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Upcycling Potential of Industrial Waste in Soil Stabilization: Use of Kiln Dust and Fly Ash to Improve Weak Pavement Subgrades Encountered in Michigan, USA

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Abstract: The State of Michigan in the United States often encounters weak soil subgrades during its road construction and maintenance activities. Undercutting has been the usual solution, while a very few attempts of in-situ soil stabilization with cement or lime have been made. Compared to the large volume of weak soils that require improvement and the cost incurred on an annual basis, some locally available industrial byproducts present the potential to become effective soil subgrade stabilizers and a better solution from the sustainability perspective as well. The candidate industrial byproducts are Cement Kiln Dust (CKD), Lime Kiln Dust (LKD), and Fly Ash (FA), out of which only a fraction is currently used for any other secondary purposes while the rest is disposed of in Michigan landfills. This manuscript describes a laboratory investigation conducted on above industrial byproducts and/or their combinations to assess their suitability to be used as soil subgrade stabilizers in three selected weak soil types often found in Michigan. Results reveal that CKD or a combination of FA/LKD can be recommended for the long-term soil subgrade stabilization of all three soil types tested, while FA and LKD can be used in some soil types as a short-term soil stabilizer (for construction facilitation). A brief discussion is also presented at the end on the potential positive impact that can be made by the upcycling of CKD/LKD/FA on sustainability.

Keywords: pavement subgrades; soil stabilization; industrial byproducts; industrial waste; Cement Kiln Dust (CKD); Lime Kiln Dust (LKD); Fly Ash (FA); sustainability

1. Introduction

The State of Michigan in the United States owns an impressive road network of paved roadway. This includes 9669 route miles of state trunk line, 89,444 route miles of county roads, and 21,198 route miles of city and village streets [1]. This road network mostly spans over a vast area of weak soils. Silty and clayey soils that are encountered in road construction projects often pose design as well as constructability challenges. In some cases, the weak soil encountered is unable to support the design loads; in other cases, the soil is not able to bear the loads of the construction vehicles (see Figure 1). These issues pose the next challenge of finding cost-effective solutions to stabilize weak soil subgrades.

Figure 1. Failure of a weak soil subgrade due to construction traffic on I-75 Detroit, Michigan [2].

Oftentimes, the solution for weak subgrade soils is to remove-and-replace with suitable materials, which is usually known as undercutting. Given the large extent of weak soil encounters, the associated earthwork volume is very large. Michigan Department of Transportation (MDOT) divides the State into seven regions for administrative purposes as shown in Figure 2. These regions are 1-Superior, 2-North, 3-Grand, 4-Bay, 5-Southwest, 6-University, and 7-Metro [3]. Out of the seven regions, Grand, Bay, and Metro are known for frequent encounters of weak soil. In general, these three regions are more populous compared to other regions, hence served by a fairly large road network which also requires routine maintenance work. It should be noted that while the above three regions have recorded the highest encounters of weak soils, there are pockets of such soils in other regions as well. This argument points again at the vastness of the undercutting required to be performed by the MDOT each year.

