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Stabilization of Loose Soils as Part of Sustainable Development of Road Infrastructure

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Abstract: In the context of growing demand for road infrastructure expansion, sustainability is of key importance. Enhancing road construction technology ensures efficient, durable transportation infrastructure, vital for economic growth. Responsible road construction, especially in areas of historical and environmental significance, is essential. Preserving ecosystems and local heritage in road planning protects valuable areas and supports regional sustainability. Rural roads, often in forested areas, should maintain natural aesthetics. Economic challenges require flexible, efficient roads. Many existing unpaved roads, especially in rural and forest environments, fail to meet increasing traffic and load of heavy agricultural and maintenance vehicles. Soil stabilization methods, discussed in various publications, offer sustainable solutions. Research on ecofriendly binding additives provides the opportunity to reduce cement consumption and CO_2 emissions. Such innovations enhance road efficiency, reduce maintenance costs, and benefit the environment. Investing in modern road technologies mitigates climate change effects by reducing emissions and protecting ecosystems. Our research indicates that soil stabilization technologies significantly improve road strength and durability. Additives can increase compressive strength by over 50% with minimal cement content. Continued research into road quality and durability is vital for sustainable transport infrastructure development. The results presented in this paper were obtained after two periods of solidification: after 7 and 30 days, with three types of ads (ion-exchangeable, chemical, and polymeric) to cement. In all tests, compaction strength improved by at least 35% in samples with the lowest cement content.

Keywords: road infrastructure; stabilization of loose soils; sustainable construction; road foundations; cold recycling; binding binders

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1. Introduction

Growing awareness of human impact on ecosystems has made sustainability relevant in the context of designing and upgrading road networks. Tests and research are conducted on new technologies to increase the durability of roads and reduce their environmental impact [1].

As a construction material for engineering purposes, soil is the oldest material, often already present at the construction site with the possibility of direct use, or after undergoing appropriate modifications. Depending on what physical properties it has, through human intervention it can be adapted to the requirements of the project requirements, such as through a process of mechanical or chemical stabilization. Such materials as loose soils are non-cohesive and do not tend to combine individual grains into larger fragments [2]. In their structure, they do not have minerals capable of electrokinetic bonds. In the dry state, individual fragments are not connected to each other in any way, while in the wet state they show apparent cohesion. Soils such as sand are characterized by high water permeability, with a filtration coefficient $k \geq 1 \times 10^{-3}$ m/s and negligible compressibility [3]. The soil skeleton is formed by grains of soil in direct contact. The more compacted it is, the tighter the grains are arranged and the better the grain size of the soil, thus obtaining a higher degree of compaction $I_D \geq 0.67$ [4]. On the other hand, loose soils without admixtures of cohesive soils have the advantage of being free from the risk of large deformation, plasticization, and swelling and formation of blowouts in the soil structure. The ground structure of sand is granular in nature, and the forces of inter-particle attraction are negligible. They are sedimentary soils of aeolian or fluvioglacial origin. They exhibit high porosity, so they easily filter rainwater without retaining it in the surface zone exposed to frost. The ability to transfer external loads, e.g., from vehicle wheels, is determined by the compaction of the non-cohesive soil (degree of compaction I_D), as well as the ability to transfer shear forces [5]. In the case of loosened sand, a vehicle can easily bury itself, while the same vehicle can freely drive over a well-compacted pavement [6]. This is because the spaces between the soil grains are maximally compressed, so that the soil skeleton is able to carry higher external loads by working up to a certain point in the elastic range. A sudden influx of water, e.g., in the form of intense rainfall, causes a partial loosening of the sandy soil structure, which can significantly reduce, for example, the bearing capacity of the road system. In such a situation, one solution is to perform soil stabilization with cement [2], which consequently improves the strength parameters of the soil in terms of transferring external loads, e.g., from vehicle wheel pressure [7]. As a result, structures become more stable and resistant to loads. The introduction of soil stabilizers also reduces susceptibility to capillary and precipitation water, thanks to hydrophobicity—the reduced ability of the material to absorb water. Stabilizers help protect against the loss of soil material, which is essential, especially in areas prone to extreme weather conditions [8].

