Stabilized soil - new material for road construction

Kateryna Krayushkina¹, Olena Oliynyk¹
¹National Aviation University, 1, Komarova ave., 03680, Kyiv, Ukraine
E-mail: ekrayushkina15@ukr.net

Abstract. Ukraine's social and economic development and its integration into the global community largely depend on the development of transport infrastructure, in particular, on the level of availability of roads. Exactly by development of highways the way out of the world economic crisis started for many countries. Thus, the USA, Germany, Japan, which once identified the development of the road network among the main priorities of economic policy, as a result received not only a developed segment of transport infrastructure, but also stimulated economic growth and achieved positive results in solving the employment problems. Among the urgent tasks of technical progress in road construction, the creation of technologies that will improve the condition of soil and allow reuse. It is known [4], that the soil is used for the arrangement of subgrade and road foundation, as well as of basic pavement layers, the strength and stability of which affect the riding quality parameters of the road - strength and evenness. The duration of construction and repair of roads depends on the volume of earth works.

1. Introduction
Manufacturing of road design articles and engineering equipment of highways - supports for road signs, finishing of stopping areas, resting places which have high values of strength and water resistance will increase the traffic safety level and the modern aesthetics of transportation routes.

It is known [5] that the soil means various rocks in a wide range of their composition and genesis. V.M. Bezruk [1] divides soils into three classes:
  I - soils with solid rigid crystallization bonds (magmatic, metamorphic and sedimentary rocks of different strength).
  II - soils without rigid bonds between separate grains (particles) - sedimentary, coarse, sandy and clayey rocks;
  III - artificial soils without rigid bonds and with rigid bonds- production wastes, crushing rocks).

In road construction, class 2 soils without rigid bonds are used, and it is necessary to strengthen them.

Strengthening of soils is a set of measures aimed at increasing the mechanical strength, density, water and frost resistance properties. It includes a number of consecutive technological operations providing, as a result of active influence of additives of binders and other substances on soil, high integrity, durability and long-term stability both in dry and water-saturated condition.

Scientific research in the field of soil strengthening began in the 20-30 years of last century with the use of bitumen, lime, cement, and later – of synthetic resins as binders [2].

As a result of many years of laboratory research and versatile studies in production conditions, a number of very diverse methods of soil strengthening have been developed and are widely used in practice.
One of the most widespread methods is the strengthening of soils with mineral binders in the form of cement or lime, characterized by the formation of crystallization structure. This structure is formed as a result of irrigating the crystals of a new solid phase that arises from a supersaturated solution, as is the case, for example, with hydration hardening of mineral binder materials.

Soil strengthening methods are constantly being improved in the direction of improving their structural and mechanical properties. In the process of development of various methods of soil strengthening, they were improved, and at the same time the new effective solutions to significantly improve their structural and mechanical properties were found. The following was established and confirmed by many years of observations in production conditions: when strengthening the soils with two different binders that are characterized by quite different but non-antagonistic properties and structure, they gain increased shear, frost and temperature resistance and, if necessary, can be less rigid and more deformable materials.

The most common method in the practice of road construction was the method of strengthening the soil with cement in combination with calcium chloride, caustic and sodium sulphide [2].

Especially widespread in the practice of road construction is a complex method of soils stabilization with cement in combination with organic additives [3]. This method was developed by V.M. Bezruk and his students. It helps to obtain optimal indicators of stabilized soil, which provide a long service life of the structural layer in the road structure. Bituminous emulsions and pastes, cutback bitumen, crude highly resinous oil and foamed bitumen have been used as organic additives in recent years.

In the practice of road construction, to improve the properties of soil cement, various surfactants are used; they are introduced into the mixture for plasticization and subsequent hydrophobicity of the material formed.

The effectiveness of additives depends on the type of soil, its chemical and mineralogical composition, type of additive and its quantity.

Improved design characteristics and physical and mechanical properties of stabilized soils can be achieved by introducing into the mixture of various synthetic materials in the form of strips or threads. Small scope of researches in this direction allowed to establish that introduction of reinforcement made of synthetic materials into cement soil positively influences its physical and mechanical properties and design characteristics. Cement content of the mixture is of great importance in this case. Characteristically, the compressive strength of samples and their frost resistance increase when introducing the synthetic materials.

