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Utilization of a New by-Product Material for Soft Subgrade Soil Stabilization

Ahmed Ebrahim Abu El-Maaty Behiry

Civil Department, Engineering Faculty, Minufiya University, Shibeen El-Kom, Egypt
Email: maaty5000@yahoo.com

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Abstract

Silt soil cannot satisfy the requirements of highway construction because of its low strength. A new stabilizer from waste aluminum industry is developed (aluminum chops (AC) and wires (AW)) to evaluate the effect of reinforcing the subgrade with low-cost by-product materials on its mechanical and durability characteristics. Laboratory tests, including modified proctor compaction, compressive strength, splitting tensile strength, and CBR are developed to evaluate the mechanical properties. The durability properties are investigated by studying the influence of environmental conditions such as water immersion effect on compressive strength, mass loss after freezing and thawing cycles, water absorption by capillarity and wetting-drying durability. Moreover, a practical application about the base course thickness saving and its economically viable as well as correlations between mechanical properties are investigated. The results indicated that the aluminium fiber can effectively improve the mechanical and durability characteristics of silt subgrade where the increase in aluminum chops grade leads to improve the majority properties. While aluminum wires of 2.0 cm length produces reduction in CBR and compressive strength compared to smaller length. Stabilization with aluminium fiber has a remarkable influence in reducing the base course thickness (especially at using 4% of AW1.0) and increasing the construction cost saving (especially at using 1% of AW1.0).

Keywords

Subgrade Soil, Stabilization, By-Product Material, Durability, Construction Cost Saving

Subject Areas: **Civil Engineering, Industrial Engineering**

1. Introduction

The rapid and extensive development in Egypt 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 pro-

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grams. One of the typical problems in the construction of roads in Delta region as well as along the river Nile Valley and a lot of regions is ascribable to the presence of the 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 the form of raveling, cracking, rutting and formation of potholes and depressions in recently built highways and expressways [1]. The usual approach to soft subgrade stabilization 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 stabilization" using different types of stabilizers. The aim of soil stabilizers 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. Stabilization 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].

1.1. Basic Mechanism of Mechanically Stabilized Subgrade

The behavior of reinforced soil is analogous to reinforced concrete. Soil, like concrete, is weak in tension. The addition of reinforcing strips or mats in the horizontal direction compensates for the weak tensile strength of soil. An axial load on a sample of soft soil will result in a lateral expansion. Because of dilation, the lateral strain is more than one-half the axial strain. However, if inextensible horizontal reinforcing elements are placed within the soil mass, these reinforcements will prevent lateral strain because of friction between the reinforcing elements and the soil, and the behavior will be as if a lateral restraining force or load had been imposed on the element [4].

When stabilizing agents are added to soils a series of reactions will take place, including pozzolanic reaction, cation exchange, flocculation, carbonation, crystallization, and dissociation. These processes strengthen the particle bonding between grains and reduce the voids in soils. Thus, the engineering properties of soils such as strength and stiffness can be improved [1].

1.2. Utilization of Waste Material in Subgrade Stabilization

For a given project site, the existing subgrade may not always be strong, hence may require upgradation in terms of improvement of strength. In recent years, the use of cementitious material like Portland cement, hydraulic lime and lime-pozzolana mixes as stabilizer is quite common. On the other hand, 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. The surface of the flexible pavement reflects the deformation of subgrade and the subsequent layers due to repetition of traffic loads. So incorporation of fabric reinforcement within the subgrade may reduce such deformation [5].

The potential for using industrial by-products for stabilization of clayey soils such as blast furnace slag, sewage sludge ash, fly ash, and rich husk ash and cement kiln dust is promising and has been investigated. These waste materials have been studied in the past and indicated positive findings. Generally the composition of the additives or stabilizer influences the performance of the soil. At the present time, new types of weak soft subgrade reinforcements are made of steel or plastic. Related to steel reinforcement, the main concern is corrosion. This is not only a function of steel properties but also of environmental characteristics. Galvanizing, plastic coating or the utilization of stainless steel or aluminum strips is the solution. Plastic reinforcement process has more complex nature, where time and temperature dependency may play an important role in its behavior. The continuous industrial development has provided a large variety of high tensile strength and stiff reinforcement materials [6].

2. Literature Review

Steel fiber reinforcements found in concrete structures are also used for the reinforcement of soil-cement composites. In addition, steel fibers can improve the soil strength but this improvement is not compared with the case of using other types of fibers. However, Ghazavi and Roustaie (2010) [7] recommended that in cold climates, where soil is affected by freeze-thaw cycles, polypropylene fibers are preferable to steel fibers. Since, polypropylene fibers possess smaller unit weight than steel fibers. In other words, the former fibers decrease the sample volume increase more than steel fibers. To the knowledge of the author, the use of waste aluminum pieces as soft subgrade reinforcement has not been previously studied. Subsequently, this section presents a brief summary of previous investigations dealing with the durability and mechanical properties of soil stabilized with different types of waste and recycled materials.

Inferior soils are usually an unavoidable problem due to the extension of constructing projects and lack of desirable grounds, so civil engineers employ several techniques to amend them. Soil stabilizing by adding chemical materials is one of the most common methods for treating fine grained soils. Lime has been used to improve some mechanical and plastic properties of fine grained soils since many years ago. However, occurrence of some unfavorable phenomena such as reduction in failure strain, residual strength, and toughness of soil has been reported due to lime application. Soil reinforcing with discrete fibers has been developed as another soil improving method in recent years. Researches explained that inclusion of natural fibers like sisal and coconut fiber provides ductility as well as increase in strength of soil [8]. Some researchers utilized advantages of fiber reinforcing by use of waste or byproduct materials as an economical and eco friendly solution for improving engineering properties of weak soils. Some researchers mixed scrap tire rubber with sand. Others mixed waste rubber with clayey soil and also, some researchers reinforced light weight soil with waste fishing net. These researchers reported that fiber reinforcing causes increasing in unconfined compressive strength, ductility and toughness of soil samples [9]. Few studies have been carried out on effects of fiber inclusion on mechanical behavior of stabilized soil. They conducted some unconfined compressive, direct shear, swelling, and shrinkage tests on polypropylene fiber reinforced lime stabilized clayey soil. While lime stabilized samples showed a brittle failure pattern, fiber-lime specimens showed strain softening ductile failure. Also, inclusion of fiber with cement stabilized soil has shown increase in strength as well as rise in ductility and reduction in brittleness of stabilized material [10].

Seasonal freeze-thaw cycles are an important problem that specially affects mechanical properties of fine grained soils. Several researchers described the destructive effects of freeze-thaw cycles on soil engineering properties. Different techniques have been proposed to provide more durability for freeze-thaw exposed soils. Some rapid stabilizers for thawing soils were examined. Waste materials such as silica fume, fly ash, and red mud for modifying granular soils against harmful impacts of freeze-thaw cycles were used. Results showed that waste additives could improve the compressive strength and CBR values of stabilized soil and also, they can increase durability versus freeze-thaw cycles [10]. A new approach for improving soil characteristics against freeze-thaw condition is reinforcing soil with randomly oriented discrete fibers. Zaimoglu (2010) [11] studied freezing-thawing behavior of reinforced soil by unconfined compressive tests. His experiments disclosed efficacy of fiber reinforcing in increasing of strength and durability of fine grained soils. Mohammad *et al*. (2012) [12] investigated the effect of tire cord reinforcement of stabilized and unstabilized soil under freeze-thaw condition by unconfined compression. They obtained that the contribution of fiber in increasing strength is enhanced as the cycles of freeze-thaw increase. Durability index is directly related to the initial strength of the specimens before freeze-thaw. The best durability index belongs to specimens with 4% lime content and it increases by inclusion of fiber.

Ambika *et al*. (2013) [13] conceded that the soil-pondash mix gives better strength than the soil-rice husk ash mix. This is valid for both unsoaked and soaked CBR. Soil-rice husk ash may give poor soaked CBR value due to its expansive nature. But for soil-pondash-lime soaked CBR values are increased than other combinations. Hejazi *et al*. (2012) [14] reviewed the concept of using discrete randomly distributed fibers in soil, *i.e*. short fiber soil composites. In this way, both natural (coir, sisal, palm, jute, flax, straw, bamboo; and Cain) and synthetic fibers (Polypropylene PP, Polyethylene PE, Polyester PET, Nylon, Glass, Polyvinyl alcohol PVA; and Steel) that have been yet used to reinforce soil are investigated. In a simple process, fibers, typically at a dosage rate of 0.2% - 4% by weight, are added and mixed into silt, clay, sand, or lime and cement stabilized soil. All of the papers have generally shown that strength and stiffness of the composite soil is improved by fiber reinforcement. It can be concluded that the increase in strength and stiffness is reported to be a function of [14]:

1) Fiber characteristics; such as; aspect ratio, skin friction, weight reaction; and modulus of elasticity;

2) Soil characteristics; such as shape, particle size and gradation;

3) Test condition; such as; confining stress.

Authors conclude that lack of scientific standard, clumping and balling of fibers and adhesion of fiber to soil are the three major executive problems involved with the short composite soil production. Availability, economical benefits, easy to work and rapid to perform; and feasibility of using in all weather conditions are the general advantages of short fiber composite soils [15]. The technical benefits of using fibers in soil reinforcement include: preventing the formation of the tensile cracks, increasing hydraulic conductivity and liquefaction strength, reducing the thermal conductivity and weight of building materials, restraining the swelling tendency of expansive soils; and decreasing the soil brittleness. As well, a comprehensive literature review shows that using natural and/or synthetic fibers in geotechnical engineering is feasible in six fields including pavement layers (road construction), retaining walls, earthquake engineering, railway embankments, protection of slopes; and soil-foundation engineering. At final, it is emphasized that short fiber composite soil is still a relatively new technique in geotechnical projects as a mimics of the past [16].

