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Beneficial Reuse of Construction Surplus Clay in CLSM

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Abstract: The disposal of on-site construction imperfect earth materials and the production of standard engineering aggregates for backfill have been facing increasingly environmental and ecological challenges in many densely populated metropolitan areas. This paper presents an experimental study using soft excavated surplus clay to produce a clay-based controlled low strength material (CLSM) as subgrade material for a pedestrian plaza. Observations have been made for physical and engineering properties based on the fresh and harden-state of the samples. The presented test results include physical and engineering properties for flowable and hardened samples. Two control parameters, the weight ratios of cement-to-water (C/W) and water-to-solid (W/S) were defined to correlate each investigated property with the variations of mixture proportions. Experimental findings indicate that a clay-based CLSM can be developed as an alternative structural backfill material. The recommended C/W and W/S design ratios for the proposed material should be 0.5-0.7 and 0.7, respectively. The fresh state of such mixture presents acceptable flowability and bleeding for easy construction. Its hardened state also behaves as stiff clay with lowest compressibility and stronger bearing capacity, and therefore qualifies for the proposed structural support. The results explore an innovative scheme for the reduction and reuse of construction surplus clay, and suggest a beneficial paradigm for the sustainable development of built environments. However, the findings presented herein can only ensure the validity of the mixtures with the materials in this study. It is highly recommended that those interested in clay-based CLSM perform site-specific experimental studies using local materials to evaluate the particular mix designs.

***Key words**: Backfill material; Controlled low strength material; Non-standard aggregate; Surplus clay.*

Introduction

The constructions of underground infrastructures and substructures of high-rise buildings in a rapid urbanized metropolitan area inevitably produce enormous amounts of surplus soils. These construction by-product materials together with other construction wastes have been enforced in many countries such as Taiwan to be recycled and reused for sustainable development [1-5]. However, because the great difference between supply and demand, there are averaged 28.8 million m^3 surplus soils per year remain unused in Taiwan for the past decade [6]. In addition, the imperfect soft clayey soils containing higher amount of water are virtually inapplicable for most of the engineering facilities. The disposal of these earth materials not only causes a dramatic cost increase for construction, but also has become a stringent environmental challenge in Taipei, Shanghai, and many other densely populated metropolitan areas. In many circumstances, disposal of construction surplus soils have caused critical social, political, and environmental controversies around the world [7].

The productions of standard engineering aggregates for backfill constructions have become increasingly difficult due to environmental and ecological protection policies for natural resource conservations [1-3, 7]. The significant deficiency of proper quarry productions has caused a strongly adverse effect on the cost and the quality of standard aggregates. As a result, distress and detrimental settlement of pavement and bearing failures of foundation have occurred often due to poor quality of the backfill materials [3, 7-9]. If construction wastes can be reclaimed or recycled as qualified aggregate materials, then not only is the waste taken out of the waste stream before it goes to landfill but also the equivalent use of natural materials is avoided [1]. Therefore, novel solutions for reduction and reuse of on-site construction waste materials as engineering aggregates are highly advocated around the world [1-2, 4, 7]. Government agencies also highly support researchers in their quest to develop practical applications for recycled non-standard aggregate materials [3, 7].

In this study, the feasibility of using a clay-based controlled low strength material (CLSM) as a subgrade material for a pedestrian plaza was evaluated. The present paper reports the findings of laboratory investigation and demonstrates a beneficial paradigm to alleviate the increasing disposal costs and stringent environmental difficulties caused by construction waste clay in a metropolitan area.

Background

Controlled Low Strength Material (CLSM)

Controlled low strength material also commonly known as flowable fill, is defined by ACI Committee 229 as a self-compacting, flowable, durable strength, cementitious material used primarily as backfill, void fill, and utility bedding in lieu of conventional compacted fill [10]. It has become a versatile construction material, which has been rapidly gaining acceptance and application in a variety of infrastructure projects [7, 9, 11]. Similar to Portland cement concrete (PCC), CLSM is mixed and placed in a plastic condition and then hardened with time as cement hydrate. However, unlike PCC, the design strength of CLSM is often produced to replicate that of a soil-like material [3, 7]. It requires a minimum

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strength to ensure an adequate bearing capacity, yet its compressive strength (0.3-2 MPa) is generally low regarding future permit re-excavation of backfill [3, 10-11]. Due to its attractive performance, many researchers and practitioners favor the use of CLSM for various geotechnical applications [3, 7, 9, 11-16].