Cement stabilization of sandy subsoil is already widely used in the construction of all types of roads and involves improving its physical and mechanical properties by introducing chemicals into the subsoil that bind particles and grains, fill pores, or change the properties of the native subsoil [9]. Unfortunately, this solution may not fully meet the design objectives, as in the long term, the modified layer is deformed, resulting in damage to all the structural layers of the road [10] (Figure 1).

Figure 1. Deformed ground under road surface (Piechowicz, K. Bumps on the Road [Photograph]; 2024).

As the scope and application of soil reinforcement methods has increased in recent years, the authors in this publication present the results of study aimed at determining the impact of the application of binding additives to cement. The additives were differentiated in terms of the proportion of their use and their effect on the mechanical properties of the tested soil was determined.

This study aims to present the purpose of using a combination of cement and additional binders in soil stabilization. To compare the obtained results, cement is used in different proportions: 5, 7, and 10% weight of dry soil mass. The presented research also used three types of additional binders: ionexchangeable, chemical, and polymer. By means of tests of the compressive strength of stabilized mixtures with soil binders, the ability of the soil to carry loads under the action of loads transferred to the pavement base and substructure was evaluated. Since the soil stabilized in this way is solid, the tests were carried out as in the case of concrete specimens—uniaxial compressive strength test, without taking into account the outflow. The results showed an improvement of compaction strength in stabilized soil with all types of binders, which allows for a preliminary estimate, for example, of how much traffic can travel on such a road with stabilized soil [11].

Soil stabilization is one of the basic methods of strengthening the subsoil. In order to find the right technology, adapted to the right soil lying in the subsoil, numerous studies are carried out, and the results obtained allow us to draw conclusions that will give directions for further research [12]. The process of soil stabilization, regardless of the destination, whether in ground pavements or highway substructures, is even necessary to improve the mechanical properties of the subsoil, i.e., compressive strength (UCS), stress dependency characteristics, strain, tangent elastic modulus Et, and secant elastic modulus Es [13].

Laboratory tests are the main source of knowledge about the parameters of soils modified with special cement additives—for example, polymers, which are a wide group of modern soil stabilization additives. Polymers strengthen the bond chains between soil particles and a hydraulic binder such as cement and ashes. A group of Iranian scientists [14] conducted research on mixtures of various types of locally occurring sands, cement, and the polymer Nikoflok. From the results obtained, an increase in the compressive strength of mixtures with the addition of the polymer was observed by an average of 0.6 MPa, compared to the control group of sand stabilized with cement alone. The advantage is that the compressive strength of the mixtures can be determined under strictly controlled conditions of stress increment. On the other hand, disadvantages include: the small size of the samples, the local nature of the soil taken for testing and the possible unrepresentativeness. Research on the stabilization of sandy soils with polymer addition was conducted by Farzad [14]. Desert sands and coastal sands were used as test material. These soils were stabilized with Portland cement 32.5 R in proportions of 4%, 8%, and 12% and polymer additive. However, the obtained results of compressive strength tests did not obtain satisfactory results, with the highest proportion of cement additive Rc28 exceeded only by 1 (Mpa). Regardless of whether the binder additives are in the form of powder or liquid, it is important to combine them thoroughly. In the search for the most suitable stabilizing agent on the research road, in addition to the required technical properties, the economic factor and environmental impact are also considered [1]. Therefore, research is conducted on many other stabilizing agents, i.e., sodium hydroxide, geopolymer, fly ash, or various types of cements. [15]. Sustainable infrastructure development encourages solutions that promote the reduction of construction waste [16]. Waste materials are also used for stabilization, e.g., blast furnace slags, fly ash, destructs, and fractionated concrete rubble. Such materials require testing in each case, in terms of mechanical, chemical, reactivity with local soils, and impact of adjacent cultivation soils [17]. The already-finished soil composite is tested for strength after maturation periods of 7 and 28 days [18]. Research is also conducted on soil stabilization with solid waste from flue gas desulfurization. As a result of the research on the synergy of individual components [19], a mixture was developed: sodium silicate 4%, carbide slag 26%, granulated furnace slag 25%, fly ash 35%, flue gas desulfurization gypsum 10%. After 7 days of maturation of the samples, the strength result (average value) 1.54 MPa was obtained.