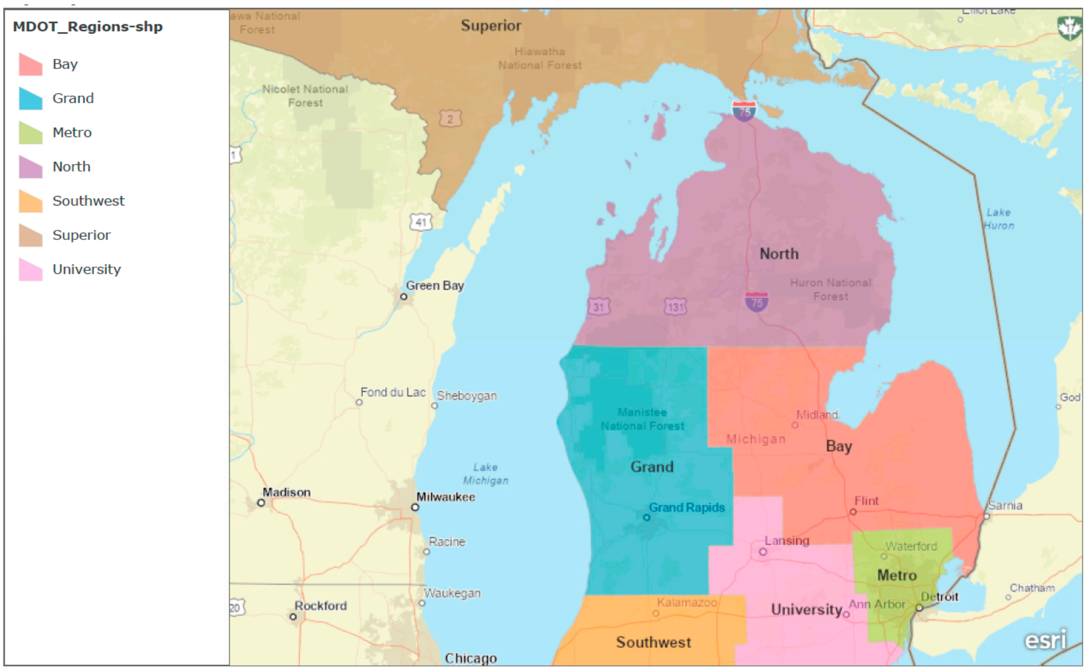

Figure 2. The 7 Michigan Department of Transportation (MDOT) regions [4].

Although the usual practice in Michigan is to undercut unsuitable soils, chemical stabilization techniques have also been employed on a few occasions in the past [2]. The most commonly used chemicals in soil stabilization are Portland cement (cement stabilization) and quicklime (lime stabilization). Both quicklime and Portland cement are commodities commercially manufactured for many other established industrial uses, and therefore, road construction projects must acquire them at competitive prices. Considering the large volumes of soils that need stabilization, higher project costs are inevitable.

During the process of lime stabilization, soil strength increase is predominantly based on the pozzolanic reaction initiated by the calcium oxide in the lime. In cement, the strength gain is due to the hydration of cement particles when mixed with water. This simply means that any other cheaper material with the required amount of calcium oxide or cementitious materials should also be able to do the job: it does not necessarily have to be Portland cement or quicklime. This concept has given rise to research and trials of industrial waste that has a considerable percentage of a cementitious material. Interestingly, the main candidate materials do come from the same two industries, i.e., manufacturing of Portland cement and quicklime. The Cement Kiln Dust (CKD) and Lime Kiln Dust (LKD) both have an appreciable amount of calcium oxide or cementitious materials, although the percentage can vary based on many factors such as the raw materials or the industrial process used. In addition to the above two, Fly Ash (FA) produced during coal-burning (e.g., power plants) is another candidate material based on the same principle.

Although some research and practical applications of CKD, LKD, and FA in soil stabilization have been reported in the literature over the past twenty to twenty-five years, in the authors' opinion, it has not reached the level of support or evidence yet to be included in most State or Federal road construction guidelines. Each year industries in Michigan generate a large volume of CKD, LKD, and FA as industrial waste [5]. Based on its potential for secondary usage they are also referred to as industrial "byproducts" rather than waste. However, the current usage of these byproducts remains at a very low level and the rest is disposed of in landfills (as elaborated more later in our discussion), raising the question of whether they should be classified as byproduct or waste. Unfortunately, this happens while there is a promising potential market for this material in road subgrade stabilization projects within the same state.

In this context, the objective of the research described in the paper was to assess the potential of stabilization of weak soils encountered in Michigan by locally produced CKD, LKD, and FA. During the research, three types of weak soils commonly encountered in Michigan were stabilized with CKD, LKD, and FA employing different mix proportions, and the resulting stabilized soils were tested to assess the improvement and freeze-thaw durability. The background, research methodology employed, and the results obtained are presented in the next three sections, which are followed by a discussion that covers not only the engineering aspects but also the environmental and socio-economic sustainability points of view of upcycling CKD, LKD, and FA.

2. Background

Subgrade stabilization materials can be divided into two categories: stabilizers and modifiers. Subgrade modifiers generally reduce the plasticity of soil and provide a short-term strength improvement. The short-term strength improvement occurs shortly after mixing and can be used for construction facilitation. On the other hand, subgrade stabilizers, provide a long-term soil modification process through pozzolanic or cementitious reactions. The history of subgrade stabilization dates back to the 1960s, but in the authors' opinion, the interest was largely limited to the properties and behavior of lime and cement as stabilizers. Economic and resource scarcity reasons have pushed the interest slowly toward materials such as CKD, LKD, and FA only in the past 20 years. A report published in 2013 [6] mentioned that 11 States were using CKD as a soil stabilizer while three States were using a combination of CKD/LKD in their State highway applications. The same report indicated that 15

States used Class C (defined in Section 2.3) fly ash while seven States used Class F fly ash for soil stabilization [7].

Most previous studies related to subgrade stabilization with such materials were also limited to understanding the immediate benefit of them as modifiers in construction facilitation. More recent studies on the properties and behavior of CKD, LKD, and FA for subgrade stabilization include exploration of whether CKD is a hazardous material or not [8,9], subgrade stabilization with CKD and lime [10], and the effects of freezing/thawing and wetting/drying for the durability of CKD-stabilized clay samples [11].