3. Research Objective

Increasing the use of waste and recycled materials in earthwork projects has created the necessity a better understanding of the durability and strength performance of these materials against weathering conditions. The reinforcing soil using randomly distributed natural or plastic fibers has been used since ancient times. However, reinforcing of subgrade with discrete metallic fibers is still a relatively new technique in highways construction. Thus, as far as the author of this paper know the mechanical and durability properties of soft silt subgrade soil stabilized with waste aluminum pieces has not been previously studied or reported in literature. Subsequently, this research aims to:

1) Exploring the possibility of soft subgrade stabilising with aluminium fiber depending on the fiber shape, size and amount;

2) Evaluating the mechanical properties of the subgrade stabilized with aluminum chops and wires;

3) Exploring the effect of environmental conditions on the performance and durability of soil stabilized with this new material;

4) Establishing correlation between the trends with regard to fiber shape, size and ratio;

5) Investigating some practical applications for the aluminum fiber reinforcement especially its effect on the road construction cost savings based on the reduction in base course thickness.

4. Materials

4.1. Subgrade Soil

Soil samples of cohesive soil used in this research are collected from Shebin El-Kom city, as an example of the cohesive soil that covering a very wide area as Delta, Nile Vally, and many other regions that exists allover Egypt. The grain size distribution test result for natural soil is shown in **Figure 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**.

4.2. The Aluminum Chops

Aluminum chops used in this research is considered as waste material from the formation process of the aluminum sections. In this investigation, the aluminum chops are divided into two categories, first category (AC10) described as the aluminum chops that pass from sieve No.10 (2 mm) and retained on sieve No.20 (0.85 mm), second category (AC20) described as the aluminum chops that pass from sieve No.20 (0.85 mm) and retained on sieve No.40 (0.425 mm). The main reason for using aluminum is that this metal does not rust as steel fibers when exposed to water. **Figure 2(a)** shows the different aluminum chops used in this research.

4.3. The Aluminum Wires

In this research, aluminum wires of about 2 mm diameter are carved into small lengths of 0.5 cm (AW0.5), 1.0 cm (AW1.0), and 2.0 cm (AW2.0) and then used as a reinforcing material. **Figure 2(b)** shows the shape of the used aluminum wires used. These aluminum wires are a local type manufactured by the Egyptian cables company. As illustrated before the main reason for using aluminum is that this metal has a high resistance against corrosion so it can be described as a durable material. Chemical analysis for used wires or chops as taken from the manufacturer is illustrated in **Table 2**.

Table 1. Physical properties of the studied subgrade.

Test	Values
Natural Moisture Content (%)	4.63
Liquid Limit (%)	23.7
Plastic Limit (%)	21.1
Plasticity Index (%)	2.6
Specific Gravity	2.39
Maximum Dry Density (gm/cm^3)	1.794
Optimum Moisture Content (%)	18.0
AASHTO Classification Group	A-4
Unified Classification Group	ML
CBR Value (%)	10.56

Table 2. Chemical properties of the aluminum pieces.

Alloy	SI %	FE %	CU %	MN %	MG %	CR %	TI %	ZN %	AL %
Chops	0.25	0.40	0.05	0.05	0.05	0.0	0.03	0.05	99.5
Wires	0.75	0.35	0.10	0.10	0.50	0.10	0.10	0.10	97.9

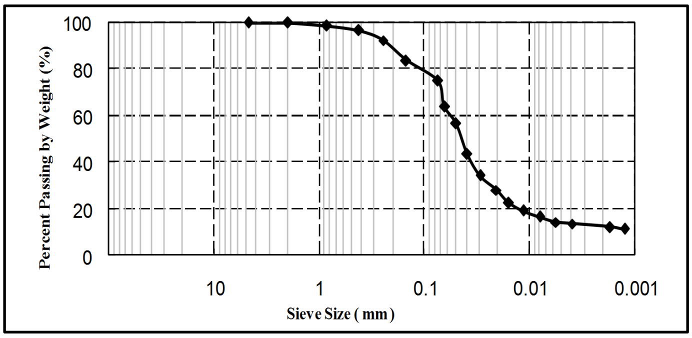

Figure 1. Grain size distribution curve for natural subgrade.

Figure 2. By-products from the aluminum industry.

5. Methodology

Comprehensive series of laboratory tests consisting of modified proctor compaction, unconfined compression strength, splitting tensile strength, California bearing ratio, mass loss due to freeze-thaw cycles, water resistance, water sorptivity and durability index after wetting-drying cycles are conducted on the selected silt soil with various percentages and combinations of stabilizers. The flow chart of the experimental study, design parameters and research activity is presented in **Figure 3**.

5.1. Specimens Preparation

The soil is dried in an oven at approximately ±105˚C for 24 h. Different percentage of the aluminum chops grades, or aluminum wires lengths have been added to soil. The percentages are chosen as 0.1%, 0.5%, 1%, and 4% by dry weight of soil. The optimum moisture content and dry density for soils with different percentages of stabilizers are determined by the modified proctor compaction test. In all mixtures, the required percent of water is added gradually to the mixture during the mixing process.

5.2. Proctor Compaction Test

The moisture content versus dry density 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 density (MDD) and optimum moisture content (OMC) for each reinforcement type and percentage are calculated. The maximum dry density and the optimum moisture content for the pure subgrade are 1.8 gm/cm^3 and 18% respectively.

5.3. California Bearing Ratio

The CBR test measures the shearing resistance and stability of a soil under controlled moisture and density conditions. California bearing ratio tests have performed accordance to ASTM D1883 on the compacted specimens at maximum dry density and optimum moisture content that obtained from the compaction test results.

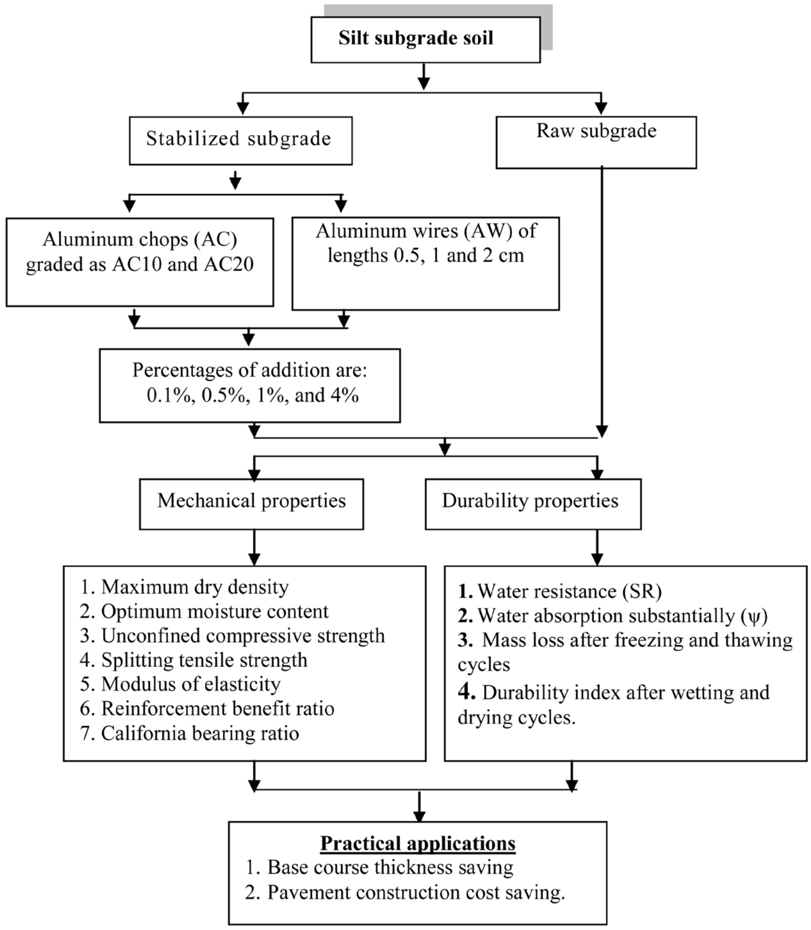

Figure 3. Research activity flow chart.

5.4. Unconfined Compressive and Splitting Tensile Strength

The unconfined compressive strength and indirect tensile strength of soil are considerably the most important designing parameters used for pavement design for city streets and highway construction. Cylindrical specimens (54 mm diameter and 135 mm length) are used for unconfined compressive strength (UCS) (ASTM D2166) and indirect tensile (splitting) strength tests (STS) (ASTM D2487). The specimens have prepared at their respective OMC and MDD. These specimens have compacted in five layers each with 25 blows in a metallic cylinder that coated with a thin layer of light tallow as a separator. The compressive and indirect tensile strengths are determined on a simple constant speed cross-head moving machine at a speed 1.14 mm/min. On the other hand, the subgrade modulus of elasticity (E) is determined with loading at a constant rate of deformation of 1.0 mm/min up to failure in an effort to obtain the stress-strain relationship at a deformation rate similar to that imposed by traffic on pavement subgrade [16].

5.5. Subgrade Durability Tests

Durability is the property of a geotechnical material that reflects its performance under freeze-thaw and wetting-drying cycles. Freeze-thaw tests should be conducted in areas that are subject to freezing conditions, such as cold regions, while wetting-drying cycles should be conducted in all geographic areas (Zhang and Tao, 2008 [17]). As the popularity of each group of subgrade stabilizers has increased through time, various organizations have been created to promote particular stabilizers and to establish procedures for their use. For example, the durability of cement-treated is determined using a sequence of freezing and thawing or wetting and drying cycles following (ASTM) D560 (Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures) or ASTM D559 (Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures). The durability of materials treated with fly ash, lime-fly ash, and lime, however, is determined using vacuum saturation according to ASTM C593 (Standard Specification for Fly Ash and Other Pozzolans for use with lime). Since these durability tests exhibit varying degrees of severity, where severity is defined as the loss of specimen strength, a comparative evaluation of the durability of different stabilizers is difficult at best [18] [19]. For the climatic and geographical conditions in Egypt, Egypt is considered one of the countries subjected to rainfall in some seasons as well as varying temperatures and fluctuating high water table. As such, an investigation of the wetting-drying, freezing and thawing and other durability evaluations of soil stabilized with aluminum chops and wires are essential to facilitating the incorporation of waste aluminum in ground-improvement projects.

