Open access Original scientific paper

https://doi.org/10.5552/crojfe.2025.2499

Application of Phytoremediation to Hydraulic Binders Alkaline Inclusion in Forest Roads Pavement Construction

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Abstract

The use of hydraulic binder materials for the improvement of pavement subgrade has many implications for the surrounding ecosystem due to the possible leakage of alkaline compounds. The objective of this study is to evaluate the capacity of plants to remedy the subgrade affected by alkaline inclusion. To reduce the impact and return the subgrade to its original state, a phytoremediation process is studied. The impact of two materials commonly used for the subgrade improvement is analysed – fluid ash (slag) and lime+cement mixture. Three different mixes of plants – Mix A, Mix B and the native natural vegetation Mix N – are proposed. Totally 99 samples were collected and 990 specimens were chemically and geotechnically analysed and statistically evaluated. The success of phytoremediation process for both Mix A and Mix B can be observed. It is considerably higher for the undersurface alkaline inclusion than for the surface one. Mix B appears to be the best for fluid ash binder and Mix A for lime+cement mixture binder. It is worth noting that the native natural vegetation in Mix N also contributes to the phytoremediation process and that the appropriate plant selection – e.g. Mix A and Mix B – can accelerate this process.

Keywords: phytoremediation, carbonates, pH value, pavement, low volume road, subgrade, soil improvement, alkaline, forest, rural

1. Introduction

Soils are one of the world's main resources of biodiversity. They play a very important role in the reduction of carbon fixation and greenhouse gas emissions. Soil is a component of terrestrial system and has the ability to support plant and animal life, contributes to the decomposition of organic matter (Duiker et al. 2003) and is part of the landscape (Angers and Caron 1998). The economic or social activities of human beings in nature – transportation, construction, recreation, sport, forest management, firefighting, connecting small rural towns etc. – are very important for the society, but they negatively influence the nature as a whole and particularly the soil. Roads must be constructed for the above mentioned activities. They need to be safe, sustainable and have sufficient load volume capacity defined by the appropriate standards. The huge amount of these roads, including forest and rural roads, belongs to the Low Volume Roads according to the American Association of State Highway and Transportation Officials (AASHTO 2001). They are limited by the average daily intensity of heavy vehicles, which must be less than 400 vehicles per day. Natural materials are mainly used for the road pavement construction, but the amount of recycled materials is growing and it is expected to dominate in the near future (Florian et al. 2015). However, any structure and its subsequent use generally influences the surrounding ecosystem, contributes to soil degradation, erosion and changes in vegetation. It must be emphasized that generally all materials including recycled materials and even natural materials used for pavement construction are foreign to the surrounding ecosystem.

For the subgrade improvement as well as the improvement of other materials used in individual pavement construction layers, the hydraulic binders – ash (slag), cement, lime, their mixtures etc. – can be used. Due to the erosive processes, these materials or their parts are washed out from the pavement structure towards the surrounding ecosystem, where it can start the process of changes in the chemical composition of the natural subgrade and consequently of the vegetation. Increased attention should be paid to hydraulic binder leaching, because it increases the total amount of carbonates in the subgrade and therefore it increases the subgrade alkalinity. An excess of carbonates can cause nutrition problems in plants due to the antagonism with other elements (Šlezingr and Fernandez-Arias 2019). Also there is a relationship between subgrade composition and plant growth, especially its roots (Torres-Guerrero et al. 2013). This influences especially endemic vegetation that develops around the construction area (Fitter 2002), if the subgrade is acidic by origin with a very low amount of carbonates, but due to alkaline inclusion it changes to alkaline.

There are two basic ways how materials in pavement constructio, n can leak into the surrounding ecosystem. The first one origins from pavement construction process and particular construction technology and techniques used, and mostly affects the surface of the surrounding ecosystem. The second one origins from the time-dependent water washing due to climatic and erosive processes following the construction and mostly affects the subgrade under the surface.

The problem of inclusion of pavement construction materials alkaline into the surrounding ecosystem was studied and measured on the Low Volume Road in the Czech Republic and on two Low Volume Roads in Spain. In the study performed in the Czech Republic, the impact of different types of hydraulic binders used to improve the subgrade – two types of fluid ash (slag), lime+cement mixture, and lime – on the forest ecosystem was observed and quantified (Ševelová et al. 2020a). In Spain, the impact of inclusion of natural materials used in construction layers on the surrounding ecosystem was observed and quantified. The results obtained proved significant influence of material inclusion due to changes in pH value as well as in the amount of carbonates before and after pavement construction. Significant changes were observed at different distances from the road and also at different depths (Ševelová et al. 2020b).