Little and Nair [10] discussed the danger posed by the presence of sulfates in the soil stabilized by the chemical stabilizers that have calcium. Therefore, it is recommended to test in-situ soil sulfate content prior to the use of stabilization. Generally, soils with more than 3000 ppm sulfate should not be considered for chemical stabilization [10].

2.1. Cement Kiln Dust (CKD) Stabilization

CKD is the waste material removed from cement kiln exhaust gas by air-pollution control devices. United States Environmental Protection Agency (USEPA) categorizes this fine-grained and highly alkaline solid as a "special waste" and has been temporarily exempted from the hazardous category [12]. CKD generally contains between 30 to 40 percent of calcium oxide (CaO) and about 20 to 25 percent of pozzolanic materials [8]. The other major constituents of CKD could be silicon dioxide (SiO_2), aluminum dioxide (Al_2O_3), potassium oxide (K_2O), and sulfur trioxide (SO_3) [13].

A few past studies on CKD explored whether or not it is a hazardous material [14,15]. Several studies have been performed on mix designs for soil/CKD mixtures to modify or stabilize pavement subgrade soils. These studies concluded that the mix-design procedures previously developed for lime could also be used for CKD/soil mixtures as well. The performance of CKD as a pavement subgrade stabilizer has been studied by several researchers. Laboratory performance was investigated by Collins and Emery [13], where 33 CKDs were tested for engineering properties (compressive strength, durability, and volume stability) and compared with conventional lime/fly ash/aggregate mixtures. Zaman et al. [11] investigated the effect of the freezing/thawing and wetting/drying cycles on the durability of CKD-stabilized clay samples. The test results showed a significant strength decrease due to the freezing/thawing and wetting/drying cycles [11]. As summarized by Button [16], multiple researchers reported mixed field results from several states in the United States using soil/CKD stabilization techniques.

A field and laboratory evaluation of CKD soil stabilization was conducted by Miller and Zaman [17] in Ada, Oklahoma, to compare its performance with quicklime. The subgrade was treated with 4% quicklime and 15% CKD (by weight). Higher strengths were observed in all cured samples, while strength loss was observed in all submerged samples during laboratory strength tests. Field tests conducted after 28 days and 56 days following compaction of the treated subgrade also produced similar trends. CKD samples showed a strength gain during the first 7 to 14 days followed by little change in strength. Durability testing using wet/dry cycles showed drastic effects on stabilized clayey soils. All clayey samples stabilized with quicklime and CKD fell apart before three wet/dry cycles. However, sandy soils stabilized with CKD showed strength gain during 12 wet/dry cycles.

In 2008, the Michigan Department of Transportation (MDOT) constructed a test section with a CKD-stabilized subgrade as a part of a comparative study. The comparison was against a second section stabilized with lime and a third section stabilized with a mixture of lime and FA of Class F (defined in Section 2.3). It was concluded that the increase in subgrade strength in the CKD-stabilized section was as good as the strength gain in sections stabilized with lime and lime/FA [2].

2.2. Lime Kiln Dust (LKD) Stabilization

LKD is a byproduct of quicklime production. Heat applied during the quicklime production process causes limestone to generate gas and dust. LKD is the dust that is screened out which also contains lime normally about 30% to 40% [8] but can be as high as 80% in some cases [13]. The rest is mainly made up of silicon dioxide (SiO_2), aluminum dioxide (Al_2O_3), magnesium oxide (MgO), and sulfur trioxide (SO_3) [13]. During lime stabilization, cations that are present in the clay structure are replaced by the calcium cations (Ca^{2+}) supplied by hydrated lime. This reaction changes the minerology of clay and improves the strength of clay by decreasing plasticity, moisture holding capacity, and swell potential. The portion of CaO readily available for this cation exchange is called free-lime. If enough free-lime is available and pH remains high in the treated soil, a long-term strength gain can occur through pozzolanic reaction—a reaction that can continue for a very long time [8].

Only a few research studies on LKD stabilization is found in the literature. Laboratory investigation briefly mentioned above by Collins and Emery [13] also considered LKD in their research and 12 LKDs were tested for engineering properties (compressive strength, durability, and volume stability) and compared with conventional lime/fly ash/aggregate mixtures. This study concluded that compared to hydrated limes, a higher percentage of LKD is required to achieve similar performance. In 2001, the Illinois Department of Transportation [18] conducted a laboratory and field performance study to evaluate alternate materials for subgrade modification of unstable (California Bearing Ratio (CBR) < 6) subgrade soils. The alternative materials included byproduct hydrated lime and Class-C fly ash (defined in Section 2.3 below). Three experimental sections were constructed, and performances of them were compared to a control section treated with LKD or dense graded aggregate base. The results showed that the application of alternate materials was successful during construction and no measurable differences in performance were noticed during the three-year monitoring period. Although there has been little research/application focus on LKD, it has been already taken up by the Indiana Department Transportation (INDOT) design guidelines. In the INDOT guidelines, while quicklime and cement are included as chemical stabilizing agents, LKD is introduced as a chemical modification agent [19].