Non-standard Aggregates in CLSM

In general, CLSM consists of water, cement, and large quantities of fine aggregates. Coarse aggregates are also used, but less often. Concrete sand and coal fly ash (CFA) are the most commonly used fine aggregates in CLSM [17-18]. CFA, a by-product from coal-burning power plants during the generation of electricity, is the most common waste material used in CLSM. CFA improves flowability, increases strength, reduces bleeding, shrinkage, and permeability, and aids in pumpability by acting as a fine aggregates [19]. In addition, ACI (1999) also recommended that any available recycled granulated material may be considered as an alternative aggregate for CLSM as long as it has been tested prior to use [10]. Non-standard materials, such as boiler slag, recycled glass, cement kiln dust, crumb rubber, incinerator ash, flue gas desulfurization materials, and other similar industrial granulated by-products have been used in the past decade to replace fine aggregates in CLSM [3, 5-6, 11-12, 17-23]. Furthermore, in areas where standard aggregates are very limited or where it is difficult to find a proper place for the disposal of excavated surplus soil, on-site native soils have been used as an alternative aggregate to produce CLSM for pipeline backfill [4, 7]. Either simple native sand or sophisticated mixture of on-site various soils has been successfully used to produce CLSM for pipeline backfill. The range of measured engineering properties compares well with those typically achieved with standard CLSM. Researches indicated that such materials could be a beneficial and practical alternative for pipeline construction [4, 7].

For most of the construction applications, the uses of recycled wastes, industrial by-products, and native soils demonstrate comparable engineering performances and specifications to those of conventional aggregates [4, 7, 22]. Therefore, such innovations not only provide beneficial engineering applications, but also help to decrease environmental difficulties and lead to better sustainable development. However, researches on a truly clay-based CLSM have never been closely evaluated in the literature.

Experimental Program

Materials

The focus of the experimental program was to investigate the feasibility of using on-site clayey soil exclusively as the aggregate material of a CLSM. The clayey soil used for this study was taken at the site in Taipei where the proposed CLSM will be used as pavement subgrade material. It was the excavated material resulting from the construction of raft foundation of a building at the site. The results of the physical characterizations of the clay are shown in Table 1 and the grain size distribution curve is shown in Fig. 1. As can be seen, the clayey material has a maximum size of about 2mm with a clay fraction over 50%. It has a liquid limit of 35% and a plasticity index of 14%, therefore, it can be classified as a low-plastic silty clay (CL) in accordance with the Unified Soil Classification System or A-6 in the AASHTO system.

Table 1. Physical Properties of the Clayey Material Used for CLSM.

Properties	Value
Liquid Limit	35%
Plastic Limit	11%
Plastic Index	14%
Specific Gravity	2.70
Fines Content (-#200)	56.65%

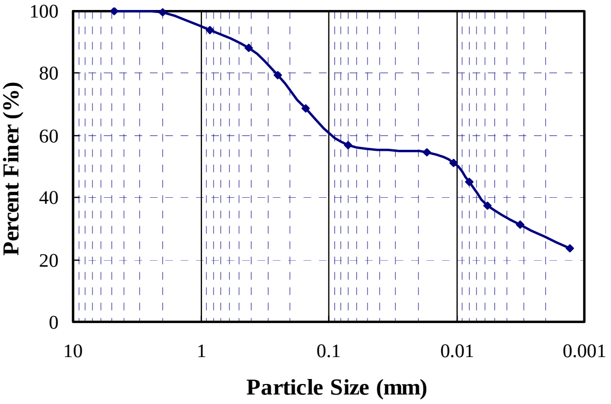

Fig. 1. Results of Grain Size Distribution of Clay.

Type I Portland cement was selected for the proposed CLSM. This is the most widely used cementitious material for the construction industry around the world. Although CLSM routinely incorporates CFA for the purpose of waste reduction and quality improvement, it was not used in this study. This is because CFA has been considered as a valuable admixture for the production of concrete in Taiwan. The use of CFA also certainly reduces the depletion of on-site remnant clayey soil. In addition, commercial admixtures such as accelerator and water reducer also were not included in the design mixes. For a feasibility study, current research aims to develop a simple, practical, and cost-effective scheme for the production of a clay-based CLSM.

Experimental Design

For the proposed construction, the clay-based CLSM must present suitable flowability, sound bearing capacity, and lowest possible settlement potential. Researches have indicated that the properties of CLSM are largely a function of the distribution of each ingredient within the mixture. However, the amounts of cement and water present the strongest effect on the properties of CLSM [3, 7, 12, 21]. Based on the previous study, the weight ratios of cement-to-water (C/W) and water-to-solid (W/S) were defined as control parameters for the mix design [3, 7].