5.5.1. Freezing and Thawing Cycles

Some specimens are 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 D560 [20]. The specimens were prepared form raw and stabilized soils and placed in a moist room having a temperature of 21˚C and a relative humidity of 70% for a period of one day. At the end of the storage in the moist room, water-saturated felt pads were placed between the specimens and the carriers, and the assembly was placed in a freezing cabinet having a constant temperature not warmer than −23˚C for 24 h. Then, the assembly was removed and placed in a moist room with a temperature of 21˚C and a relative humidity of 100% for a period of 23 h. At the end of this period, the specimens were removed and firm strokes were applied to the full height and width of the specimen with a wire scratch brush as an experimental maneuver leading to the mass loss. This process was called 1 cycle. Again the specimens were placed in the freezing cabinet and the same procedure was continued for 3 cycles. After 3 cycles, the test samples were dried in an oven at 110˚C ± 5˚C for 12 h. Considering ASTM D560-3, the corrected oven-dry mass of specimen (**CODM**) was calculated as follows:

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

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:

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

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.

5.5.2. Soaked Compressive Strength (SCS)

Cylindrical specimens (5.4 cm diameter and 13.5 cm height) as used for the unconfined compressive strength tests are examined for the effect of water immersion on compressive strength. The specimens were put into water containers stored in the curing room until testing for soaked compressive strength (SCS) after 7 days.

5.5.3. Water Absorption by Sorptivity

The experimental set-up for the sorptivity tests was prepared where the lower side of cylindrical specimens was immersed at a 5 mm constant head-water tank for a time (*t*) of 10 min and the quantity of water absorbed (*W*) was determined. The coefficient of water absorption by sorptivity (ψ) was then calculated by the following equation [3]:

$$\psi = \frac{W}{At^{0.5}} \tag{3}$$

where, *A* is the cross sectional area of the specimen.

5.5.4. Wetting and Drying Cycles

The cycles of wetting and drying were used to evaluate the strength performance and durability of the subgrade samples stabilized with AC and AW. The procedure used in this test is approximately similar to that presented in the ASTM specifications for tests with the same type of expectation regarding the number of cycles, the curing time and the soil loss. In brief, the specimens were air dried for 24 h at room temperature and then completely immersed in water for another 24 h. This process represented one cycle of wetting-drying, which requires 48 h. After completing the required cycles of wetting-drying, the specimens were tested for unconfined compressive strength. To better understand the effect of the wetting-drying cycles on the strength performance and durability of the stabilized specimens, the durability index (DI) of the stabilized specimens was considered. This index is determined by dividing the unconfined compressive strength of a specimen, after the desired number of wetting-drying cycles, by the UCS of an identical specimen without reinforcement after the same cycle number.

6. Results and Discussion

6.1. Compaction Characteristics

The variation of MDD and OMC with aluminum reinforcement percentage (ARP) is shown in **Figure 4** & **Figure 5**, respectively. Initially, it can be observed that the addition of AC or AW raises MDD and decreases OMC compared with the unreinforced subgrade. Moreover, the samples of subgrade reinforced with AC achieve higher MDD and lower OMC than samples reinforced with AW at all studied reinforcement percentages. The optimal reinforcement percentages according to MDD and OMC are 4.0% for AC and 1% for AW. For wire stabilization, the length of 1.0 cm (AW1.0) achieves higher MDD and lower OMC. For chops stabilization, AC20 achieves higher MDD and lower OMC. It can be explained that this behavior is the result of the occurrence of flocculation for the tested soil due to the addition aluminum pieces. Flocculation results in the stronger agglomeration of clay soil particles and blocks the voids between the fine soil particles. Subsequently, it causes a constraining of the water penetration inside the fine soil particles. The worst results is obtained at using AW2.0 as subgrade reinforcement where the behavior of the aluminum wires in the dry density may be due to the pieces of aluminum wire involved with soil particles are nested with each other. Hence with increasing the aluminum wires percentage more than 1.0% or increasing its length more than 1.0 cm, the MDD decreases due to the more flocculation in the soil sample but the OMC increases again to facilitate mixing and workability of the combination.

6.2. CBR Test

Figure 6 as well as **Table 3** presents the average CBR values of different aluminum reinforcement mixes. It is noticed that the CBR value increases enormously with aluminum pieces stabilization where the CBR of raw soil is about 10.56% increases to 35% by stabilizing with 4% AC20 or AW1.0. The strength offered by the compacted AC and AW samples is mainly due to the mobilization of frictional strength of the materials. With the increase in aluminum pieces content in the mixture, the quantity of formation increases, which binds the particles

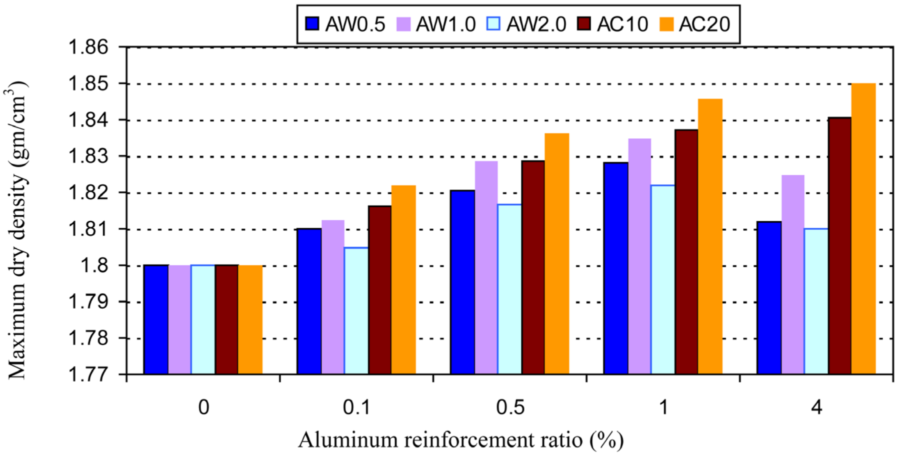

Figure 4. Effect of reinforcement content on MDD.

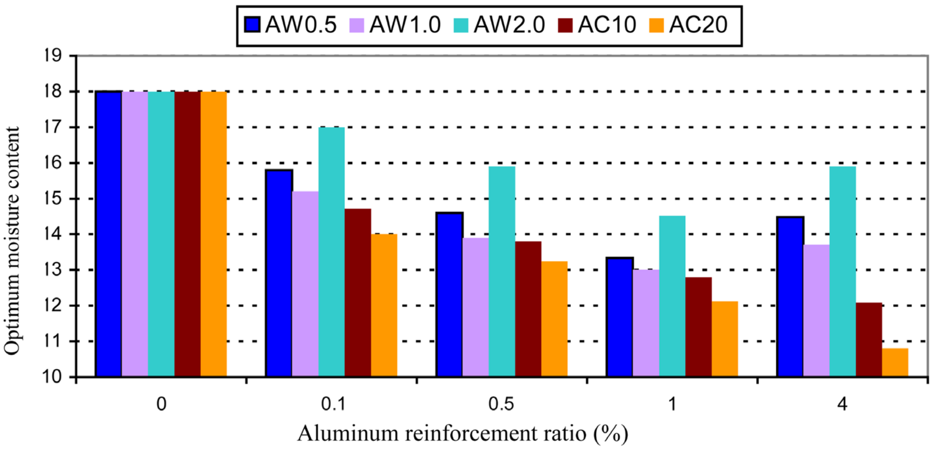

Figure 5. Effect of reinforcement content on OMC.

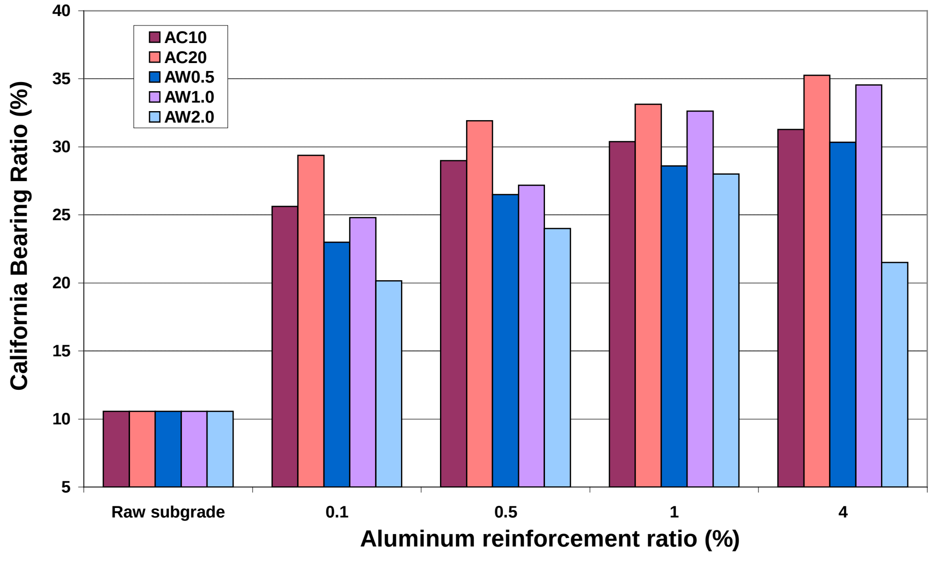

Figure 6. Effect of reinforcement content on CBR.

Table 3. Effect of aluminum reinforcement on the properties of silt subgrade.