2.3. Fly Ash (FA) Stabilization

FA is the ash produced by coal-fired electric and steam generating plants. Its properties are dependent on the source of the coal and coal-burning process. Depending on the CaO content, FA with CaO > 20% is categorized as Class-C (self-cementing), and anything less than 20% is in Class F (non-self-cementing) [20]. When mixed with water, a hydration reaction could occur in Class-C FA, which makes it suitable as a candidate material for soil stabilization [10]. On the other hand, Class-F FA has a low concentration of free calcium and requires an additional agent such as lime or cement to initiate the hardening process during stabilization. Due to this complex process involved in FA stabilization, the physical properties of FA-treated materials should be tested prior to use in soil stabilization. One such example reported in the literature is from Illinois. The Illinois Department of Transportation (IDOT) conducted a laboratory and field performance study to evaluate Class-C FA as an alternate material for a subgrade modification project [18]. Its performance was compared with a control section treated with LKD or dense graded aggregate base. The results showed that the application of Class-C FA was successful and no measurable differences in performance were noticed during the three-year monitoring period.

The Wisconsin Department of Transportation (WISDOT) has also sponsored a research study that evaluated the short-term and long-term performance of Class-C FA-stabilized subgrades [21]. While three WISDOT FA-stabilized projects were evaluated during construction, one was monitored for eight years after construction. All test sites showed significant improvement in subgrade strength during construction and the strength was not negatively affected by subsequent rain events. There were marked variations in soil types and hence different fly ash contents and moisture contents were used during construction. Based on testing, it was also concluded that the FA-stabilized sections did not display any significant reduction in strength after a number of freeze/thaw cycles. Distress surveys on test sections provided results comparable to control sections.

3. Materials and Methods

Soils to be stabilized and tested were identified in consultation with the MDOT. Weak soils encountered by the MDOT during road construction projects were selected from three locations. These soils were deemed unsuitable for construction due to poor field performance and can be presented as typical of the unsuitable soils found in Michigan. Prior to the main testing program, preliminary tests were conducted to characterize the soils. Soil characterization results are summarized in Table 1. Soil index tests and strength tests were conducted according to the American Society for Testing and Materials (ASTM) standards. Based on the Unified Soil Classification System (USCS) system (defined in Table 1), Soil-1 and Soil-3 were identified as low plasticity clay (CL), and Soil-2 was low plasticity silt (ML). However, the American Association of State Highway and Transportation Officials (AASHTO) classification (also defined in Table 1) of Soil-1 and Soil-3 differed slightly resulting in A-6 classification for Soil-1 and A-7-6 for Soil-3, while Soil-2 was distinctly different and classified as A-4. Weak soil strength is evident from the Unconfined Compressive Strength (UCS) test results also shown in Table 1, which are reported in pounds per square inch (lb/in^2 or psi) as per local practices followed in Michigan. However, the same values are also expressed in kPa in parentheses.

Table 1. Properties of selected soils.

Soil Type No.	Geographic Origin of the Soils as Per the MDOT Regions	% Passing #200 Sieve [22]	Soil Consistency [1] [23]			Soil Classification		Unconfined Compressive Strength [24]	
			LL (%)	PL (%)	PI (%)	USCS [2] [25]	AASHTO [3] [26]	Unsoaked Strength in psi (KPa)	Soaked Strength in psi (KPa)
Soil-1	Metro Detroit	99.5	31.3	19.2	12.1	CL	A-6	32.3 (222.7)	2.6 (17.9)
Soil-2	Metro Detroit	65.8	16.0	12.4	3.6	ML	A-4	36 (248.2)	3.2 (22.1)
Soil-3	Upper Peninsula	98.9	48.1	26.6	21.5	CL	A-7-6	62.5 (430.9)	1.4 (9.6)

Note: [1] LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index, [2] Unified Soil Classification System, [3] American Association of State Highway and Transportation Officials.

Stabilizers (CKD, LKD, and FA) used in the study were obtained from local industries: CKD was obtained from the LafargeHolcim Cement Factory in Alpena, Michigan; LKD was supplied by the Carmeuse Lime Plant in Detroit, Michigan; and FA was from the DTE Energy's coal-burning powerplant in Monroe, Michigan. FA contained 21% CaO. Even though it receives self-cementing or Class-C classification based on the FA classifications introduced in Section 2.3, it should be noted that it is just barely more than 20%. Therefore, a mixture of FA and LKD was also introduced as a fourth stabilizer.

