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Enhancing the CBR Strength and Freeze–Thaw Performance of Silty Subgrade Using Three Reinforcement Categories

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Abstract

Silty subgrade soil cannot satisfy the requirements of highway construction because of its low strength and durability problems. A wide range of reinforcements have been used to improve soil performance. Improving the soil properties has caused more interest in identifying new accessible resources for reinforcement. This paper investigates the effect of including different reinforcement types on reducing the rapid accumulation of pavement damage caused by freeze–thaw cycles or low strength of a silty pavement foundation. The improvement of CBR strength and freeze-thaw behavior was tested with the inclusion of three reinforcement categories: i) randomly distributed fibers (natural palm fibers and chemical polypropylene fibers), ii) chemical additives (lime and cement), and iii) waste or by-product materials (fly ash and silica fume). To represent unsaturated and saturated soil conditions for various field applications, both unsubmerged and submerged samples were investigated. Mass losses were also calculated after freezing–thawing cycles as criteria for durability behavior. The test results for the reinforced specimens were compared with unreinforced samples to clarify the effectiveness of each reinforcement type and content. Unsubmerged samples especially that reinforced with waste materials provided a significant improvement in CBR strength. For submerged conditions, the best performance was observed from the specimens treated with chemical additives. 10% of cement reinforcement and 20% of waste materials provide the highest resistance against the freeze–thaw cycles.

Key words: CBR Strength; Freeze-Thaw Behavior; Silty Subgrade; Reinforcement.

1. Introduction

The rapid and extensive development has recently led to the construction of industrial cities and the associated network of roads. This resulted in the utilization of virgin lands and large-scale urbanization programs. One of the typical problems in the construction of roads is the presence of weak fine-grained soils. Weak soft soils are associated with many geotechnical problems. Because of that, some of the pavements located on weak soil have exhibited various types of deterioration in recently built highways and expressways [1]. The usual approach to soft subgrade reinforcement is to remove the soft soil and replace it with a stronger material of crushed rock. The high cost of replacement has caused highway agencies to evaluate alternative methods of highway construction and one approach is to use stabilized soil for soft subgrade [2]. The natural durability and strength of the soil can be improved through the process of 'soil reinforcement' using different types of stabilizers. The aim of soil reinforcement materials is to increase the resistance against destructive forces of the weather by increasing strength and cohesion, reducing moisture movement in the soil and imparting water proofing characteristics. Reinforcement of soils with low-bearing capacity is an economical way to strengthen the earth for building purposes and to diminish the amount of soil exchanges [3]. In spite of the quantity of research conducted on the resultant characteristics of using different

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stabilizers for soil improvement, there are still no standard scientific outcomes or techniques and additional experimental data are necessary [4].

California bearing ratio (CBR) values are commonly used in mechanistic design and as indicator of strength and bearing capacity of a subgrade soil, subbase, and base course material for use in road and airfield pavements. The CBR may be thought of as an index value comparing the strength of the soil to that of crushed rock. Although more advanced testing methods, such as triaxial, simple shear, and direct shear tests, are available for measuring strength gain and improvement in soils, the CBR test is economical and simple. In addition, CBR is readily adapted to freezing and thawing tests. Tests are carried out on natural or compacted soils in water submerged or unsubmerged conditions and the results so obtained are compared with the curves of standard test to have an idea of the soil strength of the subgrade soil. Many researches have generally shown that; strength of the soil was improved by many stabilizers while the investigation on silty subgrade soil is still limited [5].

Moreover, in seasonally frozen areas, soils are exposed to at least one freezing–thawing cycle every year. This has a significant effect on many engineering applications such as road, railroad, pipeline, and building constructions. Most of the engineering properties of soils are severely affected by freezing–thawing period. Some engineering properties of soils (e.g., strength, permeability, and compressibility) could be changed significantly due to freezing–thawing cycles [6-10]. Guney et al. (2006) [11] have reported that in any reinforcement application, the stabilized material should also withstand additional stresses caused by seasonal temperature differences, particularly freeze–thawing cycles. The effect of freezing–thawing on fine-grained soils can be more pronounced than that of the coarse-grained soils. Fine-grained soils influenced by freezing and thawing show changes in volume, strength and compressibility, densification, water content, bearing capacity and microstructure. In the freezing period, ices in various sizes and shapes tend to segregate in soils resulting in the formation of characteristic structures in micro and macro scales [12]. The frozen layer begins to thaw from the top and the bottom at the same time during the thawing period. Thus, a great influence on performance of the silty subgrade soil will be occurred. Reinforcement material selection and its evaluation of freeze–thaw effect and strength are important to guarantee subgrade stability. The main objectives of this study was to investigate the effect of three categories of reinforcement materials as well as the adding content on the CBR strength (at unsubmerged and submerged conditions) and on the durability behavior of silty subgrade soil subjected to freezing–thawing cycles where mass losses were calculated after freezing–thawing cycles to highlight the durability behavior.

2. Utilized Reinforcement Categories

2.1. Natural and Synthetic Fibers (Palm and Polypropylene Fibers)

The current concern over the environment and greenhouse gas emissions and increase of soil strength by using the natural materials is one way that engineers and designers can contribute to a greener earth. In ancient times, natural fibers such as hey, wood and bamboo were been used in improving of the construction materials [13]. The use of appropriate elements in soil improves its engineering properties such as strength, hardness and deformability. The main reason for using natural materials is because of its environmental and economic advantages [14-16]. The fibers in date palm have special properties such as low costs, plenitude in the region, durability, lightweight, high tension capacity and relative strength against deterioration. Thus, it is possible to use the palm fibers as an alternative low-cost natural material for soil reinforcement. Adding to this, the date palm is one of the most cultivated tree crops in the world, with a distribution of around 100 million palms in 30 countries [4].

Synthetic fibers such as Polypropylene, Polyester, Polyethylene, Glass, Nylon, Steel, Carpet and Polyvinyl alcohol fibers have been used to stabilize the soil. Choubane et al. 2001 [17] reported that several studies were performed to investigate the effects of synthetic fiber reinforcements on compacted soil. The results showed that different fibers either improved or weakened the engineering properties of the test samples, depending on the type of fibers. Miller and Rifai 2004 [18], based on their test results, indicated that Polypropylene inclusion increased the crack reduction and hydraulic conductivity of compacted clay soil. All these previous studies have shown that the addition of Polypropylene-reinforcement caused significant improvement in the strength and decreased the stiffness of the soil. More importantly, Polypropylene reinforced soil exhibits greater toughness and ductility and smaller loss of post-peak strength, as compared to soil alone. Therefore, the discrete Polypropylene can be considered as a good earth reinforcement material, which causes significant modification and improvement in the engineering properties of soil. However, no firm conclusions can be drawn about effect of polypropylene fibers reinforcement on freezing-thawing resistance of fine grained soil due to differences of results.