When cement is stabilized with fine one-dimensional sands and sand mixtures, the cement consumption rate is high enough to ensure the required strength characteristics of the material, due to the increase in specific surface area of the material. Improvement of the quality of the material is possible by introducing various additives that form an additional structure in it which is common with the structure of the binder. Fuel ashes, slags and ash-and-slag mixtures, which can be simultaneously granulometric and active additives, are quite effective in this respect [4].

The best performance at stabilization of bound soil is obtained by using slaked or ground quicklime as a binder. Clayey part of soil plays a role of a kind of hydraulic additive in relation to lime. As a result, the lime, which is an air binder form, gains the properties of a hydraulic binder.

The most advanced method of soil strengthening is its stabilization, i.e. active influence on the clay-colloid part of the soil, which is the most sensitive to binders that are applied to the soil.

The stabilizer is an active substance, usually of polymeric origin, which is introduced into the soil in micro-doses and improves its building properties.

Stabilization of the soil is a set of measures aimed at providing the soil with a stable condition, constancy, preservation of unchanged properties with the help of stabilizer.

Prof. N.N. Filatov first formulated the basic principle of soil stabilization - the impact on highly dispersed part of the soil to fundamentally change the physical and mechanical properties in general. Therefore improvement of soil properties is possible only on the basis of studying the properties and composition of their finely dispersed part - absorbing complex. Correctly using the adsorption ability
of the soil, actively influencing its finely dispersed part with additives of various substances, it is possible to build such road pavement that meet technical requirements.

At the same time, there are two main requirements for stabilizing the soils used for the construction of road foundations and pavements. Firstly, the soil, after the end of hardening and structural formation period, should gain such a degree of stability and irreversible viscosity between the particles that provides reliable resistance to external loads without deformation (deflection and shear) which exceeds the permissible limits. Secondly, it must withstand for a long time the stress arising from the external environment, for example, swelling during humidification and freezing, preserve the structure it has gained during long-term humidification, temperature rise, etc. [5].

The strength of stabilized soil and its resistance to natural factors required to meet the above requirements may vary depending on the intensity of traffic and axle loads of cars and local natural conditions. This indicates the need for a differentiated approach in assessing the strength and deformation properties of stabilized soil.

2. Research of the roads state

The authors from the National Aviation University (NAU), the Department of Interior Design, have conducted extensive studies to determine the impact of such stabilizers on the most common soils in Ukraine (heavy dusty loams, light dusty loams, loamy sands and other): Rodbond EH - 1 (manufacture of the USA) RRP-235 Special - Reynolds and Rod Packer (manufacture of Germany and Canada) Rodbon SPP (manufacture of RSA and Russia); stabilizers GRB-1, GRB-2, GRB-3, GRB-4, GRB-5 (manufacture of the Institute of high-molecular binders of the National Academy of Sciences (NAS) of Ukraine); stabilizer SG (manufacture of the NAS of Ukraine); stabilizer Soilac (manufacture of company Soilworks of the USA) hydrophobic liquids ГКЖ-II, Б, ГКЖ-12, КЖ-94 (manufacture of Zaporizhia joint-stock company "Krempipolymer") soil stabilizer Perma-Zyme 11x (manufacture of the USA); liquid glass; calcium chloride (CaCl₂), Open Company "Dnipro Association - K" enzyme stabilizer Roadzyme. Stabilizers are recommended for use in the form of diluted aqueous solution.

The results of studies have shown that the best indicators of strength and water resistance can be obtained by using a complex stabilizer consisting of polymeric substance, binders and aggregate). Reinforcing additives in the form of nanofibers are used as aggregate. The combination of different substances in a single composition allows to obtain a stabilized soil with increased strength, moisture and frost resistance properties.

Also, the use of integrated soil stabilization can solve the following problems:

- Expansion of the types of soils that are suitable for stabilization and longer use in transport facilities (acidic, humus, salted, overwetted soils);
- prolongation of the construction season due to the possibility of processing the overwetted soils and works fulfillment at adverse temperatures;
- increased deformability;
- expansion of application areas at the arrangement of road foundations and pavements and at manufacturing the road design objects on the roads of different categories in all road and climatic zones of Ukraine.