3.1. Mix-Designs and Stabilization Assessment

The acceptability of chemical stabilization is usually decided based on the improvement of UCS of the stabilized material. In order for a chemical treatment to be considered "effective", an increase of 50 psi over the initial UCS of the soil must be observed [27]. The research team adopted the following criteria to differentiate the acceptability of the improvement for long-term stabilization versus short-term modification:

- Long-Term Subgrade Stabilization: An increase of strength by 50 psi or more over the UCS of the untreated soils, after 7 days of curing and 24 h of capillary soaking, is defined as the benchmark for long-term stabilization. Capillary soaking simulates the groundwater movement during the life of the pavement and resultant strength loss due to the presence of moisture.
- Short-Term Subgrade Modification (for construction facilitation): Similarly, an increase of UCS by 50 psi or more over the initial USC of the untreated soils, but only after 3 days of curing and without capillary soaking, is the benchmark for short-term subgrade modification. A curing period of 3 days was selected for short-term modification to simulate the field conditions. The usual practice is to construct the upper pavement layers not more than 3 days after subgrade modification.

The selection of optimum stabilizer mix percentages for CKD and FA were determined in accordance with the general ASTM standards [27]. For the CKD, FA, and FA/LKD stabilizer categories, three different mix percentages were chosen as summarized in Table 2. However, due to the presence of lime in it, the procedure for LKD followed the Eades–Grim test as described in ASTM D6276 [28]. The pH value plays an important role in lime stabilization, and the optimum stabilization occurs when the pH of the mixture is close to 12.4. A specific mix percentage of LKD that produces this optimum pH value in each soil was estimated with the help of the Eades–Grim tests. They are also included in Table 2.

Table 2. Mix percentages of Cement Kiln Dust (CKD), Lime Kiln Dust (LKD), and Fly Ash (FA).

Soil # (AASHTO Classification)	CKD (%)	LKD (%)	FA (%)	LKD (%)/FA (%)
Soil-1 (A-6)	6, 8, 12	6	10, 15, 25	2/5, 3/9, 5/15
Soil-2 (A-4)	4, 6, 8	4	10, 15, 25	2/5, 2/8
Soil-3 (A-7-6)	4, 6, 8	6	10, 15, 25	2/5, 2/8, 3/9

UCS tests [24] were performed on stabilized soil samples compacted at their Optimum Moisture Content (OMC) using a calibrated Harvard miniature compaction method [27]. Therefore, the OMC of the stabilized soils had to be estimated prior to compacting the soil samples. The Proctor compaction test procedure [29] was used for estimating OMC. It should also be noted that all UCS tests (before treatment as well as after) were repeated three times to prove the repeatability, and what is reported here are the average values.

3.2. *Freeze-Thaw Durability Testing*

Freeze-thaw cycles that take place in cold-wet regions can make a detrimental impact on the strength of soil subgrades. A stabilized soil should be able to withstand the potential strength loss due to freeze-thaw cycles. To assess the impact, a laboratory freeze-thaw test was performed on stabilized soils using [30] as a reference. The soil samples were prepared using the Harvard miniature compaction apparatus and cured for 28 days before subjecting them to freeze-thaw tests. One freeze-thaw cycle included 24 h of freezing at −10 °F (−23 °C) followed by 24 h of thawing at 70 °F (21 °C) and 24 h of capillary soaking. UCS tests were performed after a predetermined number of freeze-thaw cycles (1, 3, 7, and 12 cycles).

While this section briefly covered all information necessary to continue this discussion, details of the testing program are explained in an MDOT report freely accessible in the public domain [31].

4. Results

Tables 3–5 list UCS results obtained for the soaked samples cured for seven days and the unsoaked samples cured for three days for Soil-1, Soil-2, and Soil-3. Pursuant to the short-term and long-term recommendations set forth in Section 3.1, if UCS of a treated soaked sample increased by more than 50 psi over the untreated soil after seven days of curing, the treatment is suitable for long-term stabilization. If a treated unsoaked sample realized a USC gain of 50 psi over the untreated soil after three days of curing, the treatment is suitable for short-term modification. This suitability/unsuitability is indicated by a yes/no (columns with the heading "Increase > 50 psi") in all three tables below.

Table 3. Unconfined Compressive Strength (UCS) test results for stabilized Soil-1 (A-6).

Treatment	Soaked Specimen			Unsoaked Specimen		
	Improved UCS (psi) *	Increase (psi)	Increase >50 psi?	Improved UCS (psi) +	Increase (psi)	Increase >50 psi?
Untreated	2.61	-	-	32.26	-	-
6% CKD	30.33	28	No	61.72	29	No
8% CKD	71.91	69	Yes	70.71	38	No
12% CKD	77.77	75	Yes	153.51	121	Yes
10% FA	10.94	8	No	63.81	32	No
15% FA	4.71	2	No	92.81	61	Yes
25% FA	4.94	2	No	79.57	47	No
2% LKD/5% FA	8.70	6	No	88.14	56	Yes
3% LKD/9% FA	85.95	83	Yes	162.48	130	Yes
5% LKD/15% FA	147.15	145	Yes	192.55	160	Yes
6% LKD	26.27	24	No	84.27	52	Yes

* Seven days of curing, + Three days of curing.