Phytoremediation is a possible way to reduce the impact of hydraulic binders inclusion (Gray and Leiser 1982, Etim 2012). Phytoremediation is defined as the use of natural plants to decrease pollutants in the ecosystem and to achieve original balance (Salt et al. 1998). Phytoremediation uses plants to remove, reduce, transform, mineralize, degrade, volatilize or stabilize contaminants (Kelley et al. 2000, Miretzky et al. 2004, Cherian and Oliveira 2005, Eapen et al. 2007, Cho et al. 2008, Funai and Kupec 2017, Funai and Kupec 2019). It exploits the natural plant physiological processes (Megharaj et al. 2011, Singh et al. 2003) so that some of the contaminants are absorbed by the plant root system. Phytoremediation brings together many advantages, especially cleanliness and economy. Also, it does not use dangerous chemical reagents, it does not negatively affect the subgrade structure, and it only applies common agricultural practices. In addition, the process is carried out »in situ« avoiding costly transport (Cunningham et al. 1995). Thus phytoremediation represents a sustainable and low-cost alternative for the ecosystem rehabilitation affected by pollutants of different origin (Reichenauer and Germida 2008). Up to now, phytoremediation was used especially for the subgrade rehabilitation of mine waste, where for the stabilization of heavy metals pollutants, radioactive metals, organic compounds and compounds derived from petroleum was found to be successful (Cai et al. 2021). No studies or reports could be found on the use of phytoremediation process to reduce the impact of alkaline inclusions due to the use of hydraulic binders in road construction.

The aim of our study is to quantify whether phytoremediation can control the chemical changes – pH value and total carbonates amount – in the forest road surrounding ecosystem caused by leakage of hydraulic binders used to improve the subgrade-bearing capacity. The present paper analyzes the first results of phytoremediation process applied to two types of hydraulic binders – fluid ash (slag), lime+cement mixture – used to improve subgrade on the experimental forest road.

2. Materials and Methods

2.1 Experimental Forest Road

The experimental forest road is located in the southern part of the Czech Republic near the city of Brno (Ševelová et al. 2015) – see Fig. 1. Its length is 309 m, it has an average slope of 3% and it is located at an altitude of 372–388 m above sea level. The climate in the monitored area is classified as hot/temperate with Cfb classification according to the Köppen-Geiger system. The average temperature is 9.0 °C and the average rainfall is 518 mm. In the subgrade, there are igneous rocks, such as granites and volcanic rocks, and also tertiary sedimentary rocks. The area where the experimental road was built consists of rocks of various origins and age in the subsoil. There are also layers of original clay and sand that cover the older rocks.

The vegetation in the monitored area is a typical European mixed forest, mainly *Picea abies* (L.) Karsten, *Larix decidua* Mill., *Tilia cordata* Mill., *Castanea sativa* Mill.,