On the basis of the performed studies of NAU jointly with the Institute of Chemistry and Oil Chemistry of the National Academy of Sciences of Ukraine, the design of complex stabilizers on the basis of polymeric high-molecular substance with addition of inorganic binder, basalt aggregate for such types of soils were developed: KGC -1 - for loamy soils (dusty loams). KGC -2 - for sandy soils (sandy loamy sands). The developed compositions of stabilizers differ by the content of polymer and aggregate.

When using loamy soils in KGC -1, the content of high molecular weight polymer ranges from 10-30% by weight and of basalt aggregate - 25-45% by weight. To stabilize sandy and loamy sandy soils in KGC -2, the content of high molecular polymer is 20-50% by weight, and of basalt nano-aggregate - 20-30% by weight.

As inorganic binder, it is possible to use Portland cement of PC -300- PC -400 grade or quicklime.
The purpose of the work was to solve the assigned task:
- designing of soil compositions with complex stabilizers KGC -1 and KGC -2;
- determination of the optimal cost of these complex stabilizers for soil strengthening;
- determination of physical and mechanical properties of stabilized soil by additives KGC -1 and KGC -2;
- determination of durability of design objects made of stabilized soil.

Materials for study. For solving these tasks, the samples of different soils were taken for determination of the effect of mineralogical composition, humus substances and acidity of the environment on the properties of stabilized soil. Soils are represented by loamy sand (sample №1) and heavy dusty loam (sample №2) with different specific surface.

The study consisted in comparing the physical and mechanical properties of soils with the addition of stabilizers KGC -1 and KGC -2 in the amount of 5, 10, 14 % by weight of soil. From these mixtures at optimal humidity test cylinder samples and test beam samples were formed. The samples were put into special sealed chamber (in humid conditions) - over a vessel with water for 90 days and tested to determine these characteristics on the 90th day in a water-saturated state [6].

Methodology and results of the study. Characteristics of strengthened soil were determined according to standards [7].

Compressive strength was determined on test cylinder samples using a hydraulic press with a piston free move speed of 3 mm / min.

Tensile strength at bending was determined on test beam samples using the testing device MII -100 at a temperature of +20°C and a strain rate of 3 mm/min.

Freeze resistance tests were performed on three samples of each composition after curing for 90 days. After complete water saturation, the samples were alternately frozen for four hours and thawed. The number of freeze-thaw cycles was 5, 10, 15.

The freezing temperature was -18°C.

The modulus of elasticity of the samples was determined using a pendulum test device at a temperature of +20°C and the duration of the loading 0.1 s.

Durability was determined by the calculation method according by the degradation model which determines the relationship between the reliability of the element and its lifetime.

3. Results of study
Determination of physical and physical and mechanical properties of selected soil samples are in the tables 1-2.

| Type of soil | Stabilizer content, % by weight | Properties |
|--------------|-------------------------------|------------|
|              | Stabilizer content, % by weight | Particle density, g/cm³ | Density of mixture skeleton, g/cm³ | Optimal soil moisture at standard compaction, % | Yield strength Wh/Ph, % | Rolling limit (plasticity) Wh/Ph, % | The number of plasticity Ir/Ri | Capillary water saturation W, % | Angle of internal bonding, grad. |
| Heavy dusty loam with additive KGC -1 | 0 | 2.14 | 2.08 | 15.9 | 27.98 | 12.11 | 15.87 | 22.0 | 26.0 |
| | 5 | 2.15 | 2.10 | 15.3 | 26.88 | 12.11 | 15.87 | 21.0 | 26.0 |
| | 9 | 2.17 | 2.14 | 14.4 | 23.14 | 11.8 | 11.34 | 20.4 | 27.5 |
| | 13 | 2.19 | 2.17 | 13.5 | 22.18 | 10.95 | 11.23 | 19.3 | 28.0 |
As can be seen, addition of a complex stabilizer improves the physical and mechanical properties of soils of different types. Increasing of density, decreasing of humidity, as a result - the stabilized soil strengthens. The optimal number of stabilizers ranges from 5% to 14% by weight of soil.