Table 4. UCS test results for stabilized Soil-2 (A-4).

Treatment	Soaked Specimen			Unsoaked Specimen		
	Improved UCS (psi) *	Increase (psi)	Increase >50 psi?	Improved UCS (psi) +	Increase (psi)	Increase >50 psi?
Untreated	3.25	-	-	36.00	-	-
6% CKD	81.73	78	Yes	117.97	82	Yes
8% CKD	114.3	111	Yes	158.01	122	Yes
12% CKD	104.21	101	Yes	206.67	171	Yes
10% FA	4.10	1	No	59.37	23	No
15% FA	21.65	18	No	80.73	45	No
25% FA	14.15	11	No	92.00	56	Yes
2% LKD/5% FA	85.38	82	Yes	145.40	109	Yes
3% LKD/9% FA	92.33	89	Yes	187.18	151	Yes
5% LKD/15% FA	15.82	13	No	42.93	7	No
6% LKD	3.25	78	Yes	36.00	0	No

* Seven days of curing, + Three days of curing.

Table 5. UCS test results for stabilized Soil-3 (A-7-6).

Treatment	Soaked Specimen			Unsoaked Specimen		
	Improved UCS (psi) *	Increase (psi)	Increase >50 psi?	Improved UCS (psi) +	Increase (psi)	Increase >50 psi?
Untreated	1.43	-	-	62.49	-	-
6% CKD	81.42	80	Yes	176.23	114	Yes
8% CKD	105.05	104	Yes	223.26	161	Yes
12% CKD	133.43	132	Yes	220.46	158	Yes
10% FA	24.26	23	No	102.48	40	No
15% FA	67.99	67	Yes	91.12	29	No
25% FA	63.90	62	Yes	105.36	43	No
2% LKD/5% FA	45.51	44	No	105.74	43	No
3% LKD/9% FA	47.11	46	No	82.83	20	No
5% LKD/15% FA	130.12	129	Yes	121.54	59	Yes
6% LKD	35.57	34	No	44.29	−18	No

* Seven days of curing, + Three days of curing.

Results summarized in Tables 3–5 were used to propose final recommendations for the stabilizers. The final recommendation for subgrade stabilization for each tested soil type was based on the minimum percentage of stabilizer providing a strength gain of 50 psi or more in soaked condition after seven days of curing over the unstabilized subgrade strength. Similarly, the final recommendation for short-term modification was based on the minimum percentage of stabilizer providing a strength gain of 50 psi or more in unsoaked condition after three days of curing over the unstabilized soils. For short-term subgrade modification, we adopted a few exceptions to the above basis to make the recommendations more realistic and practical. If a lower stabilizer percentage provides a long-term stabilizing potential for any soil type, the potential for short-term modification was not recommended for any stabilizer percentage. Based on the UCS results for Soil-1, as shown in Table 3, 8% CKD provided a long-term stabilization potential but no modification potential. Although 12% CKD provided both a long-term stabilization potential and a short-term modification potential, this percentage was not recommended in Table 6, since 8% CKD can economically provide the potential for long-term stabilization.

A special note should be added about the performance of the LKD as a soil modifier. Although 6% of LKD improved the strength of Soil-1, it was not able to improve Soil-2 and Soil-3 to the same level. While Soil-2 did not show any increase at all after mixing with 6% LKD, Soil-3 recorded a negative improvement. This negative improvement could be due to a human, testing, or instrumentation error. It should be reminded here again about the inability of LKD and FA to become successful long-term stabilizers. As briefly explained in Section 2, the long-term stabilization with lime-based products (LKD or FA) only occurs when sufficient free-lime is available for long-term pozzolanic reaction. Since the LKD and FA used in this research only contained a minimum amount of free-lime, only the combination of LKD+FA showed some potential for long-term stabilization. In addition, the short-term modification potential LKD and FA exhibited individually is based on the drying of clay minerals present in the soil test in this research.

Based on similar considerations, the following recommendations for long-term stabilization and short-term modification are presented in Table 6.

Table 6. Final recommendations for long-term stabilization and short-term modification.

Soil Type (AASHTO Classification)	Long-Term Stabilization		Short-Term Modification	
	CKD (%)	LKD (%)/FA (%)	FA (%)	LKD (%)
Soil-1 (A-6)	8	3/9	15	6
Soil-2 (A-4)	4	2/5	25	NR
Soil-3 (A-7-6)	4	3/9	NR	NR

Note: NR = Not recommended at all.