In summary, soil stabilization is important in many respects. It can have a purely mechanical character, where local soil undergoes treatments, such as mixing, addition of other soil materials, and compaction, or it can be of a chemical stabilization nature, where the local soil changes its structure after stabilization treatment, towards improving its physical and mechanical properties [20]. The stabilization process itself can incorporate elements of recycling and CO_2 emissions reduction. Consequently, better road quality will lead to increased efficiency and fluidity of transportation, as well as the impact of traffic on the surrounding environment—reducing noise and decreasing emissions of harmful compounds into the atmosphere [17,21].

2. Materials and Methods

To examine the impact of binding additives added to cement on the compressive strength increment of unbound modified soil, laboratory tests were conducted. The materials used included: unbound soil; medium sand; Portland cement 32.5 R; an ion exchange additive marked K1; a chemical additive marked EN-1; and a polymer additive marked NC. The tests were conducted according to the norm PN-EN-14227-10. The testing procedure was designed to minimize error parameters.

In the first step, a research sample was taken from a generally accessible area, which was a forest road in the Biała Forest, Mazovian voivodship. After laboratory tests, the soil was classified as medium sand (Figure 2), a soil commonly found on forest roads in State Forests and municipal roads in northeastern Poland [22].

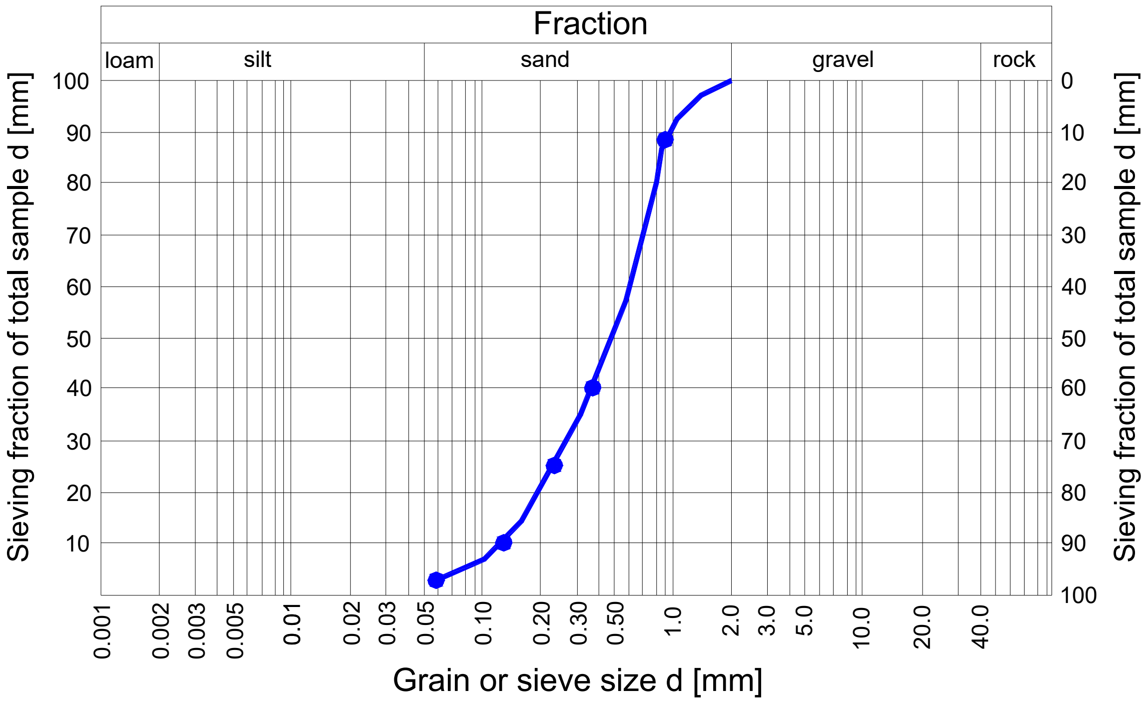


Figure 2. Particle size curve of the soil sampled for testing.