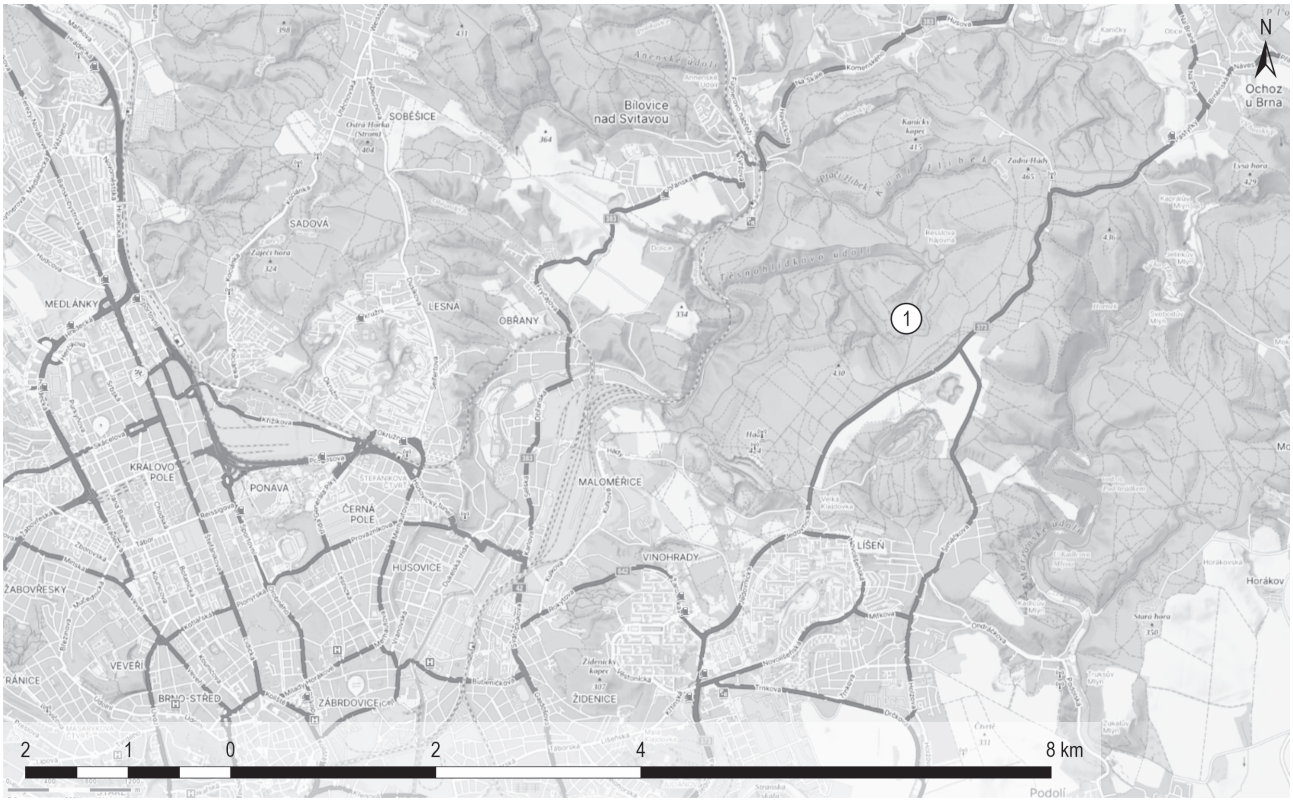

Fig. 1 Brno district map with the position of the experimental forest road (pin No. 1) (map source: OpenStreetMap)

Ulmus minor Mill., *Quercus robur* L., and *Pinus sylvestris* L. The different types of grass and herbs can be found here: *Poa nemoralis* L., *Poa angustifolia* L., *Dactylis polygama* L., *Brachypodium sylvaticum* (Huds.) Beauv., *Myosotis sylvatica* Ehrh., *Veronica chamaedrys* L., *Clinopodium vulgare* L., *Campanula persicifolia* L., *Ajuga reptans* L., *Vincetoxicum hirundinaria* Medik., *Pyrethrum corymbosum* L., and *Hypericum perforatum* L.

The principal task of the experimental road construction was to study the influence of various types of materials possibly used to improve the subgrade and thus to improve the load-bearing capacity of the road (Ševelová et al. 2020b). The experimental road was divided into individual segments with various improvement materials including the following hydraulic binders: two types of fluid ash (slag), ½ lime+½ cement mixture, and lime. The changes in the pH value and the total amount of carbonates before the phytoremediation experiment were measured and analyzed in 2012 after the construction process was completed, and in 2017 after five years of road utilization. The obtained results describing the impact of these materials on the surrounding ecosystem can be found in (Ševelová et al. 2020b).

2.2 Phytoremediation Experiment

For the phytoremediation experiment, the segments with the greatest impact on the surrounding ecosystem were chosen – the fluid ash (slag) segment and the lime+cement mixture segment. Two vegetation species mixes – Mix A and Mix B – were proposed for phytoremediation. To control the phytoremediation experimental process, Mix N containing original natural vegetation that normally occupies this area was included into the experiment, too. Two cultivation beds in the rod transverse slope direction were prepared, one for each segment analyzed. Each cultivation bed was divided into nine sections – three sections parallel as well as three sections transverse to the road, see Fig. 2. The dimensions of each section were 1x1 m. In parallel sections, the influence of vegetation mixes – Mix A, Mix B and Mix N – was studied. In transverse sections, the influence of distance from the road and of alkaline inclusion was studied. The changes in pH value and the total amount of carbonates during the phytoremediation experiment were measured and analyzed twice in 2020. First samples were taken from cultivation beds in spring before vegetation planting and the other ones after vegetation harvesting in autumn.