Rein. type	ARP	E (kg/cm^2)	Absorption coefficient, ψ (%)	UCS (kg/cm^2)	SCS (kg/cm^2)	SR (%)	CBR	*R_{BR} (%)
AC10	0.0	79.5	10.5	2.64	1.32	50	10.56	-
	0.1	84.8	6.5	2.49	1.44	58	25.62	6.66
	0.5	99.3	5.2	2.99	1.97	66	29.0	24.9
	1.0	105.7	7.4	3.3	2.37	72	30.38	32.9
	4.0	113.8	8.6	3.55	2.84	80	31.28	43.1
AC20	0.0	79.5	10.5	2.64	1.32	50	10.56	-
	0.1	87.3	8.4	2.91	1.8	62	29.38	9.8
	0.5	105.9	6.8	3.53	2.471	70	31.91	33.2
	1.0	121.5	8.1	4.05	3.07	76	33.14	52.8
	4.0	132	9.2	4.4	3.74	85	35.26	66.0
AW0.5	0.0	79.5	10.5	2.64	1.32	50	10.56	-
	0.1	82.0	8.5	2.56	1.76	69	23.0	3.1
	0.5	93.6	7.2	3.12	2.4	77	26.5	17.7
	1.0	102.	5.3	3.42	2.83	83	28.61	28.3
	4.0	112.5	5.9	3.75	3.26	87	30.34	41.5
AW1.0	0.0	79.5	10.5	2.64	1.32	50	10.56	-
	0.1	95.1	9.0	3.17	2.25	71	24.8	19.6
	0.5	114.9	8.2	3.83	3.08	80.5	27.17	44.5
	1.0	126.3	6.3	4.2	3.69	87.9	32.64	58.86
	4.0	141.0	7.1	4.7	4.28	91	34.56	77.35

*R_{BR} (%): The subgrade modulus of elasticity increment ratio between reinforced and non-reinforced soil.

more effectively resulting in higher CBR value. On another hand, the reinforced soil with aluminum chops has higher CBR values than subgrade stabilized with aluminum wires at all studied contents. Moreover, AC20 performs better than AC10, while the influence of AW addition becomes more obvious with increasing the ARP where CBR value for AW1.0 and AW0.5 are about 34.56% and 30.34% respectively at ARP of 4%. A sudden drop in CBR value is observed in the case of AW2.0. Thus, it can be concluded that the usage of aluminum wires of 2.0 cm length provides inferior performance. Therefore, AW2.0 may not be used as a subgrde reinforcement of the remained tests of this study.

6.3. Unconfined Compressive Strength (UCS)

The unconfined compressive strength of subgrade soil reinforced with aluminum pieces is summarized in **Figure 7** and **Table 3** where the stress strain curves are plotted between the axial compressive stress (kg/cm^2) and the axial strain (mm), and then the unconfined compressive strength values for each percent of each additive are recorded. It is observed that UCS increases with increase in aluminum pieces content from 0.1% to 4.0%. In general, the aluminum reinforcement has a reasonable effect on increasing the compressive strength especially at using AC20 or AW1.0 with high percentages. AC20 produces higher UCS than AC10 while AW1.0 produces the highest UCS (4.70 kg/cm^2) at 4% content. These results confirm the results obtained from the influence of the aluminum reinforcement on CBR and dry density. This indicates that addition of AW or AC ranging from 0% to 4%, to subgrade soil is certainly advantageous in increasing the strength of stabilized mixes. Secondly, this addition may make the mix well graded, thus it increases the compacted density and hence the mechanical strength of the compacted mixture. It is also observed that the strength of compacted mixes increases with increasing the wires length or the chops grade.

The effect of the dry density after compaction due to different moisture contents and compaction effort on the UCS has been studied for raw soil and stabilized soil with 4% of AW1.0 because it achieves the highest UCS value. The compaction efforts are determined according to the Egyptian code of practice for urban and rural roads (ECP) [21] as 11, 33 and 66 cm·kg/cm^3 based on 10, 30 and 60 blows respectively. **Figure 8** shows that the UCS increases with the increase in the dry density where the relation is basically linear and may therefore be expressed as a law:

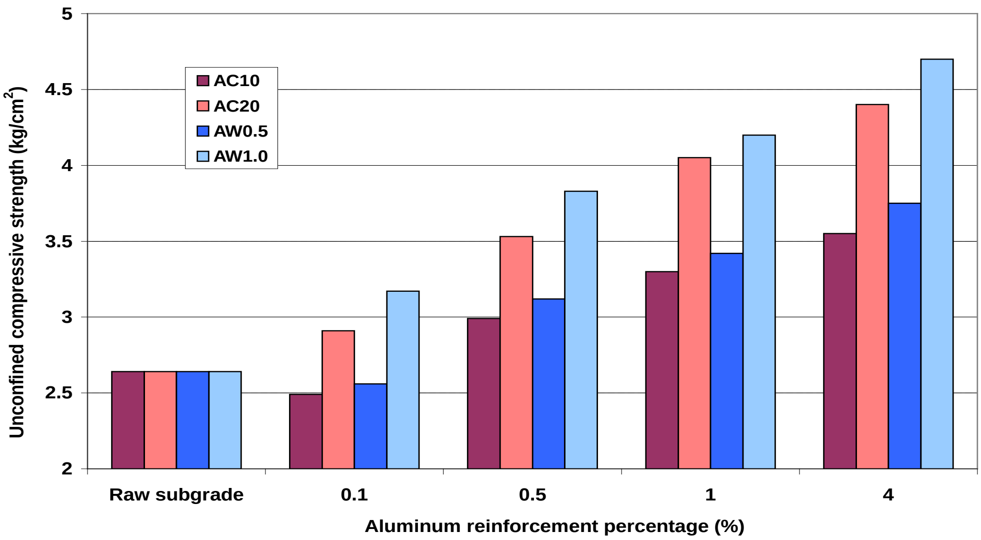

Figure 7. Effect of reinforcement content on UCS.

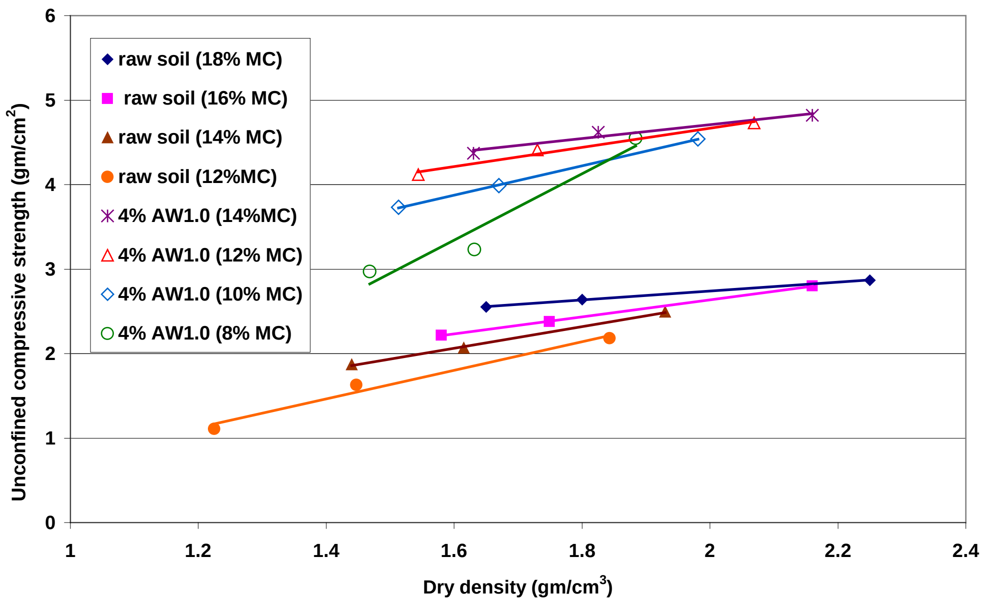

Figure 8. Influence of mixture dry density on UCS.

$$\mathbf{UCS} = \mathbf{K} + \mathbf{n}(\mathbf{DD}) \quad (4)$$

where **DD** is dry density (gm/cm^3); **K** is a constant; n is a dimensionless constant representing the tangent of the slop angle. In practice, the mixture density strongly depends on the degree of compaction where with the increase of the density, the UCS increases. As shown in **Table 4**, the slop of the curve (**n**) is a function of the moisture content (MC) where decreases with the increase in the moisture content for both stabilized and raw subgrades where values of n for stabilized soil are obviously higher than them for raw soil. In order to study the correlation between dry density and unconfined compressive strength, the data in **Figure 8** are represented in **Figure 9**. The following regression equations are obtained using gm and cm units:

For raw subgrade soil

$$\mathbf{UCS} = -\mathbf{1.5367}(\mathbf{DD})^2 + \mathbf{6.95}(\mathbf{DD}) - \mathbf{5} \quad (5)$$

For stabilized soil with 4% AW1.0

$$\mathbf{UCS} = -\mathbf{3.87}(\mathbf{DD})^2 + \mathbf{16.127}(\mathbf{DD}) - \mathbf{12} \tag{6}$$

The multiple R^2 for raw silt subgrade with moisture content from 12.0% to 18.0% is high ($R^2 = 0.9$). However, note that there is a moderate scatter for the regression equation of stabilized subgrade when its moisture content ranges from 8.0% to 12.0% ($R^2 = 0.713$).

6.4. Splitting Tensile Strength (STS)

Figure 10 presents the splitting tensile strength development where it is observed that using AW reinforcement realizes higher splitting tensile strength than using AC. The STS value increases with increasing the reinforcement content, where using 4.0% of AW1.0 produces 0.625 kg/cm^2. The addition of AW is more effective than AC where AW1.0 is moderately better than AW0.5. This may be because more wire length provides a horizontal reinforcing within the soil mass, these reinforcements prevent lateral strain due to the friction between the reinforcing elements and the soil, and the behavior will be as if a lateral restraining force or load had been imposed on the element. It is known that the use of high percentages of aluminum reinforcement, in certain cases, has some problems such as transport costs, practical problems of spreading and mixing these large quantities and increased water demand. Generally, these results agree with the other previously studied mechanical properties of stabilized subgrade with aluminum pieces.