2.2. Chemical Additives (Portland cement and Hydraulic Lime)

In recent years, scientific techniques of soil stabilization have been introduced, and developed largely from methods devised for earth roads. The use of chemical additives like Portland cement, hydraulic lime as stabilizer is quite common [19-20]. The strength of the soil can be increased reasonably by cementing clusters of particles in a manner similar to that of binding aggregates in concrete. Pozzolanic reactions between lime and certain clay minerals form a variety of cement-like compounds that can bind soil particles together and at the same time reduce water absorption by clay particles. Cement is the oldest binding agent since the invention of soil stabilization technology in 1960's. It may be considered as primary stabilizing agent or hydraulic binder because it can be used alone to bring about the stabilizing action required. Cement reaction is not dependent on soil minerals, and the key role is its reaction with water that may be available in any soil [21]. This can be the reason why cement is used to stabilize a wide range of soils. Hydration process is a process under which cement reaction takes place. The process starts when cement is mixed with water and other components for a desired application resulting into hardening phenomena. The hardening (setting) of cement will enclose soil as glue, but it will not change the structure of soil. The hydration reaction is slow proceeding from the surface of the cement grains and the center of the grains may remain unhydrated. Cement hydration is a complex process with a complex series of unknown chemical reactions [22-23].

Lime provides an economical way of soil stabilization. Lime modification describes an increase in strength brought by exchange capacity rather than cementing effect brought by pozzolanic reaction. In soil modification, as clay particles flocculates, transforms natural plate like clays particles into needle like interlocking metalline structures. Clay soils turn drier and less susceptible to water content changes [24]. Lime stabilization may refer to pozzolanic reaction in which pozzolana materials reacts with lime in presence of water to produce cementitious compounds. Lime stabilizations technology is mostly widely used in geotechnical and environmental applications. Some of applications include encapsulation of contaminants, rendering of backfill (e.g. wet cohesive soil), highway capping, slope stabilization and foundation improvement such as in use of lime pile or lime-stabilized soil columns. However, presence of sulphur and organic materials may inhibit the lime stabilization process [25].

2.3. Waste Materials (Fly Ash and Silica Fume)

Due to rapid industrialization throughout the world, significant amount of waste materials are being generated. This causes environmental hazard. So utilization of such waste material may be considered as one of the feasible solutions so as to improve weak subgrade soil and to help in reducing the environmental pollution. Stabilization is an economic and ecological method for subgrade reinforcement and its potential is extensive. The potential for using industrial by-products for stabilization of silty subgrade soils such as fly ash, silica fume, blast furnace slag and rich husk ash is promising and has been investigated [26-28]. Fly ash is a by-product of coal fired electric power generation facilities; it has little cementitious properties compared to lime and cement. Most of the fly ashes belong to secondary binders; these binders cannot produce the desired effect on their own. However, in the presence of a small amount of activator, it can react chemically to form cementitious compound that contributes to improved strength of soft soil. Fly ashes are readily available, cheaper and environmental friendly. Improved engineering properties of fly ash-stabilized soil were reported by Erdem at al. 2011[29] who conducted research on fly ash-stabilized subgrade along with nine other stabilization alternatives. The studies indicate that increasing fly ash content has a considerable effect on the strength properties of soil, and the strength strongly depends on the water-binder ratio.

Silica fume, also known as micro-silica, is a byproduct of the reduction of high-purity quartz with coal in electric furnaces in the production of silicon and ferrosilicon alloys. Silica fume is also collected as a byproduct in the production of other silicon alloys such as ferrochromium, ferromanganese, ferromagnesium, and calcium silicon. Before the mid-1970s, silica fume was discharged into the atmosphere. After environmental concerns necessitated the collection and landfilling of silica fume, it became economically justified to use silica fume in various applications [1]. Azzawi et al. 2012 [30] studied effect of silica fume addition on behavior of silty clayey soils, they investigated that there is significant important on swelling pressure and compressive strength of composite samples with silica fume. The permeability of soil increased with increase in silica fume content. It is observed that the addition of silica fume decreases the development of cracks on the surface of compacted clay samples reducing the cracks width by 75%. Venu N., 2009 [31] studied the soil properties with silica fume as stabilizer and comparing the same with other materials. The laboratory investigations indicate that soil samples possessing low strength can be treated with varying silica fume of 5% to 20% by weight of dry soil. The treated soil samples showed significant improvement in the strength characteristics.

3. Experimental Procedure

An extensive experimental program was carried out to investigate the strength improvement of a fine-grained soil by adding three reinforcement categories. The experimental program in this phase of the study consisted mainly of CBR tests and freeze–thaw tests on plain (i.e., with no additives) soil samples and soil samples improved with varying amounts of fibers, chemical additives and waste materials.

3.1. Materials

3.1.1. Subgrade Soil

Soil samples of silty soil used in this research are collected from the Delta region at top of Nile valley. The grain size distribution test result for natural soil is shown in Fig. 1. The results of the natural water content, liquid limit, plastic limit, plasticity index, specific gravity, modified proctor compaction test, CBR value, cohesion, and angle of internal friction are presented in Table 1.

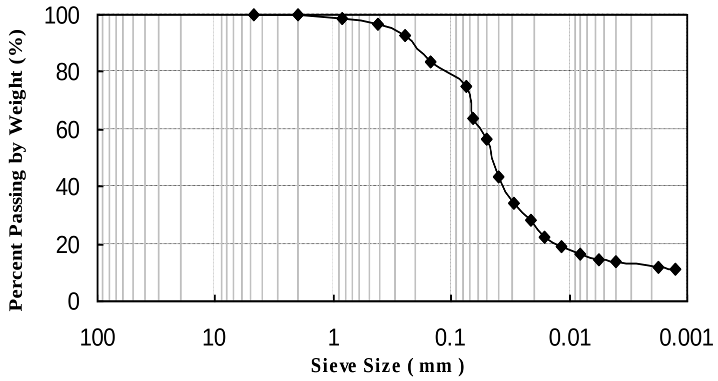

Figure 1. Grain size distribution curve for natural subgrade

Table 1. Properties of silty subgrade soil

Test	Values
Natural moisture content (%)	4.63
Liquid limit (%)	23.7
Plastic limit (%)	21.1
Plasticity index (%)	2.6
Specific gravity	2.39
Max. dry unit weight (KN/m^3)	17.5
Optimum moisture content (%)	18.0
AASHTO classification group	A-4
Unified classification group	ML
CBR value (%).	12.8

3.1.2. Palm and Polypropylene Fibers

Date palm tree or Phoenix dactylifera is a monopetalous tree from the Palm family. Date palm fibers are natural fibers with lignocellulose texture. The largest date palm-producing countries in the world are Egypt, Iran, Saudi Arabia, Pakistan and Iraq. The palm fibers in date production have filament textures with special properties such as low costs, plenitude in the region, durability, lightweight, tension capacity and relative strength against deterioration. Thus, it is possible to use the palm fibers as an alternative low-cost natural material for soil reinforcement. The experimental program was undertaken to investigate the effect of including randomly spaced palm fibers in a silty soil matrix as soil reinforcement in road [32, 33]. The properties of utilized palm fibers are shown in Table 2. The utilized polypropylene fibers were supplied by a firm in Egypt. Some properties of polypropylene fiber provided by the manufacturer are given in Table 3. According to previous researches such as [4, 10], the contents of the palm and polypropylene fibers are chosen as 0.5%, 1.0%, and 1.5% by dry weight of soil.