Freeze-thaw durability test results for the recommended stabilizer percentages are shown in Figure 3. It can be seen in Figure 3 that there is a sharp drop in UCS values after the first freeze-thaw cycle and then a more moderate drop until the end of the final freeze-thaw cycle.

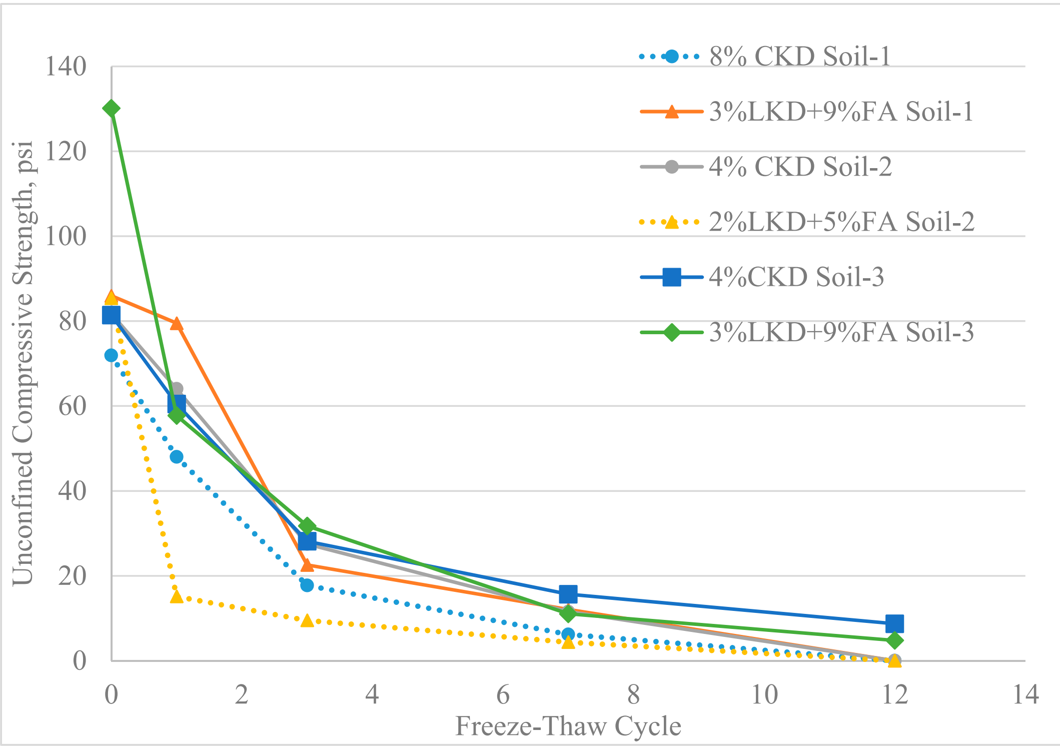

Figure 3. Reduction of UCS with freeze-thaw cycles. (24-h capillary soaking at the end of each freeze-thaw cycle).

These results show, a direct exposure of stabilized soils to freezing temperatures has drastic effect on the subgrade strength properties. Since stabilized subgrades are usually covered with aggregate bases/subbases and pavement surface layers within few weeks of constructing the stabilized subgrade, the potential for freeze-thaw damage is minimized. However, during the construction of stabilized subgrades, care should be taken to avoid direct exposure of the stabilized subgrade to freezing temperatures.

5. Discussion

The results presented above clearly show that both CKD and LKD/FA combinations are effective stabilizers for long-term stabilization for the three types of weak soil subgrades tested during this investigation. In addition, it also proved that FA did not become an effective long-term stabilizer for any of the soil types tested. However, it can still be effective in short-term stabilizing (i.e., modifying) for Soil-1 and Soil-2. The same is true about LKD but only for Soil-1. For Soil-3, none of the tested stabilizers were proven to be effective modifiers, but we should not forget that Soil-3 can still be stabilized long-term using CKD and FA/LKD as per the summary in Table 6. Direct exposure to a few freeze-thaw cycles can cause the stabilized soils to lose their strength as per Figure 3. However, in road construction, this only becomes an issue if the stabilized subgrade is not covered with the base/subbase within a reasonable time, which is highly unlikely in road construction work. Therefore, the material discussed above clearly suggests that CKD, LKD, and FA can in fact stabilize the three representative soil types from Michigan tested during this research investigation.