6.5. Subgrade Modulus of Elasticity and Reinforcement Benefit Ratio

The stress stain curve is essentially linear up to $1/3$ of the strength. The subgrade modulus of elasticity (E) and the reinforcement benefit ratio (R_{BR}), that means the ratio of subgrade modulus of elasticity improvement due to aluminum reinforcement, are calculated and presented in **Table 3**. The effect of different reinforcements and their combinations on E values are similar to that observed in the case of strength. Initially, the aluminum reinforcement improves the modulus of elasticity of subgrad where with increasing the aluminum content the E value increases. Considerably higher value of E is obtained in case of AW1.0 followed by AC20 reinforcement. As shown in **Figure 11** as well as **Table 3**, with increasing the reinforcement content up to 1%, a rapid increase in R_{BR} is occurred while with increasing the reinforcement content more than 1% to 4%; a slight increase in R_{BR} is achieved. AW1.0 followed by AC20 is obtained as the best reinforcement types according to modulus of elasticity.

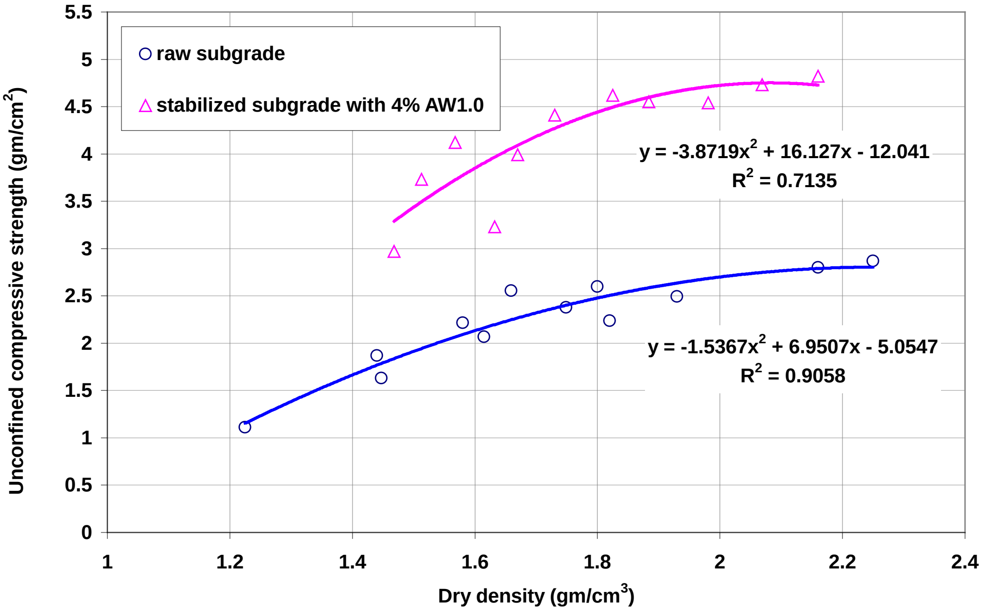

Figure 9. Correlations between mixture dry density and UCS.

Table 4. Effect of water content on the slop of the curve (n).

Raw subgrade		Stabilized subgrade with AW1.0	
MC (%)	slop of the curve (n)	MC (%)	slop of the curve (n)
12.0	1.73	8.0	3.79
14.0	1.27	10.0	1.73
16.0	1.0	12.0	1.16
18.0	0.525	14.0	0.85

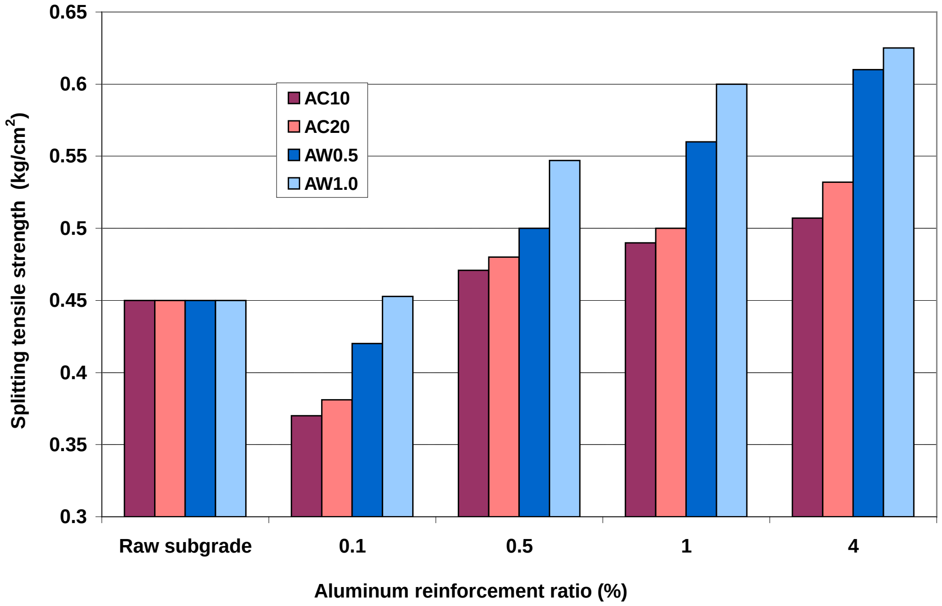

Figure 10. Effect of reinforcement content on STS.

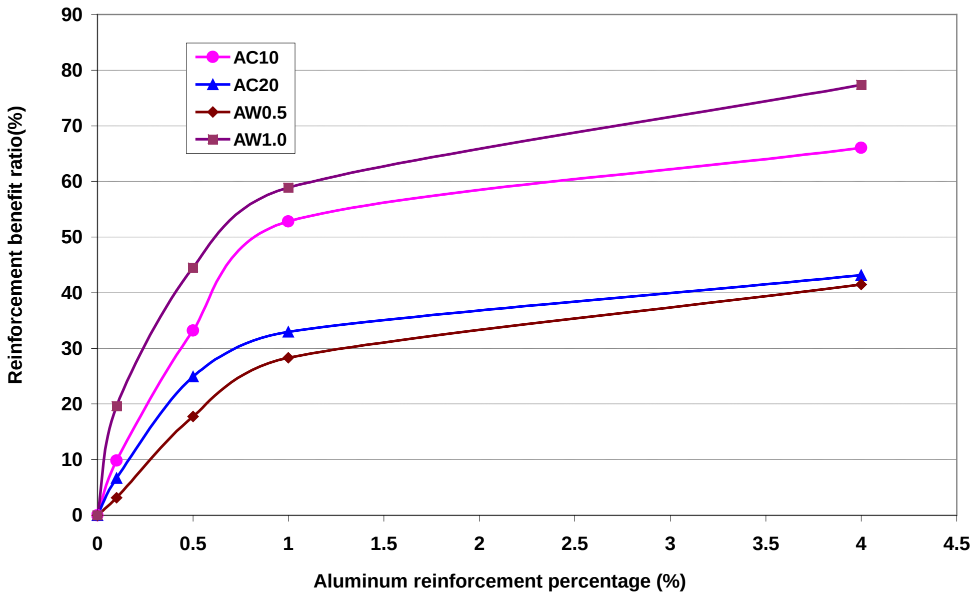

Figure 11. Effect of reinforcement content on R_{BR}.

6.6. Mass Loss after Freezing and Thawing Cycles

To investigate the effect of the aluminum reinforcement chops and wires on the durability behavior of the subgrade, mass losses are calculated after 3 freezing-thawing cycles. The variation of mass losses with the ARP is shown in **Figure 12** and provided in the following equations:

For AW1.0

$$\textbf{Mass loss}(\%) = \textbf{13.765}(\textbf{ARP}) - \textbf{0.1184} \ \left(\textbf{R}^2 = \textbf{0.97}\right) \quad (7)$$

For AW0.5

$$\textbf{Mass loss}(\%) = \textbf{16.58}(\textbf{ARP}) - \textbf{0.0847} \ \left(\textbf{R}^2 = \textbf{0.96}\right) \quad (8)$$

For AC20

$$\textbf{Mass loss}(\%) = \textbf{18.314}(\textbf{ARP}) - \textbf{0.0982} \ \left(\textbf{R}^2 = \textbf{0.91}\right) \quad (9)$$

For AC10

$$\textbf{Mass loss}(\%) = \textbf{18.744}(\textbf{ARP}) - \textbf{0.1088} \ \left(\textbf{R}^2 = \textbf{0.83}\right) \quad (10)$$

It can be seen that the addition of aluminum reinforcement into the soil decrease the mass loss of soil after the freezing-thawing cycles especially with the reinforcement content. At the end of the 3 freezing-thawing cycles, the most noteworthy effect of reinforcement was observed on the sample reinforced with AW1.0 as compared with the unreinforced sample as well as samples reinforced with AC. While the mass loss was around 27% for the unreinforced sample, the mass loss decreased up to 60% for the sample reinforced with 4.0% AW1.0. Moreover, with increasing the aluminum wires length or chops grade the mass loss decreases. In the literature it was reported that mass losses around 10% - 15% did not significantly affect the strength of soil closed to the surface at the end of the 3 freezing-thawing cycles (Chamberlain *et al.* [22]; Hassini [23]). Hence it can be concluded that the aluminum reinforcements causes the soil to exhibit more resistance against the freezing-thawing period in seasonally frozen areas.