Table 2. Properties of palm fibers

Property	Mean
Length (mm)	270
Diameter (mm)	0.5
Unit weight (KN/m^3)	8.46
Water absorption to saturation (%)	135.0
Natural moisture content (%)	6.1
Tensile strength (MPa)	126.74
Strain at failure (%)	4.86
Modulus of elasticity (GPa)	2.63

Table 3. Properties of polypropylene fibers

Property	Mean
Length (mm)	20
Diameter (mm)	0.048
Unit weight (KN/m^3)	9.8
Tensile strength (MPa)	367
Elastic modulus (MPa)	3900
Specific gravity	0.91
Specific surface (m^2/N)	27
Modulus of elasticity (GPa)	2.63

3.1.3. Chemical additives (Portland cement and Hydraulic Lime)

Hydrated lime as well as Portland cement is used as stabilizer in fine grained soils. Their properties are given in Table 4. The contents of this reinforcement category are chosen based on previous studies [9, 14, 19, and 24] as 2%, 5%, and 10% by dry weight of soil.

Table 4. Properties of the chemical additives

Portland cement		**Hydrated lime**	
Properties	**value**	**Chemical properties**	**value**
Specific gravity	3.15	Total CaO (%)	85.78
Initial setting time (min)	150	$Ca(OH)_2$ (%)	82.04
Final setting time (min)	185	MgO (%)	3.52
Volume expansion (mm)	2.0	Loss ignition (%)	22.51
Compressive strength (MPa)		SO_3 (%)	1.47
2 days	22.0	CO_2 (%)	3.89
7 days	38.7	R_2O_3 (%)	1.41
28 days	46.8	Physical properties	value
		Sandy-over 90µ	6
		Unit weight (KN/m^3)	4.72

3.1.4 Waste Materials (Class C Fly Ash and Silica Fume)

Fly Ash has particles of diameter about 10–25 µm. The particles are smooth and spherical. Silica fume is also called micro silica or condensed silica fume. It is extremely fine powder with particle size less than 1 micron and with an average diameter of about 0.1 micron, about 100 times smaller than average cement particles. The contents of utilized waste materials are chosen according to previous studies [21, 26, 28, 30 and 31] as 10%, 15%, and 20% by dry weight of soil. Table 5 shows the properties of fly ash and silica fume.

Table 5. Properties of waste materials

	waste materials	
Chemical compositions (%)	**C Fly ash**	**Silica fume**
SiO_2	61.8	98.2
Al_2O_3	26.4	-
Fe_2O_3	5.0	-
CaO	1.10	-
MgO	0.40	-
SO_3	0.42	-
K_2O	0.80	-
Na_2O	0.54	-
Specific gravity	2.37	1.89
Loss ignition (%)	2.07	0.61

3.2. Sample Preparation

A review of the available literature about the testing of laboratory samples of stabilized soils indicates that test results are highly dependent on sample preparation. The two critical factors affecting sample preparation are moisture control and mixing procedures. In this study, samples were constituted by thoroughly mixing dry soil with the water and stabilizer at predetermined amounts. Soil, stabilizer, and water were mixed in a plastic container manually. To ensure a uniform distribution of the moisture throughout the sample, soil–liquid mixtures were stored in the sealed container for about 18 h prior to compaction. It is important to introduce stabilizer to the mixture at the final step just before compaction because the adding water after stabilizer may cause it to stick together during mixing. Extreme care was taken during the mixing process to ensure a uniform mixture [34].

3.3. Test Compaction

The compaction characteristics depend on both grain size distribution and specific gravities of the soil and stabilizer. The stabilizers initially coat the soils to form large particles that consequently occupy larger spaces. Therefore, the tendency of fine-grained soils is to initially decrease the dry unit weight until the stabilizer (which tends to increase the dry unit weight) compensates for the larger spaces. The moisture content versus dry unit weight relationship for different mixes is determined by using the modified proctor compaction test according to ASTM D1557 on the soil passed No. 4 sieve. Maximum dry unit weight (MDD) and optimum moisture content (OMC) for each reinforcement type and percentage is calculated. The maximum dry unit weight and the optimum moisture content for the pure subgrade are 17.5 KN/m^3 and 18% respectively.

From Table 6, it is observed that the all utilized reinforcement materials unless palm fibers; act to interlock particles and group of particles in a unitary coherent matrix thus increasing the strength properties of the soil. It is clear that increase of palm fiber content causes increase of OMC and decrease of MDD. Increase in OMC is because of the fact that palm fibers absorb water more than soil. Decrease in MDD is because of replacing heavy soil particles with light palm fibers. Polyethylene fibers provide better influence where OMC decreases and MDD increase at 0.5% then decreases at contents 1.0 and 1.5%. Moreover, chemical additives especially Portland cement obviously increase MDD. The optimal chemical additives content that provides the highest MDD is 10% for cement and 5% for lime. With increasing chemical additives content, OMC increases with lime and decreases with cement. Waste materials provide an obvious decrease in OMC and a great improvement in soil unit weight where 20% fly ash achieves the highest MDD value (29.3 KN/m^3). While 15% silica fume provides MDD of (26.2 KN/m^3).

Table 6. Compaction test results for each reinforcement category

Reinforcing Category		Contents	MDD (KN/m^3)	OMC (%)
Plain subgrade soil			17.5	18
Fibers	Palm fiber	0.5	16.2	20.3
		1.0	14.5	21.7
		1.5	13.2	23.2
	Polypropylene 3cm	0. 5	18.6	17.6
		1.0	16.3	16.8
		1.5	15.1	15.9
Chemical additives	Lime	2.0	21.5	21.8
		5.0	23.7	25.6
		10.0	22.5	26.2
	Cement	2.0	23.3	17.2
		5.0	25.2	15.4
		10.0	27.4	12.5
waste materials	Fly ash	10.0	22.4	16.2
		15.0	26.6	15.4
		20.0	29.3	13.6
	Silica fume	10.0	21.7	16.8
		15.0	26.2	15.7
		20.0	24.5	14.4

3.4. CBR Test

The California bearing ratio CBR test that measures the shearing resistance and stability of a soil under controlled moisture and unit weight conditions have performed accordance to ASTM D, 1883–2007 procedure. The required water was added in two stages to prepare more homogenous specimens [35]. In the first stage, half of the water was added to the reinforced soil mixture, followed by 15 min continuous hand mixing. Then, the remaining water was added, followed by 5 min hand mixing. Then, the remaining water was added, followed by 5 min hand mixing. Submerged specimens were placed in water for 48 h and then taken out and allowed to drain before being loaded. Three specimens were prepared and tested for each mix parameter.