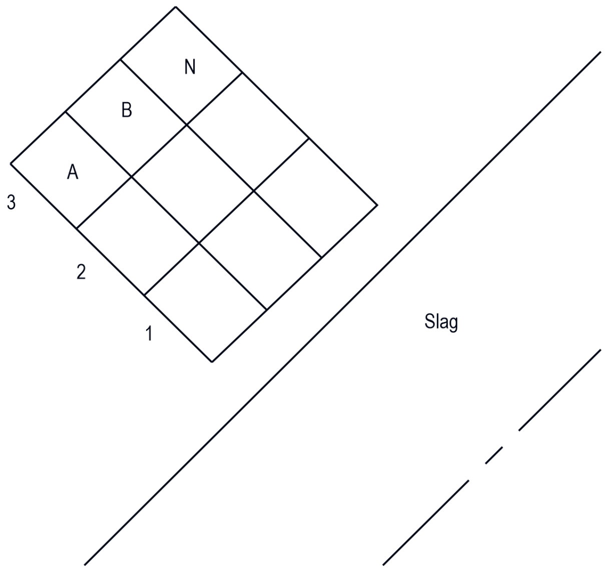

Fig. 2 Cultivation bed plan

For the preparation of Mix A, the species from the original natural vegetation, assumed to have the optimal (typical) infiltration capacity of the roots in the given natural conditions (Buček and Lacina 2000), were chosen. The chosen species were: *Poa nemoralis* L., *Dactylis polygama* L., *Brachypodium sylvaticum* (Huds.) Beauv., and *Clinopodium vulgare* L.. The proportion used for these species was 1:1:1:1, which is 1 gram of seeds of each species, 4 grams in total in each 1x1 m section.

For Mix B, the species of the gramineous family were used, because the mixture of these species is standardly used in similar natural conditions in the Czech Republic as the technical soil protection gramineous mixture, see e. g. the standard CSN 736108-2018. That is why its phytoremediation ability is potentially interesting for technical practice. The chosen species were*: Lolium perenne* L., *Lolium perenne squirrel* L., *Festuca rubra* L., and *Poa pratensis* L.; 4 grams were used in each section with the ratio 1:1:1:1.

In Mix N, the natural vegetation originally growing in this area was included: *Poa nemoralis* L. 35%, *Poa angustifolia* L. 10%, *Dactylis polygama* L. 20%, *Brachypodium sylvaticum* (Huds.) Beauv. 5%, *Myosotis sylvatica* Ehrh. 5%, *Veronica chamaedrys* L. 5%, *Campanula persicifolia* L. 3%, *Ajuga reptans* L. 2%, *Vincetoxicum hirundinaria* Medik. 3%, *Pyrethrum corymbosum* L. 5%, *Clinopodium vulgare* L. 6%, *Hypericum perforatum* L. 1%.

2.3 Sample Preparation and Statistical Analysis

The subgrade samples for phytoremediation experiment were taken twice in the year 2020 – before planting and after harvesting. They were taken from each section of vegetation A, B and N, at three distances from the road, and at depths of 0 cm (surface) and 30 cm (undersurface). When taking the samples, the section surface was first cleaned from the remains of original vegetation and from all types of roots and biological remains, so that the testing site would be uncontaminated. Each sample was always taken in the section center and sieved in the 0.5 mm sieve. As a result, 18 samples from each cultivation bed, and 36 samples in total, were taken at the beginning of the experiment and after it was completed in 2020. Ten specimens were prepared from each sample for chemical analysis to minimize random error that may occur in any measurement, five specimens for the pH value and five specimens for the analysis of the total amount of carbonates.

The samples were taken in 2012 and 2017 in exactly the same way. Of course, only for vegetation Mix N. As a result, 6 samples were taken from each cultivation bed and 12 samples in total in each year. Also, from each sample, ten specimens were prepared and chemically analyzed.

In addition, blank samples were taken in 2012, 2017 and in 2020 before planting. They were collected from the section located far from the test segments to guarantee that they were not affected by inclusion of improvement materials alkaline. Each year one sample was taken and ten specimens were chemically analyzed.

All in all, 99 samples were collected and 990 specimens were chemically analyzed in 2012 and 2017, and twice in 2020. The data obtained from both chemical tests were statistically evaluated and basic statistical parameters were determined. All data showed minimal deviations from the mean values. Due to the low random variability of the obtained test data, only mean values are presented and discussed in this paper.