6.7. Effect of Water Immersion on Compressive Strength

The effect of the 7 days water soaking on compressive strength (SCS) compared with the unconfined compressive strength is presented in **Figure 13** as well as **Table 3** in terms of strength ratio (SR) or soil water resistance expressed as (100 × SCS/UCS) It can be obtained that the SR value increases with the increase in aluminum reinforcement content. This may be due to the chance of water penetrating into the stabilized soil particles decreases with an increase in the waste aluminum ratio. On another hand, for similar dosages of stabilizer, the AW shows higher strength ratio than that of AC. Moreover, with increasing the aluminum chops grade or wires length the strength ratio increases. As shown in **Figure 13**, the subgrade strength ratio increases to be greater than 80% if the soil reinforced with AC20 by content more than about 2.25% or with AW0.5 by content more than about 0.65% or with AW1.0 by content more than about 0.5%.

6.8. Water Absorption

The coefficient of water absorption (ψ) is calculated according to Equation (1) for both AC and AW reinforcement as illustrated in **Figure 14** and **Table 3**. In general, the soil reinforcement is found to reduce the water absorption substantially where the stabilized subgrade with AC10 produces lower sorptivity than it if stabilized with AW up to reinforcement content of 0.5%. From reinforcement content of 0.5% to 4%, the AW shows lower water absorption than AC. The increase in aluminum chops grade or wires length seems to increase the sorptivity of reinforced soils. The positive effect of reducing the sorptivity of soils with aluminum stabilization can be attributed to filling of pore space in the soil and prevention of the reorientation and flocculation of soil particles which precluded formation of enlarged pores and cracks. These results confirm the discussed above about the influence of the aluminum reinforcement durability performance.

6.9. Durability Index (DI)

To better illustrate the effect of the addition of waste aluminum pieces on the enhancement of the durability for

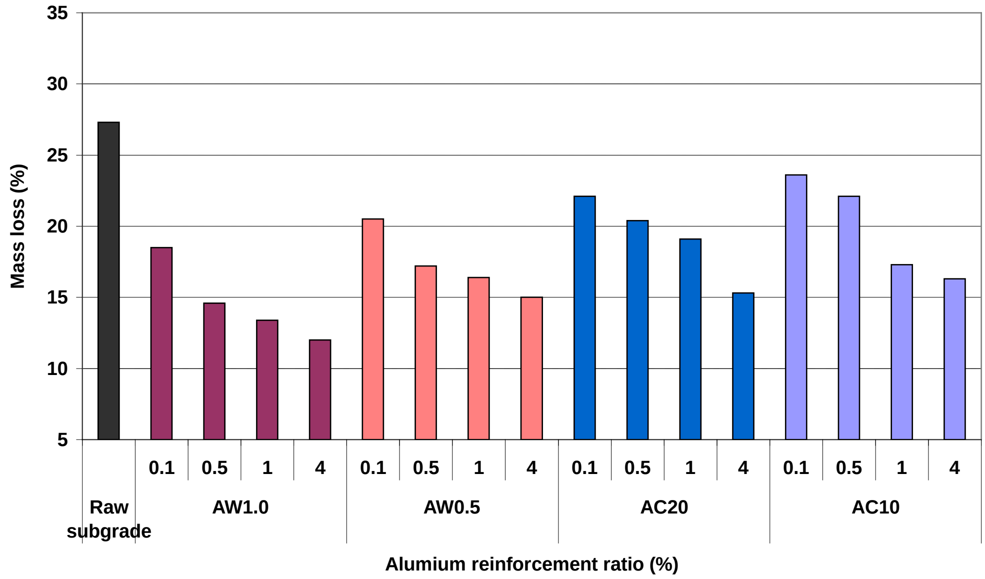

Figure 12. The variation of mass loss with aluminum ratio.

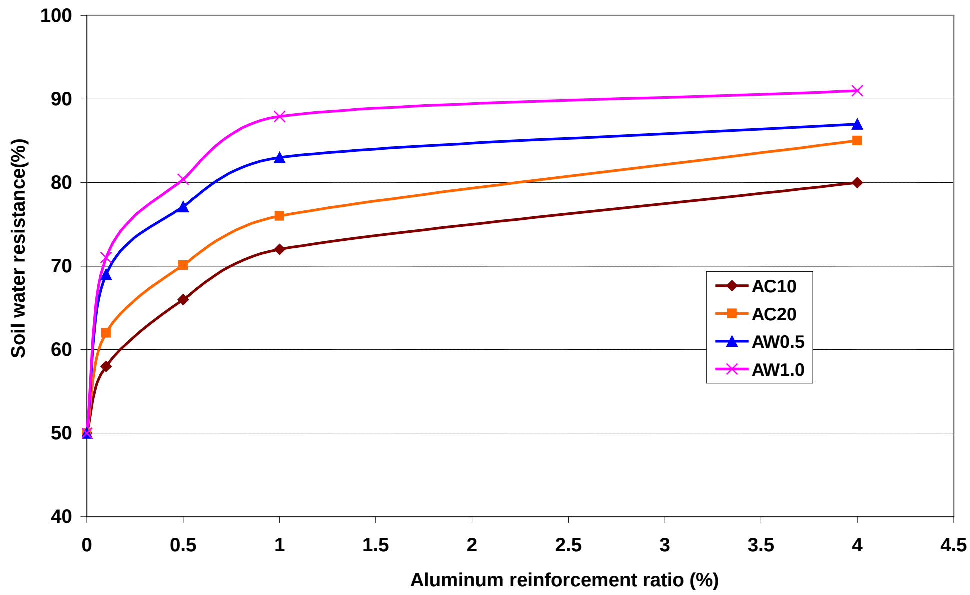

Figure 13. Effect of reinforcement content on SR.

the different wetting-drying cycles investigated, the relationship between the durability index and the aluminum ratio is determined and presented in **Figure 15** for (AW1.0) due to achieving best durability performance through the previous durability tests. Clearly, the increase in the AW1.0 ratio increases the durability index. This result can probably be attributed to the sufficient hardening which develops for the stabilized samples. Subsequently, the samples can resist the actions of the wetting-drying cycles. This hardening may be because the clay minerals flocculate around aluminum wires to form stronger blocks of clay fractions that help to delay the water distribution within the soil matrix. On another side, with increasing the number of wetting-drying cycles, the durability index decreases for ARP up to about 1.7%. For aluminum ratio more than 1.7%, the durability index for sample without cycling achieves the least DI value as obviously appears at 4%. Generally, it can be stated that soft clay soil, stabilized with aluminum wires reinforcement is durable against the actions of wetting-drying cycles where this durability encouragement obviously increases at higher reinforcement content.

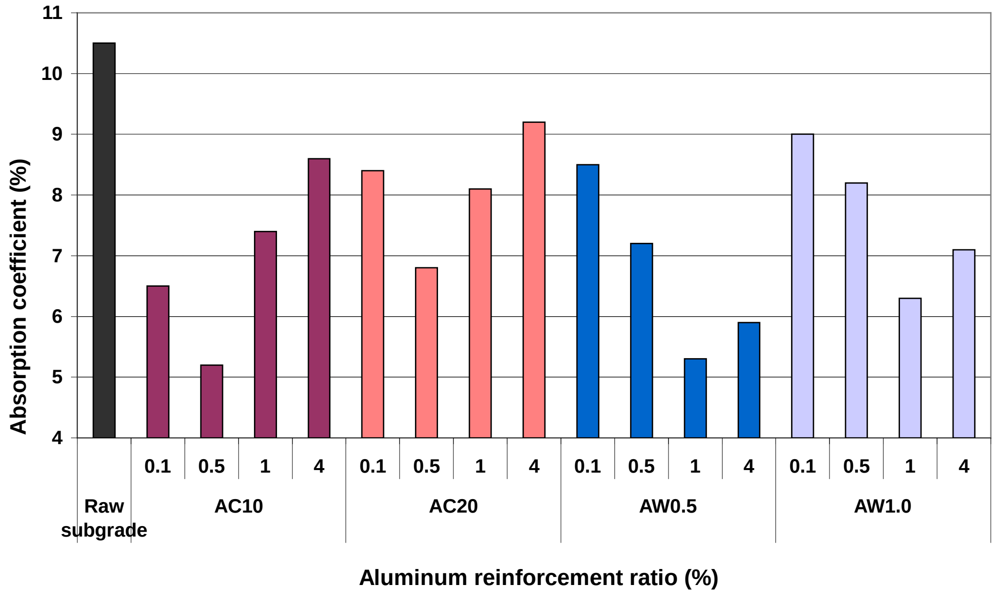

Figure 14. Effect of reinforcement content on absorption coefficient.

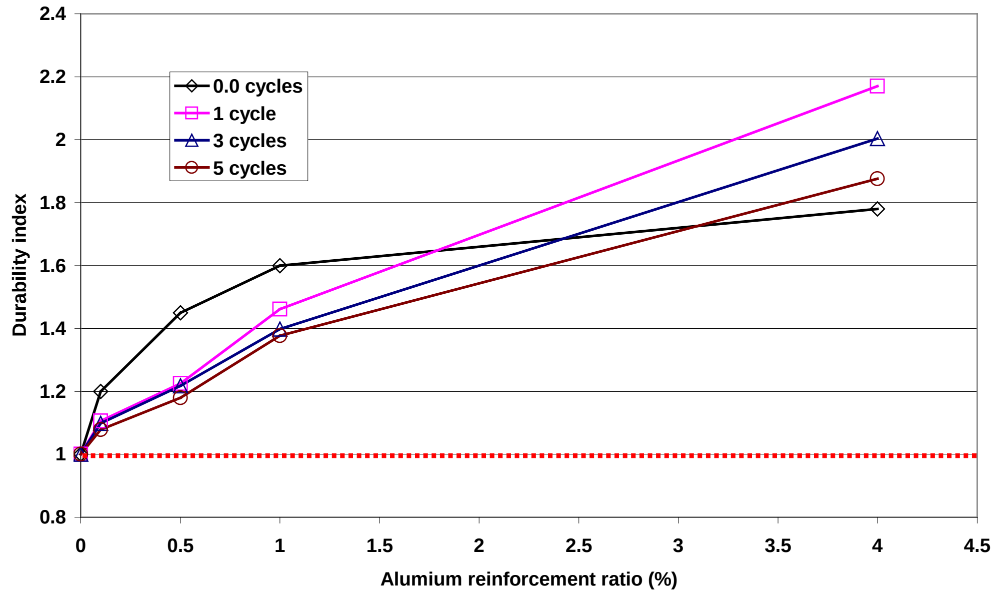

Figure 15. Effect of AW1.0 content on durability index.