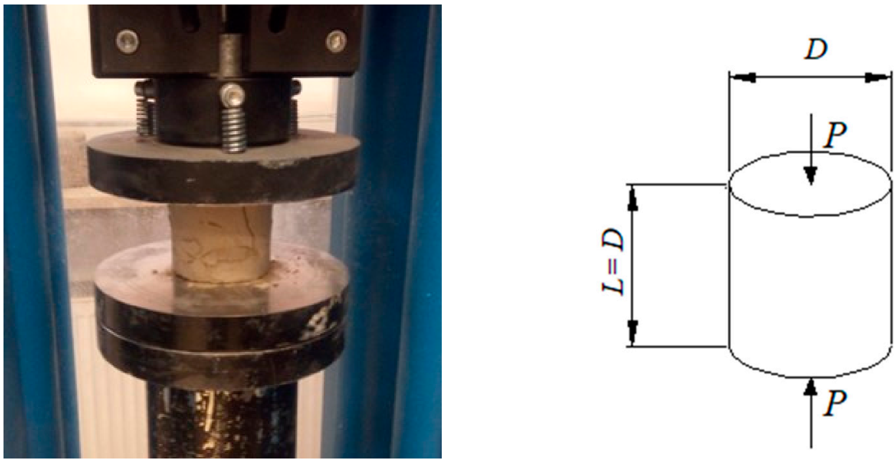
Samples of sand mixtures with the addition of 5, 7, and 10% of Portland cement 32.5 R relative to the dry mass of the soil, as well as binding additives, were prepared. The following cement additives were used in the study:

- The chemical additive EN1 is an oily extract from citrus plants (sulfonic dilimonene) dissolved in sulfuric acid. It is a deep brown liquid that should be diluted in water at a proportion of 1:200 to 1:600.
- The ion exchange additive K1 is an ion exchange agent in the form of a powder composed of salts of chemical compounds with an alkaline pH. It aids in ion exchange between particles of the stabilized soil, extending and strengthening the molecular-level bonding structure.
- The polymer additive Nikoflok is a powdered mixture of polymer particles enriched with quicklime and magnesium oxide. It reinforces the mixture, creating cross-linking bonds at the molecular level of the soil stabilized with cement, simultaneously reducing its porosity.

Preparing the samples involved thoroughly mixing the dried soil with cement. Subsequently, an ion exchange additive was applied at a ratio of 1 kg/m^3 of soil and water at

12% by weight relative to the dry mixture—to achieve optimal moisture content, ensuring the maximum density of the samples. Samples enriched with a polymer additive were prepared in a similar manner (with the weight ratio of the additive being approximately 10 kg/m^3 of soil), while the chemical additive was applied at a rate of 0.15 l/m^3 of soil.

The samples were formed into cylinders with a height and diameter of 8 cm using a Proctor apparatus at optimal moisture content, applying a standard compaction energy of 0.59 $J{\cdot}cm^{-3}$ according to PN-EN 1997-1:2008 norm. Five samples of each variant were prepared, which underwent curing according to the requirements of standard PN-S-96012:1997. Subsequently, the compressive strength values were determined after 7 and 30 days using a compression machine (Figure 3).



(a) (b)

Figure 3. Compression of a cylindrical sample along the axis: (**a**) general view; (**b**) action diagram.

Samples of sand mixtures with the addition of 5, 7, and 10% of Portland cement 32.5 R relative to the dry mass of the soil, along with binding additives—chemical, ion exchange, and polymer, were prepared in special forms with a height and diameter of 8 cm.

Subsequently, samples were compacted using a Proctor apparatus at optimal moisture content, which was approximately 12%, applying a standard compaction energy of 0.59 $J{\cdot}cm^{-3}$ (according to norm PN-EN 1997-1:2008). Five samples of each variant were prepared, which underwent curing according to the requirements of standard PN-S-96012:1997. Then, compressive strength values were determined after 7 and 30 days using a compression machine (Figure 3).

