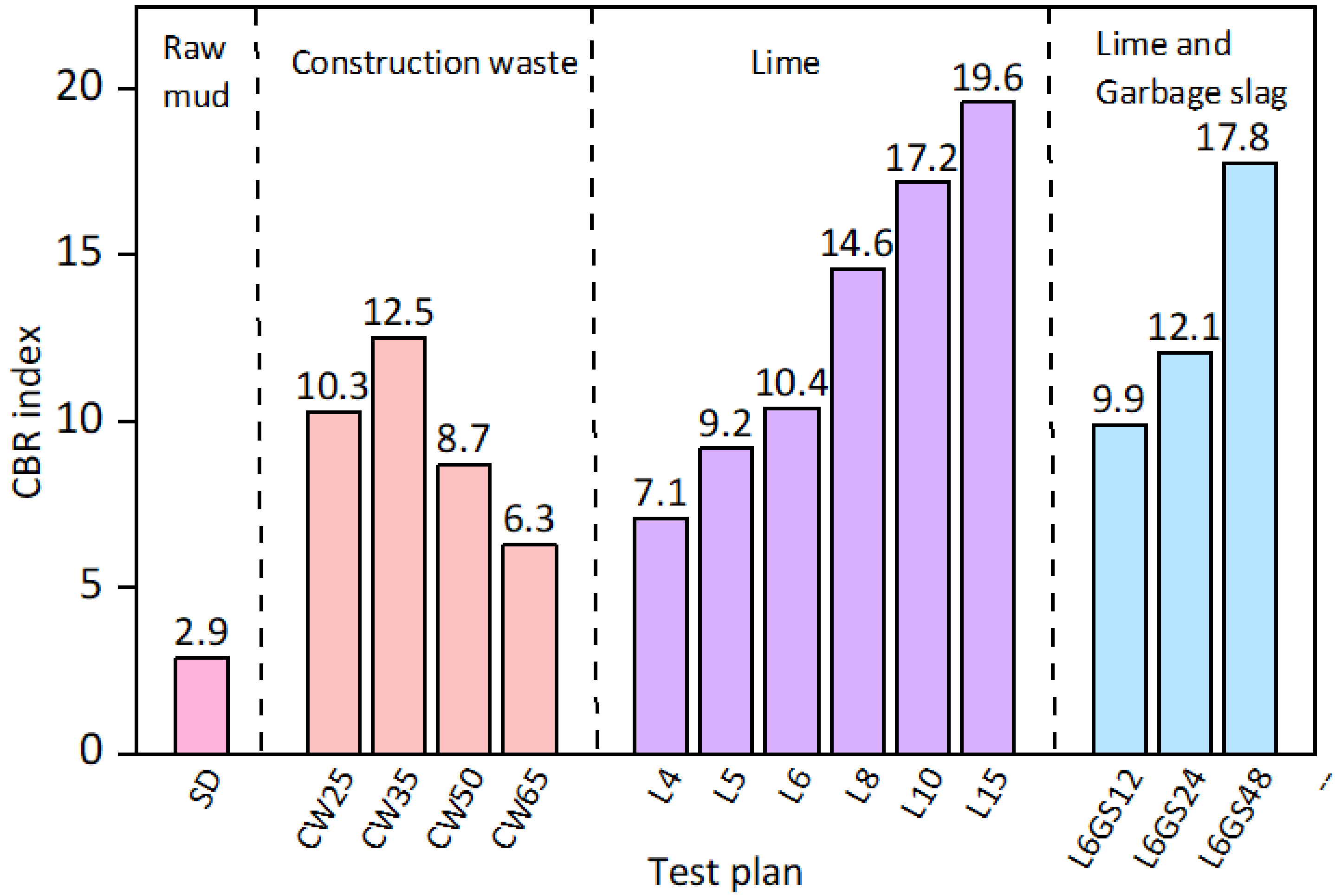

Figure 7

CBR index of each scheme

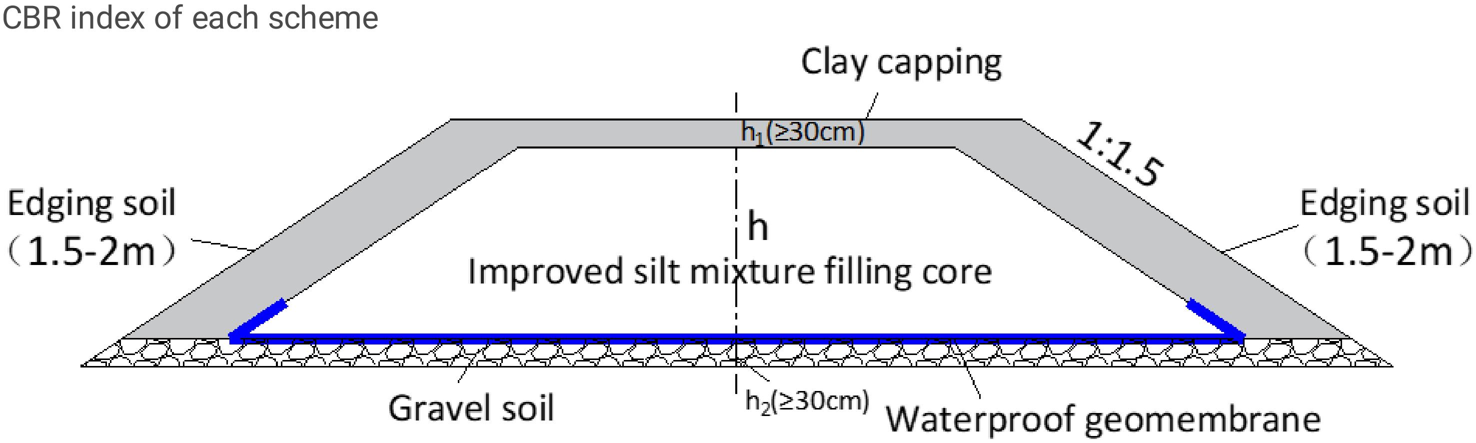

Figure 8

Schematic diagram of clay edging and waterproof geomembrane