To understand the engineering properties of the proposed material in detail, the experimental study was conducted in two phases. In Phase I, laboratory tests were initiated to determine the optimal design mix following the criteria of flowability and strength, for the proposed construction. Tests included flowability, bleeding, water absorption, unit weight, and unconfined compressive strength.

Based on the test results, an optimal design mix with the best engineering performance was selected for further investigations.

In Phase II, pavement geotechnical properties of the representative design mix were evaluated in accordance with the requirements of a subgrade under the proposed loading. Tests included: compressibility and bearing capacity. The findings of laboratory tests were then used as the design basis for the later proposed pavement.

Preparation and Testing of Specimens

To explore the effect of each constituent on the properties of clay-based CLSM, a series of C/W and W/S ratios were applied for the mix design. Fifty-one fresh CLSM mixes were prepared in Phase I study. However, some of the mixes were for preliminary evaluations only. They were discontinued for strength tests because of their unacceptable flowability or bleeding results. For hardened condition, eleven mixes with W/S ratios of 0.5-0.8 and C/W ratios of 0.3-0.7 were prepared and each mix consisted of four samples for unit weight, water absorption, and strength testing at different ages. All mixes were tested for three duplicated observations to ensure the accuracy of the test results. Table 2 presents all the mix proportions and batch unit weights of test samples for every CLSM mixture. All samples were first blended dry, following the designated mix formula. Tap water was then introduced and the sample was mixed with a Hobart mechanical mixer.

In the Phase I study, flowability and bleeding of the fresh flowable mixes were evaluated immediately after mixing. Cylindrical samples for unit weight, water absorption, and unconfined compressive strength were then cast in plastic molds. They were numbered, sealed with plastic wraps, and stored in a curing room at a temperature of 25℃. After 24 hours, all samples were de-molded, sealed with plastic wraps, and properly stored in a 100% relative humidity curing room at 25℃. They were tested at ages of 1, 7, and 28 days for compressive strength. Additional hardened samples at ages of 7 and 28 days were tested for water absorption and unit weight.

In the Phase II study, recommended design mixes, as determined in phase I, were further examined for their geotechnical properties. Each mix consisted of three duplicated samples and they were prepared in a manner the same as those described in Phase I. However, they were directly cast in each individual sample mold corresponding to each pertinent testing. They were cured as those in the Phase I study, and then tested at the age of 28 days only. All tests were performed in accordance with the procedures and corresponding standards outlined in the ASTM, except where noted.

Results and Discussion

Flowability

Flowability is the most important property that controls the self-leveling ability of CLSM. In general, flowability is primarily controlled by the amount of water contained in the composite. The larger amount of water used, the higher the flowability. However, greater water content may cause aggregate segregation, bleeding increase, and strength reduction. Therefore, the selection of a suitable water content making the material exhibit the best engineering performance was the primary priority for the mix design [3, 7].

Table 2. Mix Proportions of Clay-based CLSM Mixtures.

Group No.	W/S	C/W	Weight of Materials (kg/m^3)			Total Weight (kg/m^3)
			Cement	Water	Clay	
S55	0.5	0.5	285	570	855	1710
S57		0.7	394	563	732	1690
S59		0.9	525	583	642	1750
S63	0.6	0.3	179	597	815	1591
S65		0.5	314	629	733	1676
S67		0.7	443	633	612	1689
S69		0.9	582	647	496	1725
S73	0.7	0.3	194	647	729	1570
S75		0.5	334	667	619	1620
S77		0.7	496	708	516	1720
S79		0.9	641	713	376	1730
S83	0.8	0.3	207	689	654	1550
S85		0.5	362	724	543	1630
S87		0.7	510	729	401	1640
S89		0.9	692	769	269	1730
S73	0.9	0.5	370	739	451	1560
S75		0.7	544	777	319	1640
S77		0.9	687	763	160	1610

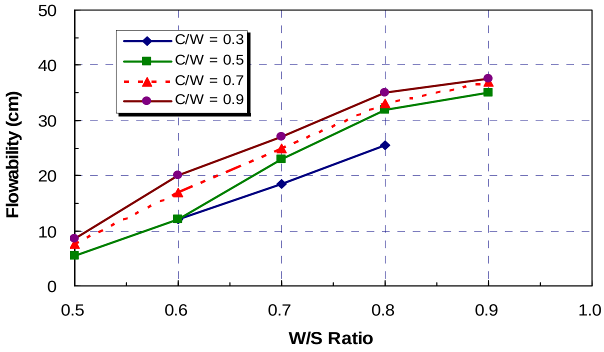

Fig. 2. Variations of Flowability for Samples with Different Mixes.