3.5. Freezing and Thawing Cycles

Durability is the property of a geotechnical material that reflects its performance under freeze-thaw cycles. Freeze–thaw cycling is a weathering process which occurs in cold climates. Cylindrical samples with 50 mm diameter and 100 mm height were prepared with the maximum dry unit weight and optimum water content. To prepare samples, firstly, the necessary OMC was determined and mixed with the soil. The soil and the fiber amounts were divided into 5 parts and compacted in the mold according modified Proctor test. After the removal of each sample from the mold, the sample is immediately covered with a plastic layer which helps it against water evaporation. Three specimens were tested for each mix parameter. Specimens of silty soil were subjected to maximum three freeze–thaw cycles to calculate the mass losses after cycles as criteria for durability behavior. Freeze–thaw test has been performed according to ASTM D 560. To prepare the samples for the closed system freezing and thawing cycles, plain and reinforced specimens were placed in a digital refrigerator at −20°C for 6 h and then at + 20°C for thawing phase for 6 h. These temperatures had been previously used in some researches [12, 36]. Six hours is a proportional period after which the alteration of specimens' height would become constant. This means that the height increase in freeze phase and the height decrease in thaw phase stop. The cycles were continued up to 9 cycles. This number of cycles was chosen since most soil strength reduction would occur in primary cycles and after 5–10 cycles a new equilibrium condition would become predominant on samples [37]. After 9 cycles, the test samples were dried in an oven at 110±5 °C for 12 h. The corrected oven-dry mass of specimen (CODM) was calculated as follows:

$$CODM = (A/B) \times 100 \tag{1}$$

Where: A is the oven-dry mass after drying at 110 °C, and B is the percentage of water retained in specimen plus 100. Then, mass loss (ML) was calculated as follows:

$$ML\ (\%) = (C/D) \times 100 \tag{2}$$

Where: C is the original calculated oven-dry mass minus final corrected oven-dry mass (i.e., C=D−CODM), and D is the original (i.e., before freezing–thawing cycles) calculated oven-dry mass.

4. Results and Discussion

4.1. CBR Strength (Unsubmerged Condition)

Figures 2a, 3a and 4a illustrate CBR strength of unsubmerged samples. Three specimens were tested for each reinforcement type and adding content. In all following results figures, the error bars based on the calculated standard deviations are illustrated. Generally it can be observed that the adding of reinforcement materials enhances the CBR strength significantly. As shown in Figure 2a, adding of fibers to soil specimens enhances the CBR strength by average values of 19%, 34% and 37% at contents of 0.5, 1.0 and 1.5% respectively. The lowest improvement rate is obtained at fiber content range of 1-1.5%. On another side, subgrade soil reinforced with polyethylene fibers provides strength higher than it if reinforced with palm fibers by about 14%, 6% and 2% for addition percentage at contents of 0.5, 1.0 and 1.5% respectively. It can be noticed that the difference between unsubmerged subgrade strength reinforced with polyethylene and palm fibers decreases with increasing the fiber content. This results agree with some previously results [38].

As shown in Figure 3a that presents the results of CBR test at using chemical additives, the adding of these reinforcements increases the strength of soil by average values of 80%, 111% and 127% compared with plain specimens at contents of 2.0, 5.0 and 10.0% respectively. Adding fiber up to 2% achieves the highest improvement rate while adding fiber from 5.0% to 10.0% provides the lowest improvement rate. On another side, subgrade soil reinforced with cement provides higher strength than it if reinforced with lime by about 8.5%, 11.5% and 20% for contents of 2.0, 5.0 and 10.0% respectively. It is observed that the difference between unsubmerged subgrade strength reinforced with cement and lime increases with increasing the adding content.

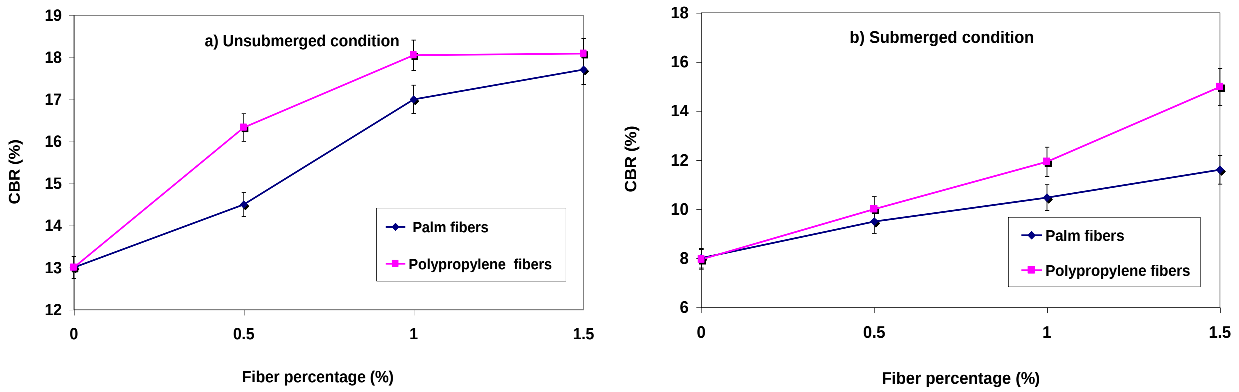

Figure 2. Effect of fibers on CBR strength (a) unsubmerged condition, (b) submerged condition