2.4 Geotechnical and Chemical Analyses

European standards (EN standards) were applied for geotechnical as well as chemical analyses of the subgrade samples. The following geotechnical analyses were performed: humidity test according to the standard CSN ISO/TS 17892-1, sieving and aerometry tests according to the standard CSN ISO/TS 17892-4, and consistency (plastic-liquid limit) test or Atterberg boundary test according to the standard CSN ISO/TS 17892-12. The above tests were used for the soil classification according to their granulometric composition and according to their Atterberg plastic-liquid limit. The subgrade classification was performed according to the Unified Subgrade Classification System

(USCS) using the standards CSN EN ISO 14689-1 and CSN EN ISO 14688-2.

The following chemical analyses were performed: pH value test according to the standard ISO 10390:2005, and the total carbonates test according to the standard ISO 10693:2015. The total amount of carbonates was determined from the volume ratio of the amount of CO_2 produced in the gaseous state as a function of equation (Ševelová et al. 2020a)

$$CaCO_3 + HCl \rightarrow CO_2 + CaCl_2 + H_2O \tag{1}$$

The pH value is a dimensionless quantity that determines soil acidity or alkalinity and it is in the range 0 to 14. In the text, the pH value is considered acidic in the range of 0–5.5, neutral in the range of 5.5–8 and alkaline in the range of 8–14. The total amount of carbonates is measured in the percentage. Carbonate content can be considered: for amount 0.3 and 0.5% (very low), between 0.5 and 3% (low), between 3 and 5% (medium), between 5 and 10% (medium high), between 10 and 20% (high), between 20 and 40% (very high), and more than 40% (extremely high).

3. Results

3.1 Geotechnical Results

Geotechnical test were performed on samples taken from both segments of analyzed pavement. The proportional amount of fine fractions smaller then 0.063 mm from the aerometric test were in the interval 40–60% and the plasticity index Ip in the interval 7.8–36.9%. According to the results obtained, the subgrade soil was classified as saSi soil according to the USCS system.

3.2 Chemical Results

The aim of the chemical analysis was to track the impact of leakage of hydraulic binders used to improve load-bearing capacity of pavement subgrade on the surrounding ecosystem in time and to verify the phytoremediation possibilities to reduce the hydraulic binder alkaline inclusion impact.

3.2.1 Fluid Ash Segment

The results for the pH value can be found in Table 1, Table 3 and in Figs. 3–5. The pH values for Mix N in 2012 ranged from 6.9 to 7.3 for the surface, and from 6.1 to 6.9 for the undersurface samples. In 2017 they increased to the range from 7.6 to 7.8, and from 7.1 to 7.9 respectively. In 2020 before planting they were in the range from 6.6 to 6.8, and from 6.4 to 6.8 respectively. After harvesting the pH values were in the range from 6.3 to 6.8, and from 6.2 to 6.7 respectively.

The pH values for Mix A in 2020 before planting ranged from 6.6 to 7.0 for the surface, and from 6.6 to 6.8 for the undersurface samples. After harvesting the pH values were in the range from 6.3 to 6.9, and from 6.1 to 6.5 respectively.

The pH values for Mix B in 2020 before planting ranged from 6.7 to 6.8 for the surface, and from 6.4 to