Procedures recommended by the ASTM D-6103 (Test Method for Flow Consistency of Controlled Low Strength Material) were used to measure the flowability. For most applications, specification requires an averaged flowability ranging from 20 to 30 cm [10]. A minimum flowability of 18 cm is required to ensure fill placement [21]. A maximum flowability slightly less than 40 cm may be acceptable as long as the material provides suitable strength and there is no visible segregation [7].

Fig. 2 shows the relationships of flowability for samples with different C/W ratios and W/S ratios. The results indicated that flowability increased with the increase of the W/S ratio but the rate of increase became insignificant when the W/S ratios were greater than 0.8. The mixtures showed greater capacity of water retention because of the presence of clayey fines. As can be seen in Table 2, the way of the mix design caused the amount of the clay to reduce for an increase of W/S ratio. Increasing the amount of water further tended to reduce the viscosity of the flowable material and therefore caused the flowability to increase. When the viscosity dropped to the minimum, increasing the amount of water showed only a minor effect on the flowability. A W/S ratio of 0.8 appeared to be the threshold value for the maximum flowability.

For samples with a lower water content (W/S = 0.5), their flowability were less than 20 cm. However, CLSM with spreads slightly below 20 cm can be acceptable as long as the construction allows for a lower flowability [12]. As W/S ratio increased to 0.6, the slurry mixtures flowed reasonably well and met ACI criterion. The flowability of most mixes became unacceptable and produced spreads over 30 cm when W/S ratios increased to 0.8. However, most of the flowable samples did not show visible segregation due to their viscous natures of clayey material. Based on the test results, using C/W ratios of 0.3 to 0.9 and W/S ratios of 0.6 to 0.8 should satisfy the criteria of flowability of a clay-based CLSM.

The flowability increased slightly with the increase of C/W ratios. This is because the sample was prepared in such a manner that the amounts of water and solid were fixed for a specified sample. Increasing of cement caused the amount of clay to reduce and therefore caused an increase in flowability (Table 2). W/S ratio represents the proportion of water compares to the amount of total solid in a particular sample whereas C/W ratio only shows a relative comparison between water and cement. Despite of the difference of different C/W ratios, flowability increased about four times when W/S ratio increased from 0.5 to 0.8. However, if holding W/S ratio as a constant, flowability only showed a maximum of about 1.5 times increase when C/W ratio increased from 0.3 to 0.9. Although W/S and C/W appear to be interactive with each other because both of them include the effect of the water, evidences have shown that W/S ratios give better indications for flowability. Based on the above discussion, the W/S ratio shows the strongest effect on the variations of flowability. C/W ratios are more specific to represent the potential of cementation effects as those reported for concrete.

Bleeding

Volume stability is important for the quality control of CLSM placement. As solid particles gradually settle to the bottom, water and entrapped air in the placed flowable material simultaneously move upward to the surface, resulting in a reduction of strength and placed volume. Mixtures with excessive bleedings are highly likely to induce an unacceptable weak formation at the surface and a significant post-placement settlement. Therefore, measurements of bleeding per ASTM C 940 were taken immediately after the completion of mixing by directly placing 800 mL of each flowable sample in a 1000 mL graduated cylinder and measure the volume of bleed water that accumulated on the surface. Readings were taken at 15-min intervals for the first 60 minutes and thereafter at hourly intervals for 24 hours or final settings have been observed.

As shown in Fig. 3, bleeding increased substantially with the increase of W/S ratio. Mixtures with lesser W/S ratios bled less than 3% and became stable within 6 hours. Samples with a W/S ratio over 0.8 experienced rapid bleeding in the first 25 minutes and exhibited higher bleeding ranging from 4.66% for lower C/W ratio to 12.67% for higher C/W ratio. Bleeding increased with the increase of C/W ratios. It appears to be anomaly as one would expect that higher C/W ratio with higher amount of cement would result in less bleeding. The amount of water and the properties of the aggregates are the most important factors that influence the bleeding of the fresh CLSM mixes. Clayey material presents a great potential of water absorption because of mineral composition. For a given W/S ratio, as can be seen in Table 2, the increase of C/W caused a reduction of the clay and therefore caused an increase in bleeding.