7. Correlation between Mechanical Properties

The relationships between all mechanical properties such as CBR, compressive strength, STS and modulus of elasticity for stabilized subgrade soil with aluminum wires and aluminum chops using amounts of (0.1%, 0.5%, 1.0% and 4.0%) are illustrated in **Figures 16-19**. A linear relationship between CBR and compressive strength as well as between modulus of elasticity and compressive strength is obtained. Moreover, linear relationship between CBR and modulus of elasticity as well as between unconfined compressive strength and splitting tensile strength is achieved. It has been found that the relation is basically linear and may therefore be 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. The following relationships can be achieved:

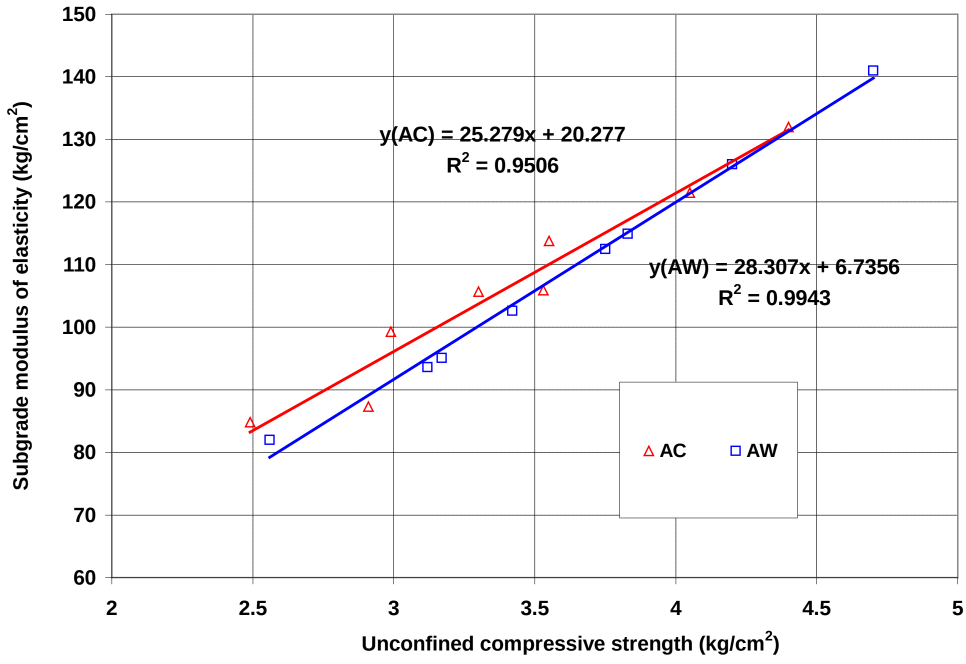

Figure 16. Correlation between E and compressive strength.

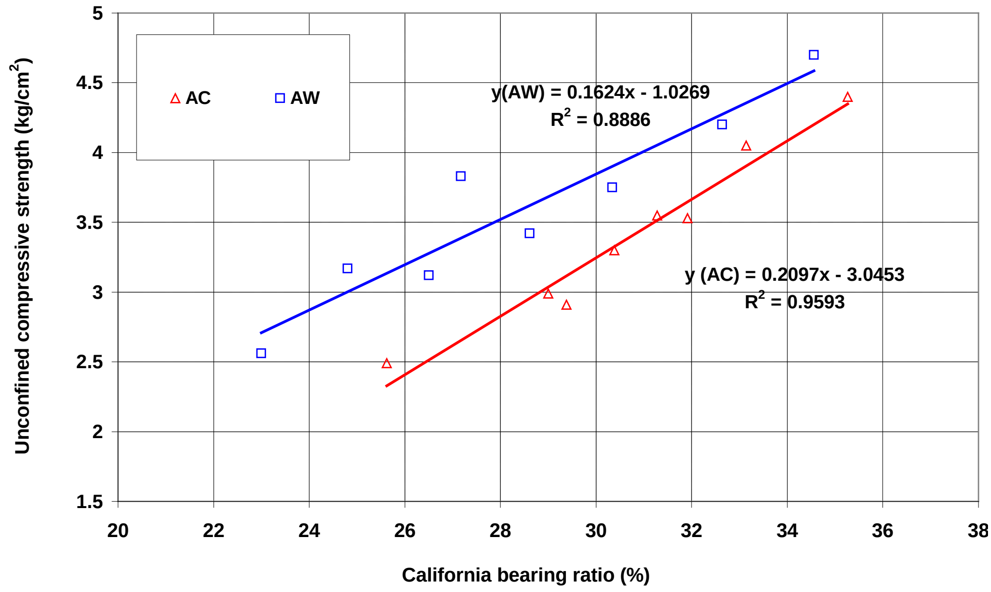

Figure 17. Correlation between compressive strength and CBR.

For aluminum wires (AW)

$$\mathbf{STS} = \mathbf{0.0999} \times (\mathbf{UCS}) + \mathbf{0.1784} \ (\mathbf{R}^2 = \mathbf{0.8371}) \quad (11)$$

$$\mathbf{UCS} = \mathbf{0.1624} \times (\mathbf{CBR}) - \mathbf{1.0269} \ (\mathbf{R}^2 = \mathbf{0.8886}) \quad (12)$$

$$\mathbf{CBR} = \mathbf{0.1926} \times (\mathbf{E}) + \mathbf{7.5614} \ (\mathbf{R}^2 = \mathbf{0.8873}) \quad (13)$$

$$\mathbf{E} = \mathbf{28.307} \times (\mathbf{UCS}) + \mathbf{6.7356} \ (\mathbf{R}^2 = \mathbf{0.9943}) \quad (14)$$

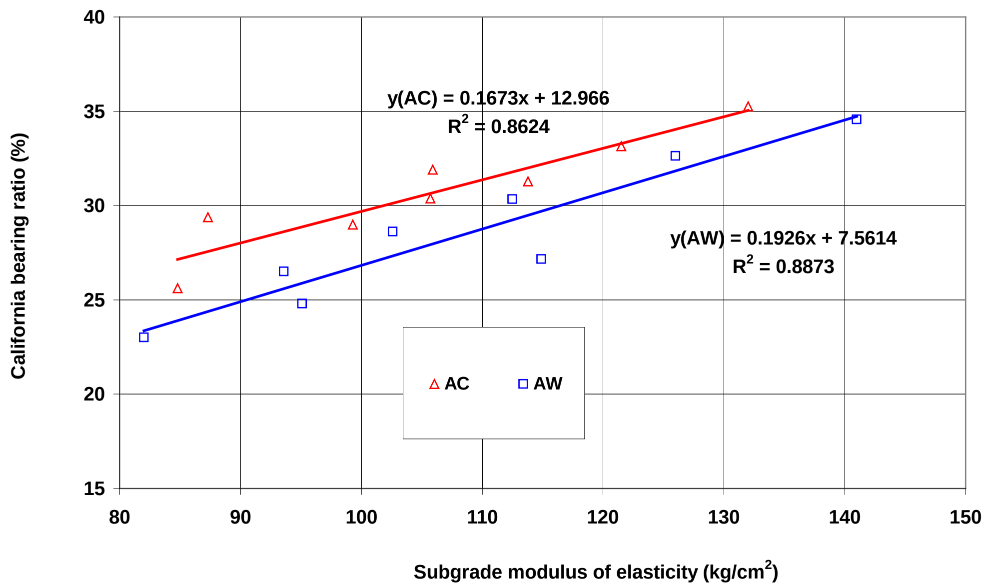

Figure 18. Correlation between CBR and modulus of elasticity.

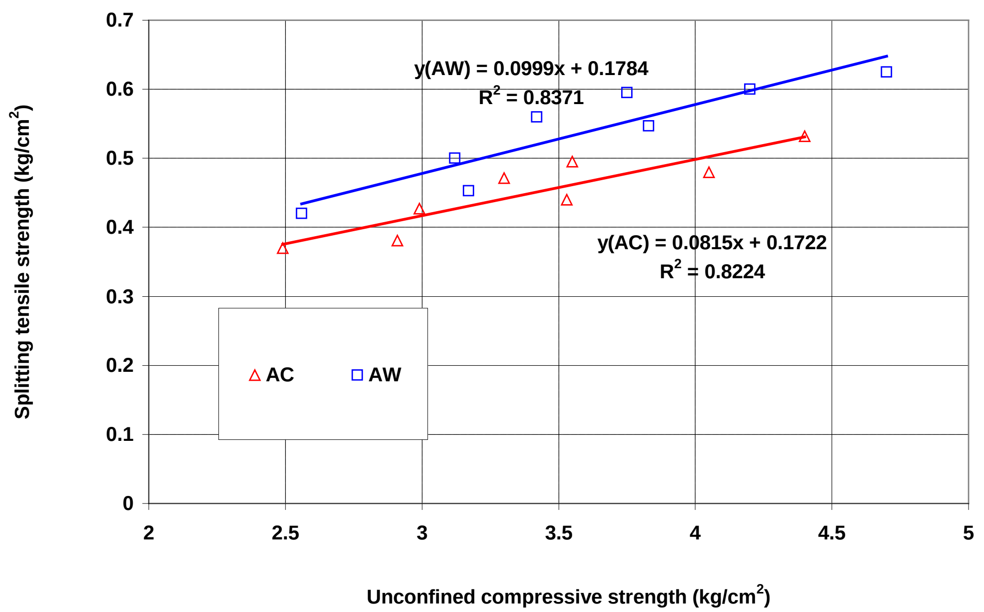

Figure 19. Correlation between compressive strength and STS.