The dependences of compressive and tensile strength at bending of stabilized soils on the number of used KGC -1 and KGC -2 are shown in Figure 1-2.

| Loamy sand with additive | 0 | 2.26 | 1.81 | 13.9 | 25.44 | 19.63 | 5.8 | 28.5 | 32.0 |
|--------------------------|---|------|------|------|-------|------|----|------|------|
| KGC -2                   | 5 | 2.31 | 1.93 | 12.8 | 23.17 | 18.51| 4.66| 27.9 | 32.0 |
|                          | 9 | 2.35 | 1.96 | 11.4 | 22.41 | 18.02| 4.39| 26.5 | 32.5 |
|                          | 13| 2.30 | 2.03 | 10.8 | 21.56 | 17.48| 4.08| 25.4 | 33.0 |

**Figure 1.** Dependence of compressive strength of soils when using different amount of stabilizers.

Determination of limit compressive strength of soil samples of heavy dusty loam and sandy loam showed that heavy dusty loam with addition of 5% of KGC -1 stabilizer has compressive strength of 0.96 MPa, which is 70% higher than that of sandy loam with the same amount of KGC -2.

As the amount of stabilizer increases, the strength of the samples increases reaching 2.9 MPa at 9% KGC -1 for heavy dusty loam and 4.32 at 13% KGC-1. Sandy loam was characterized by a 12% increase in strength. This indicates that the maximum strength can be obtained by strengthening the soils with a high specific surface area of particles, namely soils with clayey particles.

**Figure 2.** Dependence of tensile strength at bending of soils when using different amount of stabilizers.
Determination of limit tensile strength at bending showed that in the heavy dusty loam at 5% content of KTC-1 the strength is 0.22 MPa, in sandy loam - 0.19, which is 26 % higher. After increasing of the stabilizer amount, the strength increases and reaches 0.52 MPa and 0.4 MPa, respectively. That is, there is the same dependence as at determination of the compressive strength.

The study of freeze resistance showed that stabilized soils of heavy dusty loam and sandy loam are freeze resistant materials and can be used for the manufacture of road design objects.

The results of determination of the modulus of elasticity of stabilized soils with different content of stabilizers KGC-1 and KGC-2 are presented in Table 2.

| Type of soil                  | The amount of stabilizer, % by weight | Elasticity modulus, MPa |
|------------------------------|--------------------------------------|-------------------------|
| Heavy dusty loam with the addition of KGC-1 | 5                                     | 126, 121, 122 | 123.0 |
|                              | 9                                     | 353, 356, 358 | 354.0 |
|                              | 13                                    | 517, 518, 522 | 519.0 |
| Sandy loam with the addition of KGC-2 | 5                                     | 108, 111, 114 | 111.0 |
|                              | 9                                     | 268, 272, 270 | 270.0 |
|                              | 13                                    | 316, 318, 322 | 319.0 |

An important area of use of complex stabilized soil is the manufacture of road design objects. Durability of road design objects made of complex stabilized soil was determined by the calculation method based on the theory of reliability. It is known [8] that durability is the ability of the object to keep operable condition to the limit state with the established maintenance system. The quantitative parameter of durability is the service life before overhaul.

The durability of design objects was determined at the stage of operation, taking into account the standard service life of the road before overhaul.

Durability is related to the equation of reliability.

\[ T = \int_0^\infty P(t)dt \]  

where \( T \) – average service life, year;
P(t) – reliability function (probability of trouble-free operation)

The reliability of design objects made of complex stabilized soil was determined as the probability that the limit state (destruction) will not be reached by a certain service life:

\[ P(t) = P(S \leq S_d) \]  

(2)

where \( S_d \) - reserve of operation capacity of an object;

\[ S_d = R - Q \]

(3)

where \( R \) – generalized resistance of the object to the current destructive material;
\( Q \) – generalized action of destructive factors (natural and climatic, load).

The process of destruction of design objects can be described by a model based on the theory of random Kharkiv processes.