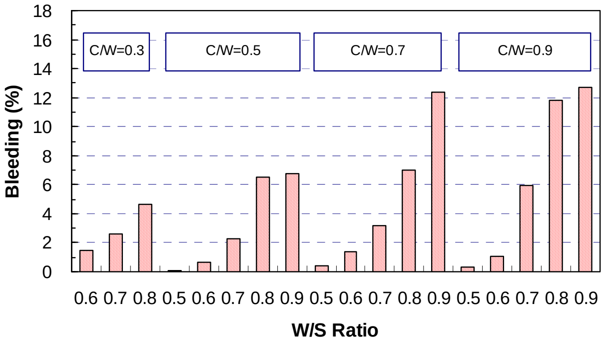

Fig. 3. Bleeding of Various Mixes of Clay-based CLSM.

The amount of water used in the mixture apparently was the most prominent factor that controlled the determined bleedings. Other researches also reported similar results and suggested using 2 to 3% bleeding as the tolerable limit for the production of CLSM [12, 22]. Based on such criterion, the C/W and W/S ratios for all mixtures should be controlled below 0.7 to ensure an acceptable bleeding.

Unit Weight and Water Absorption

Unit weight and water absorption for hardened CLSM is important for the calculation of the exact total vertical loading imposed on a potential soft subgrade or the lateral trust against a shoring system. Because values of unit weight and water absorption are changing with time after the placement of CLSM, therefore, they should be observed with time to provide crucial information for the determination of the thickness of placement.

Tests of unit weight and water absorption were conducted in accordance with the procedures outlined in ASTM C 642. Observations were made immediately before the testing of compressive strength at 7 and 28 days. The measured water contents ranged from 5.67 to 19.83% and 0.12 to 2.86% for 7 day and 28 day samples, respectively. The process of cement hydration continues at a decreasing rate and the moisture within the sample reduced with time. Once the water is removed, hydration ceases and cannot be restarted. The potential of water absorption (w_a) of the hardened CLSM was evaluated by comparing the difference of the oven-dry mass and the saturated mass after immersion. Test results indicated that values of w_a varied from 2.52 to 29.4% and 6.28 to 28.1% for 7 day and 28 day samples, respectively. Values of w_a increased with the increase of W/S ratios. For sample prepared at a higher W/S ratio, its hardened state certainly preserved a greater volume of permeable pore space and therefore leading to a higher potential of water absorption.

Fig. 4 depicts the observed values of unit weight ranged from 14.5 to 16.7 kN/m^3 and 12.2 to 15.8 kN/m^3 for 7 days and 28 days, respectively. The unit weight decreased with the increase of W/S

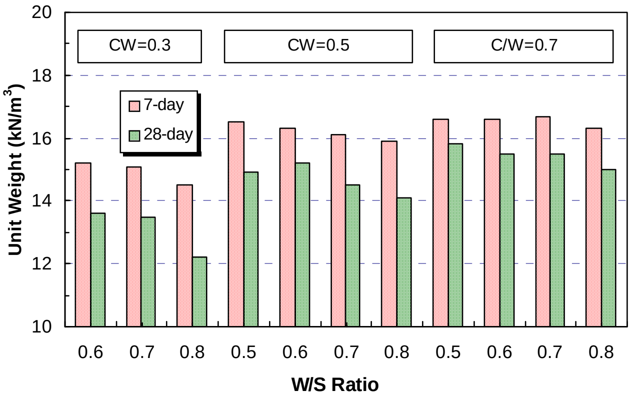

Fig. 4. Changes of Unit Weight for Hardened Clay-based CLSM Samples with Various Mixes and Curing Time.

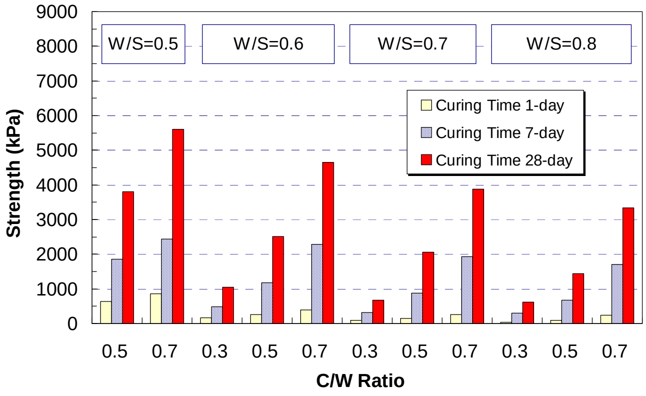

Fig. 5. Unconfined Compressive Strength of Different Mixes and Curing Time.