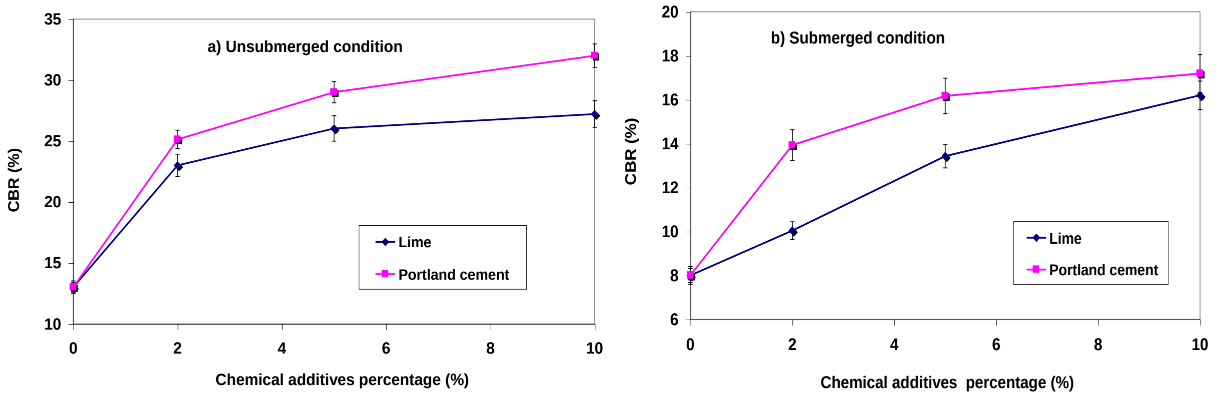

Figure 3. Effect of chemical additives on CBR strength (a) unsubmerged condition, (b) submerged condition

Figure 4a illustrates the results of CBR test at using waste materials. It is indicated that adding of waste material semi-linearly increases the strength of plain soil by average values of 92, 123 and 160% at reinforcing contents of 10%, 15% and 20% respectively. Thus, the waste materials provide the maximum improving in unsubmerged CBR strength followed by the chemical additives and then the fibers category. On another side, strength of soil reinforced with fly ash is slightly higher than it if reinforced with silica fume by about 4.0%, 7% and 9% at contents of 10%, 15% and 20% respectively where the difference increases with increasing the adding content.

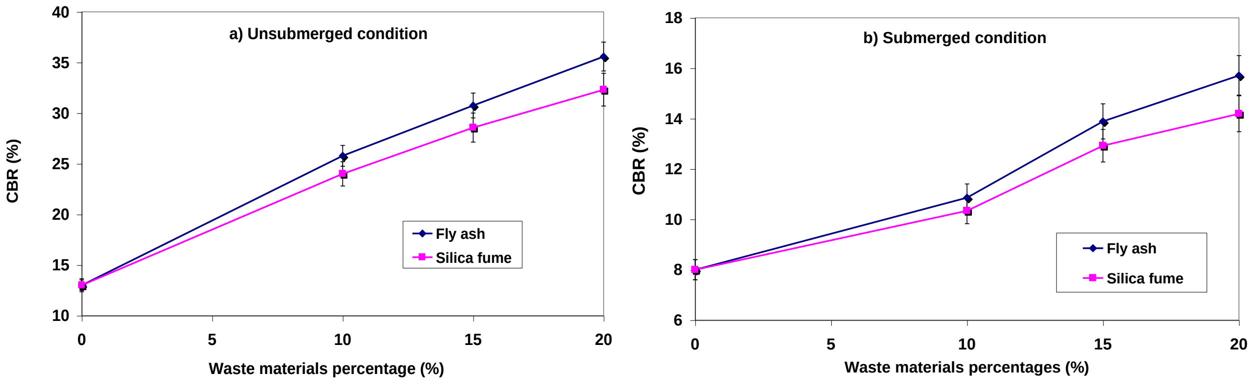

Figure 4. Effect of waste materials on CBR strength (a) unsubmerged condition, (b) submerged condition

4.2. CBR Strength (Submerged Condition)

Saturation has obviously important influences on the soil behavior that can be explained in view of three aspects. First, the strength and modulus of soil itself decrease because of the interaction of water with fine cohesive particles. Second, the loss in capillarity caused because the saturation reduces the effective stress and the soil-bearing capacity. Third, the frictional resistance between reinforcement materials and soil particles reduces as water lubricates the surfaces of soil particles and stabilizers and thus the pullout capacity of the stabilizers reduces. Figure 3b presents the CBR strength of fiber reinforced specimens under submerged condition showing standard deviations. The adding of fibers to submerged soil specimens improves the strength by average values of 21%, 42% and 65% compared with plain specimens at contents of 0.5, 1.0 and 1.5% respectively. These improvement ratios are higher than them in case of unsubmerged specimens. This point can illustrate the great influence of fiber reinforcement (especially polypropylene fiber at higher content) on increasing the CBR strength in submersion condition. Unlike case of unsubmerged specimens, the difference between CBR strength values of the two utilized fibers increases with increasing the fiber content.

As shown in Figure 4b, the usage of chemical additives, especially Portland cement, increases the submerged CBR strength of plain soil by average values of 50%, 87% and 108% at contents of 2.0, 5.0 and 10.0% respectively. For reinforcing with waste materials, Figure 4b shows that the utilized waste materials improve the strength of unreinforced specimens by about 32%, 67% and 86% at contents of 10, 15 and 20% respectively where the fly ash provides slight more improvements than the silica fume. Its observed that the improving in submerged CBR strength using chemical additives and waste materials is lower than it in case of unsubmerged condition. According to previous results, it can be concluded that with increasing the reinforcement content, both unsubmerged and submerged CBR strength increase significantly. Moreover, the chemical additives provide the maximum improvement in submerged CBR strength followed by the waste materials and then the fibers category in the last. Thus, usage of waste materials reinforcement is the most efficiency in improving the CBR strength in unsubmerged condition while utilization of chemical additives is the most efficiency in improving the CBR strength in submerged condition.

According to the results of this research and literature in the past years, it can be illustrated that soil reinforcement is one of the conventional methods used to improve the quality of road subgrade and pavement layers. This method enables enhancing the existing material properties at the project site and reaching the needed specifications. Besides, improving the quality of pavement and filling layers would reduce the total thickness of pavement and leading to a reduction in administrative costs [39, 40].

4.3. Mass Loss after Freezing and Thawing Cycles

To investigate the effect of fibers, chemical additives and waste materials as reinforcement on durability behavior of silty subgrade soil, the mass losses are calculated after 9 freezing–thawing cycles. The variation of mass (average from three specimens) losses with each reinforcement type and content is shown in Figure 5. The standard deviation for each case based on three test replications is calculated and the corresponding error bars are shown in Figure 5. It can be seen that addition of chemical additives and waste materials decrease mass loss of the soil after 9 freezing–thawing cycles especially at higher reinforcement ratio. The most noteworthy reinforcement effect on durability behavior is observed at usage waste materials (especially fly ash) at all contents as well as at utilization 10% cement. While the mass loss is around 27% for the unreinforced sample, the mass loss decreases up to 58%, 70% and 80% for specimens reinforced with fly ash and decreases up to 51%, 61% and 72% for specimens reinforced with silica fume, at contents of 10, 15, and 20% respectively. The lowest mass loss ratio (4.5%) is achieved at adding of 10% cement where it decreases by about 83% compared with unreinforced soil.