The prepared samples of medium sand soil with the addition of cement and binding additives—ion exchange, chemical, and polymer—underwent compressive strength tests after 7 and 30 days. The samples were successively compressed on a compression machine. The force causing sample failure ranged between 8 and 12 kN. With the obtained results of the force causing failure, compressive strength was straightforwardly calculated using Formula (1) (according to norm PN-EN-14227-10):

$$Rc = P/A\ [kN/cm^2] \times 10, \quad (1)$$

where:

Rc—compressive strength, [MPa],
P—destructive force [kN]
A—sample area [cm^2].

3. Results

First, the sandy soil used to prepare the samples was examined to estimate the optimal moisture content, which directly depends on the maximum density of the soil structure. The optimal moisture content of the tested soil was 12%, which allows for achieving the maximum density of the structure (Figure 4). In further tests, samples with a water content of 12% were prepared.

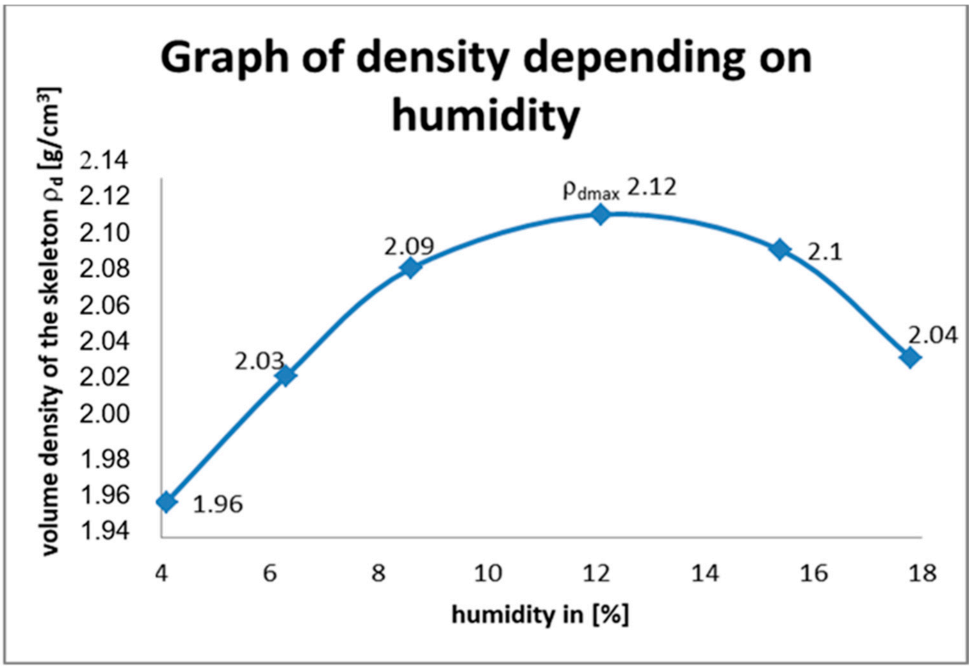


Figure 4. Relationship between maximum density ρ_d [g/cm^3] and humidity in [%].

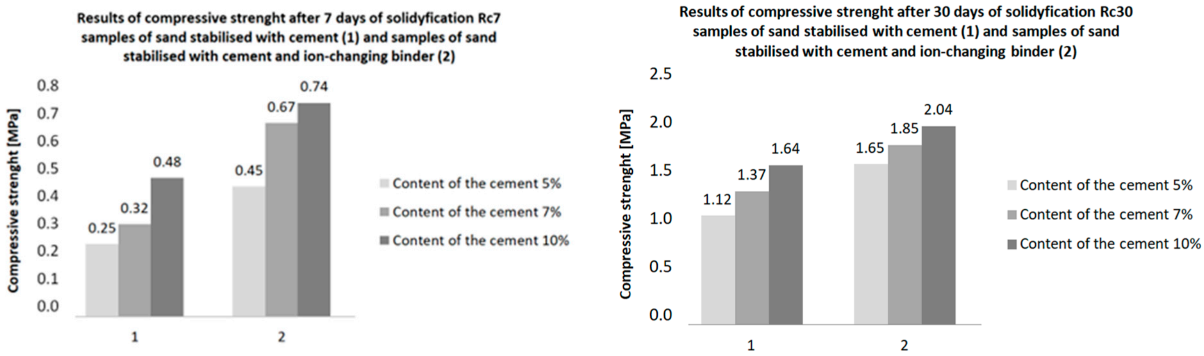
An example of the test results for compressive strength for the soil–cement mixture at a proportion of 5%, and at a proportion of 5% with an ion exchange additive, is shown in (Table 1).