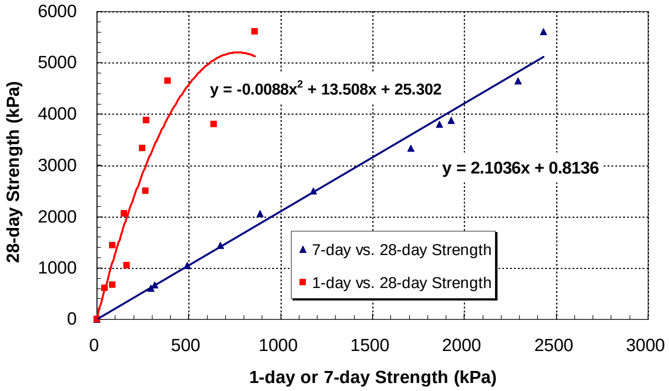

Fig. 6. Variations of Strength Gain with Curing Time for All Samples with Different Mixes.

ratios but it generally increased with the increase of C/W ratios. The amount of solid in the mix was mainly responsible for the unit weight. For samples with identical mix ratios, the water content became lesser with time and therefore the unit weight reduced with increasing curing time. The observed unit weights for 28-day samples are only about 61 to 79% compare to those of a compacted earth fill. Considering the imposed load of a backfill on a clayey subgrade, such lightweight can be beneficial to warrant a lesser potential of settlement and therefore further promotes the use of this material for the proposed site.

Compressive Strength

The clay-based CLSM gradually hardened and achieved strength through the hydration of the cement. The hardened composites were examined for strength per ASTM D 4832 after curing them for 1, 7, and 28 days. Fig. 5 indicates that the unconfined compression strength (q_u) of each mix varied as a function of W/S, C/W, and curing time. The values of q_u increased with the increase of C/W and curing time but decreased with the increase of W/S. However, the decreases of q_u became lesser for W/S ratio higher than 0.7.

The values of q_u cured for one day ranged from 43 to 861 kPa and those for a 28-day curing period were 610 to 5,613 kPa. The improvement of strength with curing time was more significant for samples with higher W/S and lower C/W ratios. Such phenomenon can be attributed to a slower but continuing cementation in a fully hydrated environment. Samples with higher short-term strength can be produced using a higher C/W and a lower W/S ratio. However, the efficiency of strength gain appears to be lower due to the limitation of cement hydration giving by a lesser amount of water. Fig. 6 shows the strength gain with curing time for all samples with different C/W and W/S ratios. It can be seen that the 28-day strength values showed about 5 to 16 times increase compared with those of 1-day. The strength increase became linear with curing time and the observed overall 28-day strength values were about twice of those cured for 7-day.

For a soil-cement mixture, a number of factors influence the magnitude of its strength development. In general, these factors can be roughly divided into four categories: (1) characteristics of the cement, (2) characteristics and condition of soil, (3) mixing conditions, and (4) curing conditions [24]. For a clay-based CLSM, the basic strength increase mechanism is closely related to the chemical reaction between the soil and the cement. Therefore, among these factors, the characteristics of the cement and the treated clay in terms of their stabilizing mechanisms demonstrate the strongest effect on the strength of the clay-based CLSM.

When the cement mixes with water, cement minerals react rapidly with water to produce cement hydration products and subsequently form a hardened skeleton matrix. In addition, the hydration of cement leads to a pozzolanic reaction to form insoluble compounds, which harden when cured to stabilize the clay. The cement hydration and the pozzolanic reaction can last for a long time after the mixing, and so the strength of cement treated clay-based CLSM is expected to increase with time [24].

Although many studies have been conducted to explore the effects of different types of recycled materials on the production of CLSM, little discussion is available for nature clay [7]. Researches and practical experiences of conventional cement-improved soil technique, soil-cement, for example, have indicated that the types of soil present strong effect on the strength development of the treated clay [25]. The improvement decreases generally with increasing plasticity index of the clay [24]. Researches also found that the physicochemical factors of the original soil are the most dominant factors influencing the stability of the treated soils [25]. The productions of the clay-based CLSM in this study are in a manner similar to the off-site cement-improved soil procedures. The findings of conventional soil improvement with cement may be applied for clay-based CLSM. Further studies should be conducted to verify the effects of soil types on the behaviors of CLSM.