The operable period of one or another design object is divided into 5 states depending on the surface damage in %.

The reliability of the design objects in each of the states is shown in table 3.

| № | Object state            | Surface damage, % area | Reliability P(t) |
|---|-------------------------|------------------------|------------------|
| 1 | Serviceable             | 0                      | 0.999            |
| 2 | Limitedly serviceable   | 0-10                   | 0.9893           |
| 3 | Operable                | 1-200                  | 0.992            |
| 4 | Limitedly operable      | 20-30                  | 0.979            |
| 5 | Non-operable            | 30-50                  | 0.958            |

When \( n = 5 \), the end time of operation which must occur after the end of the normal service life before the overhaul of the road is determined.

Graphical interpretation of the reliability of operation of design objects is shown in Figure 4.

Thus, it is determined that the non-operable (critical) state of the design objects occurs after 10 years of operation in natural conditions.
4. Examples in design
Today, the development of environmental design and the creation of small architectural forms occurs in the context of changing values of society and the priorities of technologies that ensure sustainable development with energy saving. The figures show examples of objects and objects of environmental design made of fortified soils.

Figure 5. Enclosing columns from the strengthened soil.

Figure 6. Decorative container for flowers from fortified soil.

Figure 7. Flowerports from the strengthened soil.
The main methods used for the manufacture of most MAF are vibrocasting using a vibrating table (Figure 8) and vibropressing. During vibrocasting, ready-made molds are used for future products (Figure 9). These methods are studied by students-designers of NAU during industrial practice and are applied at development of subjects of design and small architectural forms (Figure 10-18).

Figure 8. Flowerports from the strengthened soil.

Figure 9. Supports under a bench from the strengthened soil.

Figure 10. Vibrating table for the manufacture of small architectural forms by vibrocasting.

Figure 11. Bench with flower garden. Development of students. NAU N. Plipenko.

Figure 12. Wheelchair. Development of students. NAU A. Fabiyanska.
Figure 13. Street benches. Development of students. NAU A. Klimchuk.

Figure 14. Bench. Development of students. NAU M. Sheligan.

Figure 15. Development of students. NAU Yu. Fedorova.

Figure 16. Development of students. NAU G. Pishna.

Figure 17. Bicycle parking. Development of students. NAU N. Pilipenko.

Figure 18. Information stand. Development of students. NAU N. Pilipenko.
Creation of a harmonious artificial landscape (anthropogenic complexes) with preservation of the natural environment is a problem of search of functional and aesthetic conformity, thanks to introduction of new ideas, technologies, existing experience.

5. Conclusions
1. Studies have confirmed the positive impact of different types of the first developed complex stabilizer KGC-1 and KGC -2 which combines the use of high molecular polymer and inorganic binder on soils.
2. The introduction of basalt nanofiller to the composition helps to increase the strength of the stabilized soil mixture, provides a radical change in the structure with the formation of new bonds between soil particles, increase density, water resistance and durability.
3. In loamy stabilized soils, the value of construction (physical and mechanical) properties is higher than in sandy soils due to their mineralogical composition, i.e. the content of the most active and most important finely dispersed part of the soil - granular particles.
4. Studies of complex stabilizers KGC -1 and KGC -2 and literature analysis showed that the soils stabilized by KGC -1 and KGC -2 meet the requirements for reinforced soils in accordance with the requirements of the standards of Ukraine.
5. The change of physical and mechanical properties of complex stabilized soils in a wide range depending on the amount of additives and soil type indicates the possibility of active regulation of its properties, as well as the possibility of use for different layers of pavement and manufacture of road design objects.
6. The calculation of the durability of complex stabilized soils showed that the design objects produced of this material can be operated for 10 years without significant damage and destruction.
7. Technical and economic advantages of road foundations and pavements of stabilized soils can be fully realized only with a clear organization of work and the use of modern mechanization, namely, an important role in formation of the properties of stabilized soil play physical and mechanical processes that occur when grinding soil, its combination with a complex stabilizer, as well as when moistening and compacting the mixture to ensure long-term optimal humidity and temperature mode of hardening.
8. Stabilized soil can be used for the design of transport and service facilities.

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