Table 1. Example of Rc7 and Rc30 test results for soil stabilized with 5% cement and with 5% cement and an ion exchange additive.

Cement 5%			Cement 5% + Ion Additive K_1		
Sample No.	**R_{C7} [MPa]**	**R_{C30} [MPa]**	**Sample No.**	**R_{C7} [MPa]**	**R_{C30} [MPa]**
Cem 1	0.18	1.17	(Cem + K_1)1	0.52	1.54
Cem 2	0.34	1.22	(Cem + K_1)2	0.54	1.63
Cem 3	0.29	1.05	(Cem + K_1)3	0.38	1.78
Cem 4	0.23	1.09	(Cem + K_1)4	0.41	1.72
Cem 5	0.21	1.07	(Cem + K_1)5	0.4	1.58
Average	0.25	1.12	Average	0.45	1.65

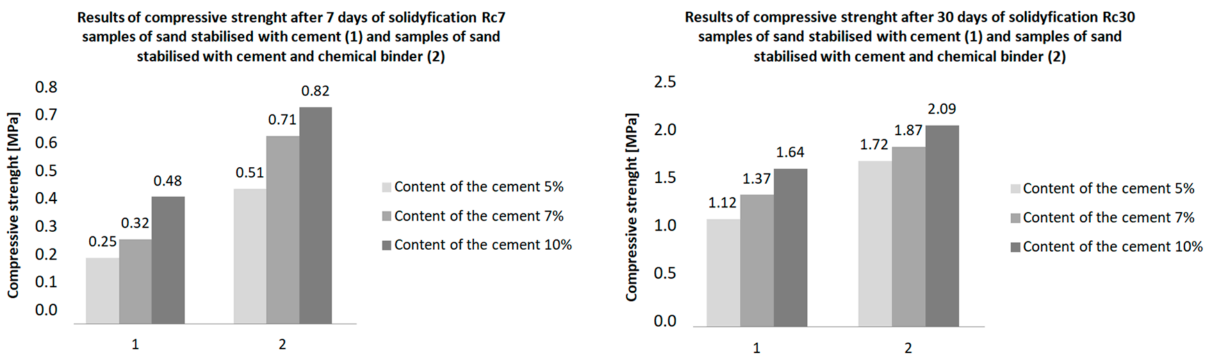
Further in the article, due to the large number of test results, the average values of compressive strength for each tested variant will be presented.

The results shown on the graphs (Figures 5–7) represent averaged values from each test (one test comprised five repetitions). Deviations from the mean value varied depending on the series of tested samples: for the ion-changeable binder, the deviation reached about 8%, for the chemical binder, the deviation reached 11%, and for polymer, the deviation was about 15%. The variations may result from each mixture being prepared separately, soil grain size in soil content, different specifications and properties of binders, and conditions of the binding process, which could affect divergent results of deviations of mean value.