Most specifications require CLSM to have a minimum strength for acceptable bearing capacity and a maximum strength to allow for future excavation [12]. The target unconfined compressive strength is often required to be at least 345 kPa, whereas the maximum strength is often limited to 1,380 kPa [7, 10-12]. The proposed clay-based CLSM will be used to support a permanent pedestrian plaza. Considering the effect of construction uncertainties and ensure a long-term safe bearing capacity, the designer conservatively requested the 28-day strength should be within a range of 1,000 to 4,000 kPa. Based on the test results given in Fig. 5, most of the tested mixes exhibited qualified strength values than requested. However, considering the criteria of flowability and bleeding described earlier, the recommended C/W and W/S ratios for the proposed clay-based CLSM should be 0.5~0.7 and 0.7, respectively as shown in Fig. 7.

Pavement Geotechnics

The clay-based CLSM will be used to level up all the lowland areas around the site to the design grade of pedestrian plaza. Pavement bearing failure and differential settlement are likely occurring for fill materials with poor geotechnical properties. Therefore, the suitability of the mixture for such concerns was further verified in the Phase II study.

Based on the mix design in Phase I, representative samples with recommended mix ratios were prepared for further tests on deformability and bearing capacity. The curing time for all samples was 28 days. All tests were conducted in accordance with the procedures outlined in ASTM.

Deformability

Clayey soil generally presents noticeable potential of settlement upon additional loading. Conversely, the compressibility of a hardened cementitious material usually is insignificant due to the effect of cementation [3]. To verify the stress-strain-time relationship of the clay-based CLSM material, one-dimensional consolidation tests were conducted and the test results are given in Fig. 8. The preconsolidation pressure of the hardened samples ranged from 1,100 to 1,450 kPa, whereas that of untreated clay was only about 160 kPa. The addition of cement caused a significant increase in preconsolidation pressure and a stiffer behavior compared to that of untreated clay. Sample with smaller C/W ratio showed a slightly greater vertical strain for similar vertical stress. It is clear that mixture with higher amount of cement presented lesser compressibility due to the effect of stronger cementation. The virgin compression ratios for all hardened samples ranged from 0.17 to 0.19, and their recompression ratio was about 0.006. These results suggest that the solidified clay-based CLSM appears to be heavily overconsolidated due to the cementation of cement, leading to a negligible compressibility. Kang and Santagata (2006) reported similar results for an illitic clay treated with 4 to 10% type I cement [26]. For such soil conditions, detrimental settlement is unlikely to occur with commonly imposed service loads on a pedestrian plaza.

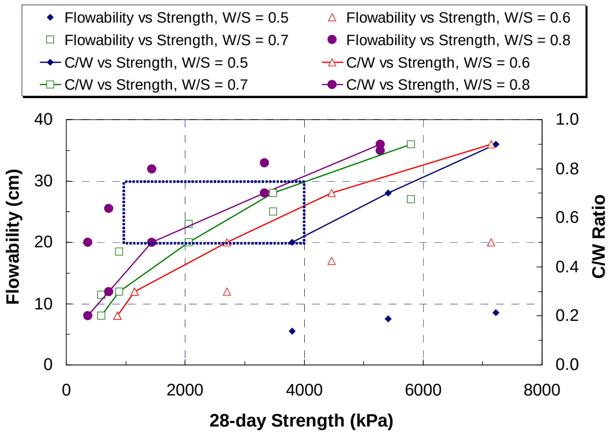

Fig. 7. Recommended Design Mixes Based on the Criteria of Flowability, Bleeding, and Strength.

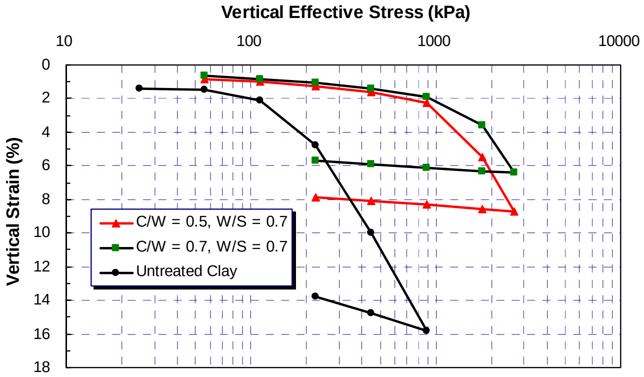

Fig. 8. Compressibility of Untreated Clay and Hardened Clay-based CLSM.