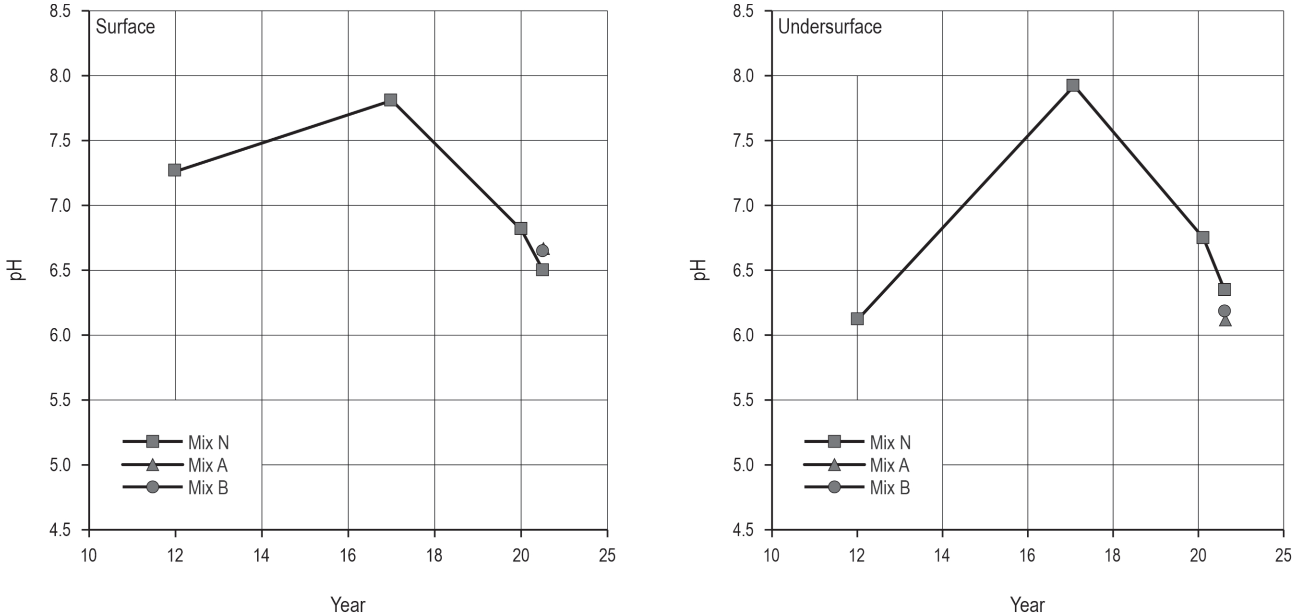

Fig. 3 pH values in years, ash (slag), profile 1 m from road

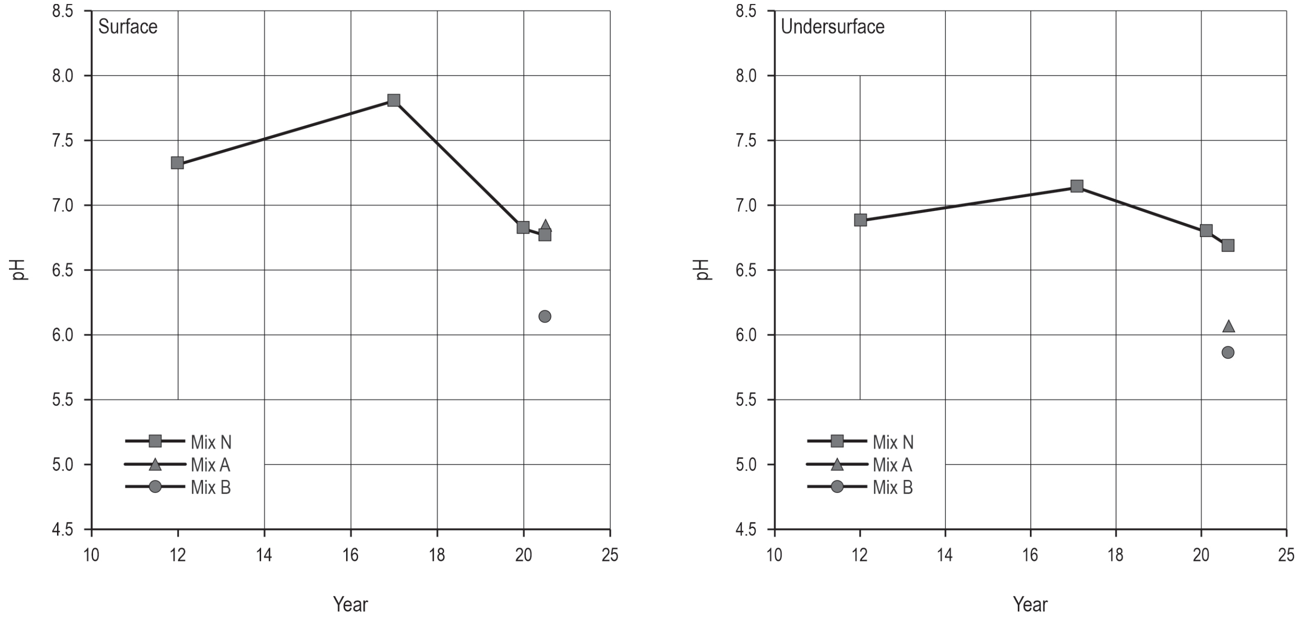

Fig. 4 pH values in years, ash (slag), profile 2 m from road

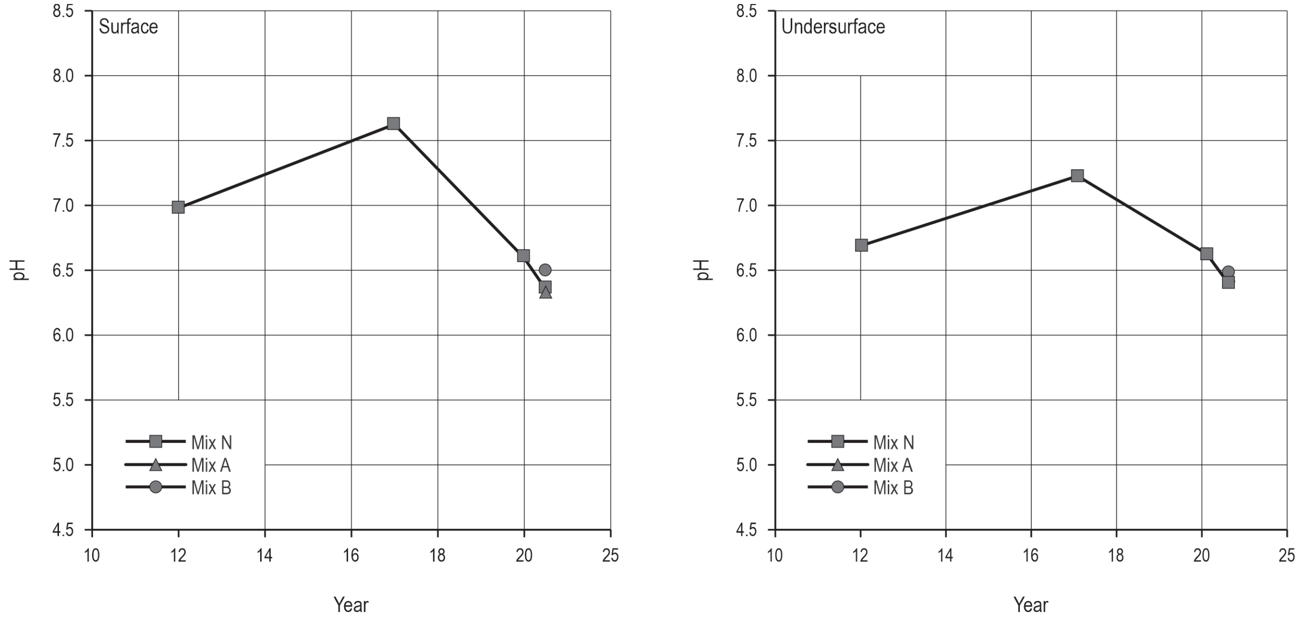

Fig. 5 pH values in years, ash (slag), profile 3 m from road

6.8 for the undersurface samples. After harvesting the pH values were in the range from 6.1 to 6.7, and from 5.8 to 6.5 respectively.

The pH values from Blank tests started at 4.8 in 2012, increased to 5.0 in 2017, and decreased to 4.9 in 2020. The pH value for all samples was acidic.

When comparing the pH values for Mix A, Mix B and Mix N, the same trend can be observed for samples taken in the years 2012, 2017 and twice in 2020. For Mix N the pH value increased in 2017 compared to 2012 for all samples. The increase is slightly larger for samples taken from the surface compared to ones taken under the surface. Thus the grater is the depth from which samples are taken, the lower is the appropriate pH value. The pH value for all samples is neutral. When compared to acidity of samples from Blank

Table 1 pH values and carbonates [%] in years, ash (slag), plant Mix N

	pH							Carbonates, %						
DEPTH	0.00			0.30			BLANK	0.00			0.30			BLANK
PROFIL	1.0	2.0	3.0	1.0	2.0	3.0		1.0	2.0	3.0	1.0	2.0	3.0	
2012	7.260	7.320	6.980	6.120	6.880	6.690	4.780	0.110	0.050	0.000	0.000	0.000	0.000	0.014
2017	7.804	7.806	7.626	7.920	7.138	7.226	4.974	1.672	3.520	1.000	7.640	1.150	0.860	0.005
2020_1	6.812	6.821	6.602	6.745	6.795	6.425	4.902	0.150	0.000	0.000	0.000	0.000	0.000	0.000
2020_2	6.496	6.768	6.360	6.340	6.684	6.200	4.925	0.050	0.000	0.000	0.000	0.000	0.000	0.000