For fiber reinforcement category, at the end of the 3 freezing–thawing cycles, the palm fiber provides higher mass loss than unreinforced soil especially with increasing its content. This may be because the replacing heavy soil particles with light palm fibers decrease the soil density. Moreover, the addition of polypropylene fibers decreases the silty soil mass loss especially at 1.0% content where the mass loss decreases up to 36% compared with the plain sample. In the literature it was reported that mass losses inside the safety limit of 12.5%, did not significantly affect the strength of soil closed to the surface at the end of the freezing–thawing cycles [41, 42]. Hence it can be concluded that waste materials at all contents as well as Portland cement at 10% provide mass loss ratios inside the safety limit. Thus, they cause the silty subgrade soil to exhibit more resistance against the freezing–thawing period in seasonally frozen areas.

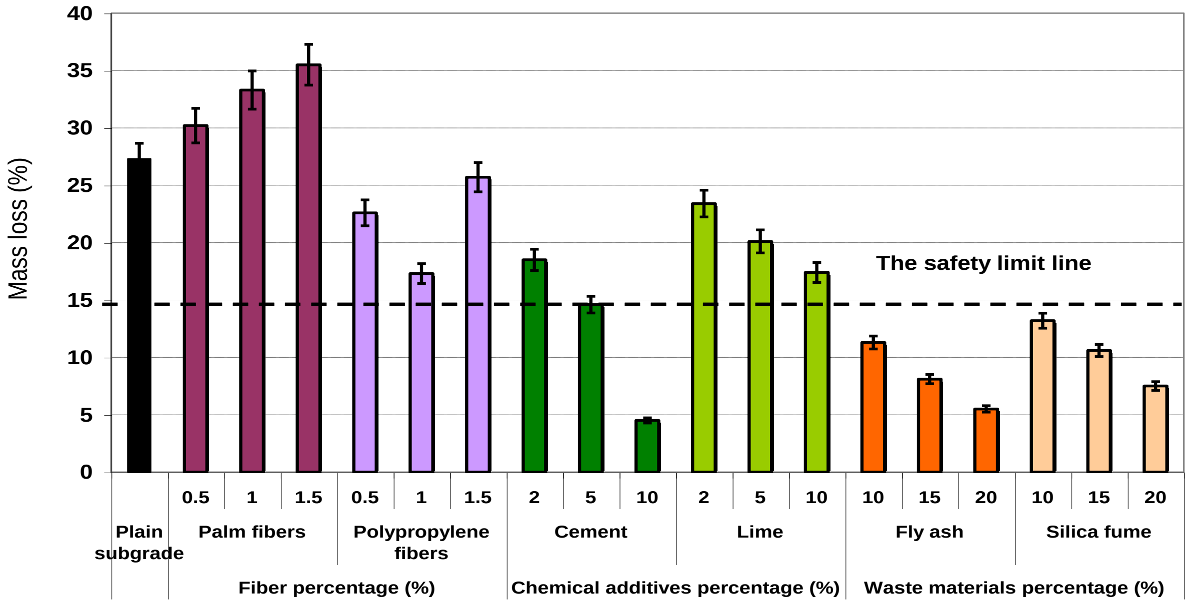

Figure 5. Variation of mass loss for each reinforcement category

4.4 Correlations between CBR strength and mass loss

The relationships between CBR strength and mass loss for reinforced silty subgrade soil with three reinforcement categories using different amounts of each category are illustrated in Figures 6, 7 and 8 where three specimens were prepared and tested for each mix parameter. Linear relationships between CBR strength and mass loss for the three reinforcement categories are obtained where the mass loss decreases as CBR strength increases. It has been found that the linear relations may expressed as a law (y = n(x) + k), where k is a constant; n is a dimensionless constant representing the tangent of the slop angle. According to the slope of the linear relations (n), it can be obtained that addition of waste materials provides the highest relation sensitivity between the subgrade strength and mass loss where tangent of the slop angle (n) is about 0.54, followed by chemical additives (n is about 0.4) and fibers in the last (n is about 0.08). Moreover, the coefficient of correlation (R^2) for waste materials reinforcement is higher than 0.9 while fiber materials provide very poor correlations (R^2 about 0.0075). For chemical additives, lime addition shows reasonable correlation (R^2 of 0.7) however cement addition shows weak correlation (R^2 = 0.2). Thus, the silty subgrade soil reinforcing with waste materials achieves more reasonable.

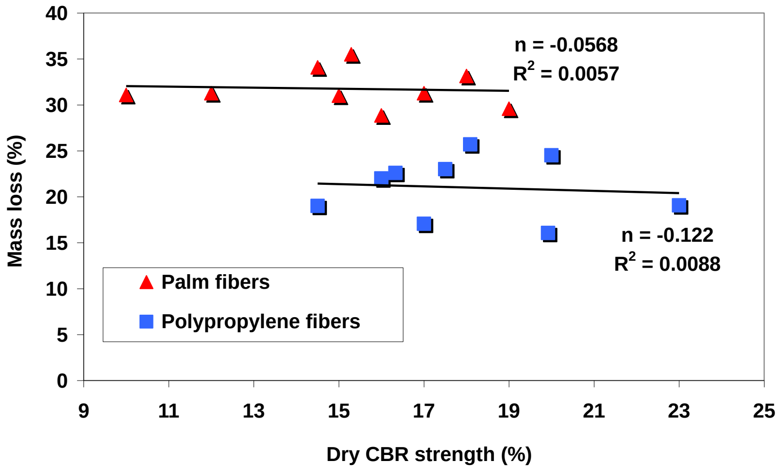

Figure 6. Relation between strength and mass loss at using fibers category

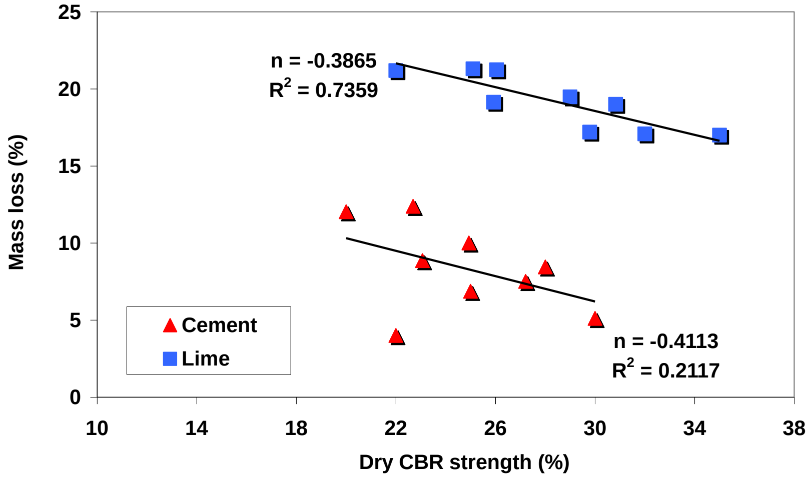

Figure 7. Relation between strength and mass loss at using chemical additives category