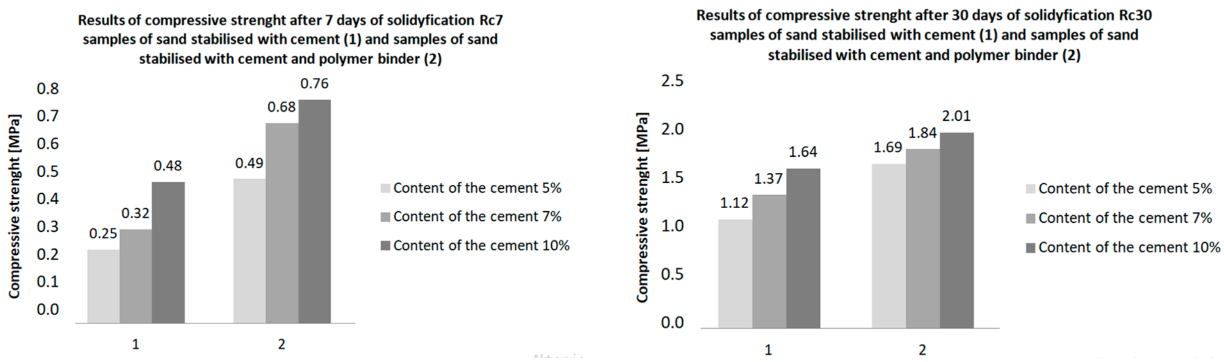
(**a**) (**b**)

Figure 5. Compressive strength of cement-stabilized sand and sand stabilized with cement with the addition of an ion-exchange binder: (**a**) after 7 days; (**b**) after 30 days [23].



(**a**) (**b**)

Figure 6. Compressive strength of cement-stabilized sand and cement-stabilized sand with the addition of a chemical binder: (**a**) after 7 days; (**b**) after 30 days [23].



(**a**) (**b**)

Figure 7. Compressive strength of sandy clay stabilized with cement and stabilized with cement with the addition of a polymer binder: (**a**) after 7 days; (**b**) after 30 days [23].

The research results unequivocally demonstrate that all binding additives resulted in a significant increase in the compressive strength of soil enriched with cement and additives. The mere presence of cement already positively influences the soil stability. However, cement in combination with binding agents achieves significantly better results. Cement additives with chemical and polymer binders resulted in nearly identical increases in compressive strength after 7 days.

However, after 30 days, the greatest increase in compressive strength was observed in the case of soil with the addition of cement with chemical binders. The suitability assessment of the tested mixtures for stabilizing road surfaces and subgrades was based on comparing the strength parameters Rc of the samples (Rc7, Rc30) with the applicable criteria according to PN-S96012, 1997 norm.

It should be noted, however, that to determine the parameters of the designed road surface construction, the expected traffic load must first be determined. Traffic on unpaved roads falls into the light category, denoted by the symbol KR1 [24].

4. Discussion

Based on the conducted research, it can be concluded that cementitious additives can be an effective way to improve the mechanical properties of sandy soils. Their impact is significant enough for the soil to meet the requirements outlined in the standard PN-EN-14227-10_14. An average increase in compressive strength of 105% (deviation from the mean value: approximately 15%) was achieved after a solidification period of 7 days, and approximately 40% (deviation from the mean value approximately 8%) after a maturation period of 30 days. To achieve higher strength values, further research should explore variants with different binders and proportions of stabilizing material additives.

The research results have significant practical application as they can be used to develop effective methods for stabilizing sandy soils, including soils with low bearing capacity [8]. Soil stabilization using binding additives is an integral part of the construction process [15]. Their impact on the soil is multifaceted, and their application contributes to improving the mechanical properties of soils, ensuring the durability and efficiency of engineering structures. The data will allow for the selection of mixtures with lower cement content and the use of recycled materials, which positively affects the emission of greenhouse gases required for cement production and new materials.