Recent studies on cement and lime treated soils showed swelling and pavement failures due to the formation of high swelling minerals such as ettringite and thaumasite [27]. Therefore, the potential harmful effect of clay swelling if the hardened CLSM deteriorated with time was investigated by conducting expansion index tests based on ASTM D 4829. Samples were prepared by manually broken the hardened CLSM to particles and sieved them pass through #4 sieve. Values of expansion index (EI) were calculated by comparing the differences of vertical deformations before and after inundations of the samples. Based on the classification of ASTM D 4829, the averaged value of the observed EI was 26 indicating a very low potential of swelling if the hardened clay-based CLSM deteriorated with time.

Bearing Capacity

Subgrade stability plays an important role to ensure the safety of pavement structure. The assessment of the bearing capacity of the subgrade is therefore mandatory to prevent the occurring of pavement distress. Considering future serviceability, heavy vehicles and equipment may be traveled on the pedestrian plaza periodically for business activities and the maintenance of the surrounding buildings. Therefore, the designer has requested that the subgrade should have a sound bearing capacity to ensure a safe support for these traffic loadings.

Although there are a number of empirical index tests to characterize the competence of a subgrade material, California Bearing Ratio (CBR) method has been the most widely used in Taiwan in practices. The bearing capacity of the hardened clay-based CLSM was evaluated using CBR method in accordance with ASTM D1883. The averaged CBR value was 46 and 64 for C/W ratios of 0.5 and 0.7, respectively. Such values are more than equivalent to that of a standard compacted well-graded aggregate subbase and base course [28]. Parametric study performed by others also demonstrated that the influence of cementation significantly increases the mobilized bearing resistance of footings in soft soils [29]. Therefore, clay-based CLSM developed in this study should be suitable for the required applications.

Beneficial Evaluations

The disposal of construction surplus clay is troublesome and costly in a congested metropolitan area. The clay-based CLSM developed in this study presents an attractive scheme for the potential use of surplus soft clayey soils. Test results gathered in this research indicated that the use of native soft clay for the production of CLSM results in comparable engineering properties with those of a conventional CLSM. Furthermore, use of such material essentially alleviates the difficulty of depleting on-site waste clay and eliminates the consumption of limited standard aggregates. The competence of subgrade for pedestrian plaza also can be greatly improved due to the inherent merits of CLSM. Base layer stabilization may also reduce the total thickness of the pavement structure, resulting in a more economical overall design. Considering the increasingly environmental challenges and critical resource deficiency in many congested areas, the beneficial use of a clay-based CLSM appear to warrant a better sustainable development of built environments.

Based on our findings, the proposed clayey materials used for the production of clay-based CLSM are acceptable. However, it should be noted that the derived results in this research are site-specific. The findings can only ensure the validity of the mixtures with the materials in this study. For a safe performance, only inorganic clayey material with lower plasticity (USCS classified as ML or CL) should be used for the production of a clay-based CLSM. It is highly recommended that those interested in this type of material perform site-specific experimental studies using local materials to generate particular mix designs.

Conclusions

The engineering properties of a clay-based CLSM using on-site construction surplus clay were investigated. Based on the results obtained in this research, the following specific conclusions can be drawn.

1. The results presented in this paper indicate that the ratios of W/S and C/W are the main control parameters for the physical and engineering properties of the proposed material.
2. For fresh mixes, the values of flowability and bleeding generally increase with the increase of W/S ratios indicating a predominant effect of water within the samples.
3. The amount of cement and the subsequent development of the cementation totally control the mechanical properties of the hardened CLSM. The observed values of 28-day compressive strength have shown good correlations with C/W, W/S ratios, and curing time. Considering the criteria of flowability, bleeding, and strength, the recommended C/W and W/S ratios are 0.5~0.7 and 0.7, respectively.
4. Further pavement geotechnical evaluations for these design mixes indicated that the hardened clay-based CLSM behaved as heavily overconsolidated stiff clay due to strong cementation of cement and leading to a sound bearing capacity and negligible compressibility.
5. The study confirms that clay-based CLSM with acceptable properties can be developed to alleviate the difficulty of depleting imperfect on-site surplus clay. Proposed mix design not only can be used as guidelines for the development of such a beneficial alternative but also for other similar soil-based CLSM materials.
6. Because site conditions vary, the findings can only ensure the validity of the mixtures with the materials in this study. It is highly recommended that those interested in clay-based CLSM perform site-specific experimental studies using local materials to generate particular mix designs.

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