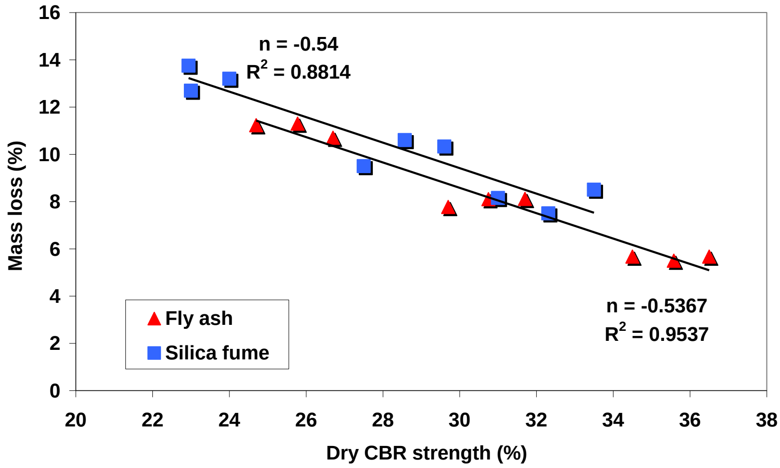

Figure 8. Relation between strength and mass loss at using waste materials category

5. Summary and Conclusions

Fine-grained soils are usually known as frost-susceptible and considered to be marginal because they lack the required engineering properties for use in pavement foundation. This study was performed to investigate the effect of three different reinforcement categories on the unsubmerged and submerged CBR strength and the durability behavior of a silty subgrade soil. Randomly distributed fibers (natural palm fibers and chemical polypropylene fibers), chemical additives (lime and cement) and waste or by-product materials (fly ash and silica fume) were utilized as reinforcing materials. Based on findings and results, the following conclusions can be drawn:

1. Potential benefit of reinforcement depended on the type and content of stabilizers. Waste materials (especially fly ash) followed by chemical additives (especially Portland cement) increased the maximum dry unit weight of the silty subgrade soil where the highest values were achieved at adding of 20% fly ash, 10% cement and 15% silica fume.
2. Increasing in reinforcement content increased the silty soil strength for both unsubmerged and submerged conditions. The waste materials (especially fly ash) provided the maximum improving in unsubmerged CBR strength followed by the chemical additives (especially Portland cement) and then the fibers category (especially polypropylene fiber). The efficiency of palm and polypropylene fibers in improving CBE strength of silty soil was more obvious in submerged condition than unsubmerged condition thus; fibers reinforcement can be perfectly used in rainy or wetted areas.
3. Submergence of plain and reinforced specimens caused the CBR bearing strength to decrease considerably. This can be attributed to the interaction of water with soil particles and the reduced frictional resistance of stabilizers caused by water. In this condition, also adding of the three reinforcement categories increased the strength of the soil. In submerged case, the chemical additives provided the maximum improvement in strength followed by the waste materials and then the fibers category in the last. Thus, usage of waste materials is the most efficiency in improving the CBR strength in unsubmerged condition while utilization of chemical additives is the most efficiency in improving the CBR strength in submerged condition.
4. For soil durability, waste materials reinforcement (at all contents) and 10% of Portland cement provided more resistance against the freezing–thawing cycles in seasonally frozen areas where their mass loss ratios were inside the safety limit of 12.5%.
5. Linear relationships between unsubmerged strength and mass loss are obtained, the addition waste materials to the silty subgrade soil obtained more reasonable, sensible and credible correlations. It should be pointed out that the results reported herein are meaningful for the individual soil and reinforcement parameters tested in this study. Further studies considering different soil and reinforcement conditions are needed to make a more reasonable engineering judgment.

6. References

[1] Anupam, Aditya Kumar, and Praveen Kumar. "Use of Various Agricultural and Industrial Waste Materials in Road Construction." Procedia-Social and Behavioral Sciences 104 (2013): 264-273.

[2] Hossain, K. M. A., M. Lachemi, and S. Easa. "Stabilized soils for construction applications incorporating natural resources of Papua New Guinea." Resources, Conservation and Recycling 51, no. 4 (2007): 711-731.

[3] Hossain, K. M. A., and L. Mol. "Some engineering properties of stabilized clayey soils incorporating natural pozzolans and industrial wastes." Construction and Building Materials 25, no. 8 (2011): 3495-3501.

[4] Sarbaz, Hossein, Hossein Ghiassian, and Ali Akbar Heshmati. "CBR strength of reinforced soil with natural fibres and considering environmental conditions." International Journal of Pavement Engineering 15, no. 7 (2014): 577-583.

[5] Chegenizadeh, Amin, and H. R. Nikraz. "CBR test on reinforced clay." In The 14th Pan-American conference on soil mechanics and geotechnical engineering (PCSMGE), the 64th Canadian geotechnical conference (CGC), Oct, vol. 2. 2011.

[6] Hohmann-Porebska, Maria. "Microfabric effects in frozen clays in relation to geotechnical parameters." Applied clay science 21, no. 1 (2002): 77-87.

[7] Qi, Jilin, Pieter A. Vermeer, and Guodong Cheng. "A review of the influence of freeze-thaw cycles on soil geotechnical properties." Permafrost and periglacial processes 17, no. 3 (2006): 245-252.

[8] Qi, Jilin, Wei Ma, and Chunxia Song. "Influence of freeze–thaw on engineering properties of a silty soil." Cold regions science and technology 53, no. 3 (2008): 397-404.

[9] ASTM D 560-03. Test methods for freezing and thawing compacted soil cement mixtures, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA.

[10] Zaimoglu, A. Sahin. "Freezing–thawing behavior of fine-grained soils reinforced with polypropylene fibers." *Cold regions science and technology* 60, no. 1 (2010): 63-65.

[11] Guney, Yucel, Ahmet H. Aydilek, and M. Melih Demirkan. "Geoenvironmental behavior of foundry sand amended mixtures for highway subbases." Waste Management 26, no. 9 (2006): 932-945.

[12] Roustaei, Mahya, Abolfazl Eslami, and Mahmoud Ghazavi. "Effects of freeze–thaw cycles on a fiber reinforced fine grained soil in relation to geotechnical parameters." Cold Regions Science and Technology 120 (2015): 127-137.

[13] Khedari, Joseph, Borisut Suttisonk, Naris Pratinthong, and Jongjit Hirunlabh. "New lightweight composite construction materials with low thermal conductivity." *Cement and Concrete Composites* 23, no. 1 (2001): 65-70.