These studies can be compared with studies on the stabilization of silty soils with cement supplemented with an ion exchange agent, aimed to determine the effectiveness of the mentioned additive in cement stabilization under Polish conditions. Bottom sediments from reservoirs classified as silty sand (from the Czorsztyn Reservoir) and silt (from the Rzeszów Reservoir) were used as research materials. Compressive strength and frost resistance of four mixtures were determined after various periods (from 7 to 365 days) and curing methods (water curing or freeze–thaw cycles). The use of cement with an ion exchange agent significantly increased the compressive strength and frost resistance of silty sand compared to stabilization with cement alone, but this did not affect the qualification of this material for use in road construction. A similar relationship was not observed for silt; mixtures of silt stabilized with cement supplemented with an ion exchange agent showed even less favorable compressive strength and frost resistance parameters than those stabilized with cement alone [25]. The studied ion exchange agent is a relatively new binder used in stabilization, hence the lack of a wider range of literature and research to which one could refer. Nevertheless, in one publication [26], the authors compared several stabilization agents, including the ion exchange agent. The research procedure was carried out in accordance with the Technical Approval AT/2010-02-1830:2010. The soil material subjected to the research was sandy clay. Based on the obtained results, the authors concluded that the addition of the ion exchange binder did not significantly affect the increase in compressive strength after 7 days of curing compared to samples stabilized only with cement, similarly to the samples after a curing period of 28 days. There was also no increase in compressive strength compared to samples stabilized exclusively with cement. However, an increase in the initial modulus of deformation Ep was observed in field tests from 17 MPa to even 450 MPa [27], which is a good prognosis and at the same time an impulse for further research on the strength of this soil–binder mixture.

In studies on soil–binder mixtures with the addition of chemical binders [11], conducted at the Institute of Technology and Life Sciences in Falenty, satisfactory results were obtained regarding the increase in compressive strength of samples stabilized with cement supplemented with a chemical binder, compared to the control group, which consisted of samples stabilized only with cement. The results of the research will vary depending on many factors, such as the soil material used for the study, its particle size distribution, organic content, clay mineral content, laboratory conditions, proper sample curing, etc. For example, in the study by [28], an increase in compressive strength of samples with chemical additives by 65% compared to samples stabilized only with cement was observed.

It is in our common interest to ensure the high efficiency of roads and reduce their impact on the surrounding environment. Research shows that soil erosion and surface distortions negatively affect traffic, thereby increasing CO_2 and PM emissions [21]. Increased concentrations of heavy metal compounds in surrounding road soils have also been confirmed [17].

Laboratory and field research play a crucial role in adapting the stabilization process to specific conditions and the needs of a given project. The research presented in this article focused solely on obtaining the parameter of compressive strength, without investigating the effects of water and frost on the specimens. Research in this area will be conducted by researchers at a later stage, naturally opening the prospect of continuation and expansion of the above issues. An attempt should also be made to conduct research with other stabilization additives, significantly enriching previous achievements with new experiences and perspectives for further research efforts.

5. Conclusions

The deficit of investment areas with good soil conditions and the development of road infrastructure encourages the exploration of areas with challenging soil conditions. In this process, responsible construction, and modernization of roads, especially in areas of significant historical and environmental value, become an indispensable element of planning. Care for preserving ecosystems and respecting the heritage of local communities in designing and implementing road investments contributes to the protection of valuable areas and supports the sustainable development of regions.

It is important to accurately determine soil parameters and then select the appropriate stabilization technology. Unfavorable ground conditions for road investments may result not only from the presence of soils with poor bearing capacity but also from loosened layers, such as sands. To modify these soils, chemical stabilization methods are commonly used, including surface stabilization, deep mixing methods, or soil injections [29]. All road projects should be preceded by laboratory or field research, which will enable the determination of the appropriate soil parameters, followed by the development of a recipe used in the stabilization technology. This process is outlined in this article using research methods focusing on soil modification. Research should be supplemented by interactions between stabilized soils with water and negative temperatures, illustrating the possibilities of using these binders and additives in different regions of the country with varying climatic conditions.

Soil stabilization using binding additives is an extremely important element in the field of civil and construction engineering. This process aims to improve the mechanical properties of soils, resulting in increased load-bearing capacity and durability of structures [26]. It is worth considering the overall impact and diverse applications of these stabilizers in various engineering areas according to norm PN-EN 1997-1:2008. It is possible to minimize disruptions in existing ecosystems by avoiding sensitive areas, protecting breeding grounds, and maintaining the ecological continuity of areas. Improved accessibility and safety of transportation support economic and social development. Increased durability and efficiency of infrastructure reduce maintenance and repair costs, bringing economic benefits to society. By limiting greenhouse gas emissions and protecting natural ecosystems, road projects can help mitigate the effects of climate change.

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