For aluminum chops (AC)

$$\mathbf{STS} = \mathbf{0.0815} \times (\mathbf{UCS}) + \mathbf{0.1722} \ (\mathbf{R}^2 = \mathbf{0.8224}) \quad (15)$$

$$\mathbf{UCS} = \mathbf{0.2097} \times (\mathbf{CBR}) - \mathbf{3.0453} \ (\mathbf{R}^2 = \mathbf{0.9593}) \quad (16)$$

$$\mathbf{CBR} = \mathbf{0.1673} \times (\mathbf{E}) + \mathbf{12.966} \ (\mathbf{R}^2 = \mathbf{0.8624}) \quad (17)$$

$$\mathbf{E} = \mathbf{25.279} \times (\mathbf{UCS}) + \mathbf{20.277} \ (\mathbf{R}^2 = \mathbf{0.9506}) \quad (18)$$

According to the slope of the linear relations (n) for both AC and AW reinforcement, it can be obtained that the AW addition to the subgrade soil increases its sensitivity in calculating the following mechanical properties compared with AC: splitting tensile strength, CBR and modulus of elasticity. While the AC addition to the subgrade soil increases subgrade sensitivity in predicting only the unconfined compressive strength. The coefficient of correlation (R^2) for both AC and AW reinforcement are almost similar in all mechanical properties relationships. According to the coefficient of correlation and the direction of the relations, it can be concluded that the subgrade reinforcing with aluminum wires or aluminum chops are reasonable, sensible and credible. However, such a relationship can be applied strictly to the soil investigated in this study. The following equations obtain the correlations between the various results as function of aluminium fiber ratio; chop size (S) and wires length (L):

For aluminum wires (AW)

$$\mathbf{E} = \mathbf{0.7} \times \mathbf{CBR} + \mathbf{23} \times \mathbf{UCS} + \mathbf{0.185} \times \mathbf{ARP} + \mathbf{4.2} \times \mathbf{L} \ \left(R^2 = 0.91\right) \tag{19}$$

For aluminum chops (AC)

$$\mathbf{E} = \mathbf{4.26} \times \mathbf{CBR} - \mathbf{8.65} \times \mathbf{UCS} + \mathbf{4.26} \times \mathbf{ARP} - \mathbf{2.3} \times \mathbf{S} \ \left(R^2 = 0.87\right) \tag{20}$$

where, all units using kg and cm excl the chops size (S) that measured by mm.

8. Practical Applications

8.1. Saving in Base Course Thickness

Strength of subgrade affects the thickness of pavement layers placed over it. Stronger subgrade results in reduction in design thickness of the pavement layers placed over the subgrade. Developed stabilized soils can be used in the construction of low cost houses and road infrastructure. The road construction cost savings are based on the savings or reduction in base course thickness. Past researchers have attempted using waste materials, such as industrial waste, flyash, waste glass, bottom ash, waste plastic, pumice waste in the subgrade (Prased, *et al*., 2011 [24]; Davidovic, *et al*., 2012 [25]; Rao & Pothal 2009 [26]; Saltan *et al*., 2011 [27]). They found that lower thickness is being achieved by using those waste materials by increasing strength.

To investigate the effect of Egyptian subgrade soil reinforcement with aluminum industry waste on the saving in base coarse thickness, pavement design software is used (strDesign) which based on the AASHTO pavement design procedure. A standard single-axle load of 18,000 Ib with ESAL of 4.6 × 106, reliability of 90% and standard deviation of 0.45 are considered according to Egyptian Code of Practice for urban and rural roads [21]. For subgrade CBR higher than 9%, a typical highway cross section is supposed as shown in **Figure 20**. **Table 5** summarizes the effect of aluminum reinforcement on the reducing of base thickness where the base course reduction (BCR) is expressed as saving the reinforced base thickness compared to unreinforced section. A great influence for the subgrade stabilized with aluminum pieces is observed in decreasing the base course thickness. Using 4% of AW1.0 achieves the greatest effect where the base course thickness of 25 cm can be reduced to 16.2 cm (BCR = 35%). Moreover, the raw section of 25 cm base thickness can be reduced to 17.3 cm (BCR = 31.4%) if the subgrade reinforced with 4% of AC20. Furthermore, using 4% of AC10 provides BCR of 28% while using 4% of AW0.5 achieves BCR of 25.7%.

8.2. The Economically Viable

In order to effectively evaluate the benefits of subgrade reinforcing with aluminium fiber, the cost analysis should be performed to determine the cost-benefits. The construction cost savings are based on the savings in reduction of base course thickness. The cost benefits of reinforced pavements are not limited to reduce the materials and construction costs but also the pavement maintenance costs. The construction cost saving (CCS) for highways are determined according the following equation:

$$\mathbf{CCS/area} = \mathbf{CBA} \times \left(\mathbf{ZU.} - \mathbf{ZR.}\ \right) - \mathbf{CAF} \tag{21}$$

where,

CBA: Cost of base course aggregate including transit cost (LE/m^3);

ZR: Thickness of base layer after stabilization (m);

ZU: Thickness of base layer before stabilization (m);

CAF: Cost of aluminum fiber including installation and flipping (LE/m^2) considering the thickness of the stabilized soil is 0.25 m and the natural dry density is 1.1 (t/m^3).

Table 5. Effect of stabilized subgrade on base thickness.

Can reduce to — If reinforced with

Unreinforced Thickness (cm)	Reinforced Thickness (cm)	Type	Addition ratio (%)	BCR (%)	Cost saving (CCS) (LE/m^2)	CCS for road 1 km × 7.5 m (LE)
25	18.4 16.2	AW1.0	0.1 4.0	26.4 35.0	1.775 −1.45	13312.5 −10,875
25	19.5 17.3	AC20	0.1 4.0	22.5 31.4	1.1 −2.0	8250 −15262.5
25	20.0 18.0	AC10	0.1 4.0	20.3 28.0	0.875 −2.35	6562.5 −17,625
25	21.0 18.6	AW0.5	0.1 4.0	17.2 25.7	0.425 −2.62	3187.5 −19,650

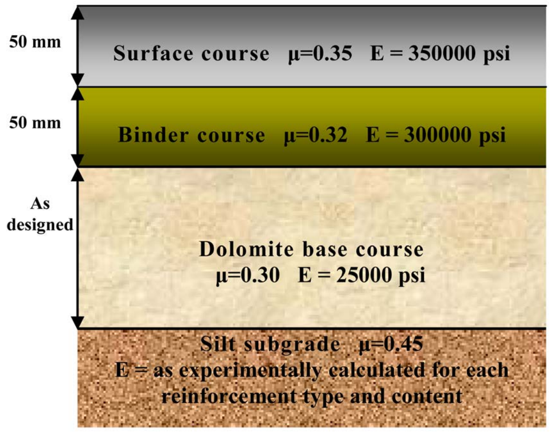

Figure 20. Typical highway cross section.

In this study the cubic meter cost of limestone base aggregate including transit cost and compaction can be consider 45 LE/m^3. The cost of aluminium chops or wires that considered as by-product material is about 0.50 LE/kg. From the above equation, CCS for reinforced pavement section can be estimated. The negative value of cost saving means that the base thickness reduction of reinforced section doesn't compensate the cost of aluminum reinforcement while for a long time; the cost saving for reinforced section can be appeared clearly due to the reduction in maintenance costs. Table 5 shows the CCS for one square meter and for a roadway section of 1 km length and 7.5 m width. It can be concluded that adding ARP of 4% is a useless economically in the stage of pavement construction. While adding ARP of 1% is economically feasible especially at using AW1.0.

9. Conclusions

This study presents the characteristics of fine grained subgrade soils stabilized with randomly distributed aluminum chops (AC) as well as wires (AW) as a new material in reinforcing soil. The effects of environmental conditions, referred to as freeze-thaw and wet-dry cycles, on the performance, durability, and strength of the stabilized soil were investigated in this study. Based on findings and results, the following conclusions can be drawn:

1) Subgrade aluminum reinforcement enhances mechanical and durability characteristics. The potential benefit of is found to depend on shape, size and amount of aluminium fiber. Aluminum chops especially AC20 shows higher dry density, higher CBR and lower moisture content. AW1.0 produces higher compressive strength, splitting tensile strength and modulus of elasticity.

2) The increase in aluminum chops grade leads to increase the majority of mechanical and durability proper-

ties. For aluminum wires, length of 2.0 cm produces reduction in CBR and UCS compared to smaller length.

3) For the environmental effects on the durability properties, the aluminum reinforcement fiber reduces the water absorption and increase water resistance substantially. The AC addition up to 0.5% produces lower sorptivity, after that the AW achieves lower water absorption than AC. While the mass loss is around 27% for the raw sample and decreases up to 60% for the sample stabilized with 4.0% AW1.0.

4) With increasing the aluminum wires length or chops grade the mass loss decreases and the soil water resistance increases. The aluminum fiber provides more resistance against the freezing-thawing period in seasonally frozen areas. Moreover, soft silt soil stabilized with AW is durable against the actions of wetting-drying cycles where this durability encouragement obviously increases at higher reinforcement content.

5) A linear relationships between the mechanical properties are obtained, where the addition of AW to the subgrade soil increases its sensitivity in calculating the each splitting tensile strength, CBR and modulus of elasticity. While the addition of AC increases subgrade sensitivity in predicting only the UCS.

6) Studying the practical viability proves that the subgrade stabilized with aluminum pieces has a remarkable influence in reducing the base course thickness (especially at using 4% of AW1.0) and subsequently increasing the construction cost saving (especially at using 1% of AW1.0).

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