[14] Seyed Esmaeil Mousavi and Leong Wong" Performance of Compacted and Stabilized Clay with Cement, Peat Ash and Silica Sand." Jordan Journal of Civil Engineering, Volume 9, No. 1(2015).

[15] Mesbah, A., J. C. Morel, P. Walker, and Kh Ghavami. "Development of a direct tensile test for compacted earth blocks reinforced with natural fibers." Journal of Materials in Civil Engineering 16, no. 1 (2004): 95-98.

[16] Bouhicha, M., F. Aouissi, and S. Kenai. "Performance of composite soil reinforced with barley straw." Cement and Concrete Composites 27, no. 5 (2005): 617-621.

[17] Choubane B., Robert K., and Armaghani J." Full-scale laboratory evaluation of polypropylene fiber reinforcement of subgrade soils." Transportation Research Record (TRB) 01-2157, Washington D. C (2001).

[18] Miller, Carol J., and Sami Rifai. "Fiber reinforcement for waste containment soil liners." *Journal of Environmental Engineering* 130, no. 8 (2004): 891-895.

[19] Al-Rawas, Amer Ali, A. W. Hago, and Hilal Al-Sarmi. "Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman." *Building and Environment* 40, no. 5 (2005): 681-687.

[20] Bahar, R., M. Benazzoug, and S. Kenai. "Performance of compacted cement-stabilised soil." *Cement and concrete composites* 26, no. 7 (2004): 811-820.

[21] Zhang, Yang, Alex E. Johnson, and David J. White. "Laboratory freeze–thaw assessment of cement, fly ash, and fiber stabilized pavement foundation materials." *Cold Regions Science and Technology* 122 (2016): 50-57.

[22] Mac Laren, and White M. A." Cement: Its Chemistry and Properties." Journal of Chemical Education, Vol.8 (No.6), 623(2003).

[23] Li, Lin, Wei Shao, Yadong Li, and Bora Cetin. "Effects of Climatic Factors on Mechanical Properties of Cement and Fiber Reinforced Clays." *Geotechnical and Geological Engineering* 33, no. 3 (2015): 537-548.

[24] Jafar Oujghaz, Hamid Shabanzadeh and Ghader Bagheri "Laboratory investigation on divergent fine-grained soil stabilized with sewage sludge ash and lime." Indian Journal of Fundamental and Applied Life Sciences, Vol. 5 (S4), pp. 351-361(2015).

[25] Euro Soil Stab" Development of Design and Construction Methods to Stabilize Soft Organic Soils: Design Guide for soft soil stabilization." CT97-0351, European Commission, Industrial and Materials Technologies Programme (Rite-EuRam III) Bryssel(2002).

[26] Chauhan, Mahipal Singh, Satyendra Mittal, and Bijayananda Mohanty. "Performance evaluation of silty sand subgrade reinforced with fly ash and fibre." *Geotextiles and Geomembranes* 26, no. 5 (2008): 429-435.

[27] Sezer, Alper, Gözde İnan, H. Recep Yılmaz, and Kambiz Ramyar. "Utilization of a very high lime fly ash for improvement of Izmir clay." *Building and environment* 41, no. 2 (2006): 150-155.

[28] Yi, Yaolin, Liyang Gu, and Songyu Liu. "Microstructural and mechanical properties of marine soft clay stabilized by lime-activated ground granulated blastfurnace slag." *Applied Clay Science* 103 (2015): 71-76.

[29] Tastan, Erdem O., Tuncer B. Edil, Craig H. Benson, and Ahmet H. Aydilek. "Stabilization of organic soils with fly ash." *Journal of geotechnical and Geoenvironmental Engineering* 137, no. 9 (2011): 819-833.

[30] Al-Azzawi, Dr Adel A., Khalida A. Daud, and Muhammed A. Abdul Sattar. "Effect of Silica Fume Addition on the Behavior of Silty-Clayey Soils." *Journal of Engineering and Development* 16, no. 1 (2012).

[31] Venu Gopal N. "Study of soil properties with silica fume as stabilizer and comparing the same with Rbi-81 and cost estimation." Post Graduate Diploma Thesis, Visvesvaraya Technological University, Belgaum(2009).

[32] Yusoff, Mohamed, Mohd Zuhri, Mohd Sapuan Salit, Napsiah Ismail, and Riza Wirawan. "Mechanical properties of short random oil palm fibre reinforced epoxy composites." *Sains Malaysiana* 39, no. 1 (2010): 87-92.

[33] Kozlowski R. " Handbook of natural fibers: processing and applications." vol. 2. UK: Cambridge(2011).

[34] Wei, Haibin, Yubo Jiao, and Hanbing Liu. "Effect of freeze–thaw cycles on mechanical property of silty clay modified by fly ash and crumb rubber." *Cold Regions Science and Technology* 116 (2015): 70-77.

[35] Hazirbaba, Kenan, and Hamza Gullu. "California Bearing Ratio improvement and freeze–thaw performance of fine-grained soils treated with geofiber and synthetic fluid." *Cold regions science and technology* 63, no. 1 (2010): 50-60.

[36] Güllü, Hamza, and Ali Khudir. "Effect of freeze–thaw cycles on unconfined compressive strength of fine-grained soil treated with jute fiber, steel fiber and lime." *Cold Regions Science and Technology* 106 (2014): 55-65.

[37] Aldaood, Abdulrahman, Marwen Bouasker, and Muzahim Al-Mukhtar. "Impact of freeze–thaw cycles on mechanical behaviour of lime stabilized gypseous soils." *Cold Regions Science and Technology* 99 (2014): 38-45.

[38] Hejazi, Sayyed Mahdi, Mohammad Sheikhzadeh, Sayyed Mahdi Abtahi, and Ali Zadhoush. "A simple review of soil reinforcement by using natural and synthetic fibers." *Construction and building materials* 30 (2012): 100-116.

[39] Modarres, Amir, and Yaser Mohammadi Nosoudy. "Clay stabilization using coal waste and lime—Technical and

environmental impacts." *Applied Clay Science* 116 (2015): 281-288.

[40] Marandi, S. M., M. H. Bagheripour, R. Rahgozar, and H. Zare. "Strength and ductility of randomly distributed palm fibers reinforced silty-sand soils." *American Journal of Applied Sciences* 5, no. 3 (2008): 209-220.

[41] Wang, Tian-liang, Yao-jun Liu, Han Yan, and Lei Xu. "An experimental study on the mechanical properties of silty soils under repeated freeze–thaw cycles." *Cold Regions Science and Technology* 112 (2015): 51-65.

[42] Cui, Zhen-Dong, Peng-Peng He, and Wei-Hao Yang. "Mechanical properties of a silty clay subjected to freezing–thawing." *Cold Regions Science and Technology* 98 (2014): 26-34.