The general observation from our results is that the road construction industry in Michigan has the potential to benefit immensely from CKD/LKD/FA. These benefits are certainly important from the engineering point of view. However, the importance of our findings goes far beyond engineering. These results also explain the upcycling potential of CKD/LKD/FA in the State of Michigan. Upcycling is usually described as a process of transforming byproducts or waste materials into new materials. This is exactly what happens with CKD/LKD/FA stabilization: a material that could end up in a landfill is becoming a part of a stabilized soil matrix instead. Therefore, the above findings are also extremely important from the sustainability point of view as well. Social, economic, and environmental aspects are considered the main pillars of sustainability. In the following few paragraphs, we briefly argue how the findings of this research offer a glimpse of hope to support the cause of sustainability.

5.1. Socio-Economic Sustainability

As briefly mentioned before, some MDOT regions are known for frequent encounters of soils with poor engineering properties. Based on the data from 2017–2019, on average, the percentage undercut quantity of the total earth volume for the Grand region was 48%, the Bay region was 13%, and the Metro region was 11% [32]. It should be noted that these numbers represent the "planned" earthwork quantities; the final quantities might have been higher or lower. Nevertheless, these are large volumes of soil undercutting that could have been prevented if there was an economically feasible situ soil stabilization method. On the other hand, this is exactly why undercutting has become the preferred solution so far, as it is cheaper compared to other established solutions such as cement stabilization of soils. However, CKD, LKD, and FA are already waste materials (or byproducts, in the best-case scenario), thus the cost of stabilizing soil with them is going to be substantially lower. In addition, there is a guaranteed supply of all three stabilizers in large quantities (details presented in Section 5.2) thanks to local industries in Michigan. This in-State demand and supply for CKD, LKD, and FA make a positive business case and impact on society with the creation of new jobs.

5.2. Environmental Sustainability

All stabilizers tested during this investigation are recognized by the Michigan Department of Environmental Quality (MDEQ) as industrial byproducts [5]. Industrial wastes are defined as byproducts when they have an established secondary purpose or value. While this could be true for

LKD in Michigan, it is certainly not the case for CKD and FA. As of 2017, only 6% of CKD has been put into any secondary use, and the rest (359,746 tons) was disposed of in Michigan landfills, as reported by Roskoskey and Hiday [5]. The same report also shows that only 15% of FA was used, and the rest (1,208,560 tons) was disposed of as waste. Landfilling is the least preferred option in the sustainable waste management pyramid, which suggests that reuse or recovery should be considered to the fullest extent possible, before considering landfill disposal as an option [33–36]. In this sense, promoting the use of CKD/LKD/FA material in soil stabilization is certainly a way to promote environmental sustainability. The environmental benefits are multi-fold if you are choosing CKD/LKD/FA over the next two methods Michigan has used: undercutting or cement/lime stabilization. Since CKD/LKD/FA is already a waste or a secondary resource, diverting it from landfills is already the visible benefit. On the other hand, if someone is choosing CKD/LKD/FA over cement/lime stabilization or undercutting, the opportunity cost of the unused natural resources (i.e., good soils that need to be brought from elsewhere, or the raw material needed to produce cement or lime) is another benefit that is not readily visible.

6. Conclusions

During this research, three types of locally available industrial byproducts (and their combinations) were evaluated in the laboratory to assess their suitability to be soil stabilizers. The stabilizer materials used were Cement Kiln Dust (CKD), Lime Kiln Dust (LKD), Fly Ash (FA), and a combination of FA/LKD. The soil stabilized with them represented three types of weak road subgrade soils that are commonly encountered in Michigan which were identified as A-6 (Soil-1), A-4 (Soil-2), and A-7-6 (Soil-3) as per AASHTO classification. The main findings of the research can be summarized as follows:

- CKD and a combination of FA/LKD can be effectively used for long-term soil subgrade stabilization of all three soils tested.
- FA and LKD may be used for soil modification (i.e., short-term stabilization). While FA is recommended to be used as a short-term stabilizer in Soil-1 and Soil-2, LKD may be used only for short-term stabilization in Soil-3.
- The use of CKD/LKD/FA in soil subgrade stabilization in Michigan has the potential to become a cost-effective and sustainable alternative to the current practice of undercutting and more costly and less sustainable option of cement/lime stabilization. However, we emphasize the importance of conducting new mix-design tests, if there is a considerable deviation in stabilizer composition, from what was found in this research.
- CKD/LKD/FA are locally available as industrial byproducts, but currently, only a fraction of them is used for secondary purposes, while the rest ends up as waste in Michigan's landfills. Therefore, upcycling them in soil subgrade stabilization has the potential to become a sustainable cost-effective alternative.
- Stabilized soil strength loss occurs when subjected to direct freeze-thaw cycles, which should be an important topic for future research on this subject. However, this observation should not pose any adverse impact on the decision to use them in road construction projects, as direct exposure of soils subgrades to freeze-thaw is unlikely in the scenario of existing construction practices.

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