Table 2 pH values and carbonates [%] in years, lime+cement mixture, plant Mix N

	pH							Carbonates, %						
DEPTH	0.00			0.30			BLANK	0.00			0.30			BLANK
PROFIL	1.0	2.0	3.0	1.0	2.0	3.0		1.0	2.0	3.0	1.0	2.0	3.0	
2012	5.240	4.870	5.450	5.220	4.890	5.070	4.780	0.000	0.000	0.030	0.000	0.000	0.000	0.005
2017	7.890	7.936	8.092	7.480	7.674	6.774	4.974	0.828	1.960	1.200	0.960	0.200	0.184	0.000
2020_1	6.822	6.884	7.121	6.428	7.012	6.078	4.902	0.130	1.454	1.120	0.050	0.110	0.090	0.000
2020_2	6.456	6.586	6.770	6.134	6.746	5.918	4.925	0.120	1.288	1.040	0.030	0.110	0.050	0.000

Table 3 pH values in years, ash (slag) and lime+cement mixture, plant Mix A and Mix B

	MIX	A						B						
	DEPTH	0.00			0.30			0.00			0.30			BLANK
	PROFIL	1.0	2.0	3.0	1.0	2.0	3.0	1.0	2.0	3.0	1.0	2.0	3.0	
Ash (slag)	2020_1	6.708	6.948	6.647	6.658	6.692	6.781	6.743	6.696	6.736	6.612	6.452	6.773	4.902
	2020_2	6.668	6.844	6.332	6.116	6.072	6.464	6.642	6.138	6.494	6.180	5.854	6.484	4.925
Mixture	2020_1	6.782	6.981	6.889	6.392	6.801	6.337	6.703	6.977	6.916	6.123	6.925	6.224	4.902
	2020_2	6.552	6.514	6.340	5.826	6.154	6.180	6.418	6.708	6.512	5.790	6.398	6.132	4.925

Table 4 Carbonates [%] in years, ash (slag) and lime+cement mixture, plant Mix A and Mix B

	MIX	A						B						
	DEPTH	0.00			0.30			0.00			0.30			BLANK
	PROFIL	1.0	2.0	3.0	1.0	2.0	3.0	1.0	2.0	3.0	1.0	2.0	3.0	
Ash (slag)	2020_1	0.110	0.000	0.000	0.000	0.000	0.000	0.110	0.000	0.000	0.000	0.000	0.000	0.000
	2020_2	0.050	0.050	0.000	0.000	0.000	0.000	0.150	0.000	0.070	0.000	0.000	0.000	0.000
Mixture	2020_1	0.125	1.600	0.820	0.040	0.095	0.070	0.110	0.950	0.820	0.030	0.080	0.050	0.000
	2020_2	0.120	1.454	0.360	0.000	0.000	0.000	0.060	0.200	0.000	0.000	0.000	0.000	0.000

tests it is quite clear, that there was alkaline inclusion to the surrounding ecosystem and as the result, the soil pH value changes from acidic to neutral.

After the year 2017, the pH value decreased for all plant mixes. For Mix A and Mix B, the larger decrease of the pH value is observed for samples taken under the surface compared with those taken from the surface. For mix N the decrease is more or less the same for all samples. Mix B seems to show the best result for the decrease of the pH value on the surface, followed by Mix N and Mix A. Mix A seems to show the best results for the decrease of the pH value under the surface, followed by Mix B and Mix N. As a whole, plant Mix B seems to be the best choice for phytoremediation of the fluid ash binder alkaline inclusion to the surrounding ecosystem, followed by Mix A and Mix N.

The results for the carbonate content can be found in Table 2 and Table 4. Carbonate content for Mix N as well as Blank tests is close to zero in the year 2012 and thus completely insignificant in comparison with the year 2017. In 2017, the carbonate content increased to a maximum of 7.7%. However, this absolute value can be considered as medium high and thus not very significant as a whole, and especially so, if in the following years the same drop down to values close or even equal to zero occur no matter what plant mix is applied in the cultivation beds.

3.2.2 Lime+Cement Mixture Segment

The results for the pH value can be found in Tables 2–3 and in Figs. 6–8. The pH values for Mix N in 2012 ranged from 4.8 to 5.5 for the surface, and from 4.9 to 5.2 for the undersurface samples. In 2017, they increased to the range from 7.9 to 8.1, and from 6.8 to 7.7, respectively. In 2020, before planting, they were in the range from 6.8 to 7.1. and from 6.1 to 7.0, respectively. After harvesting, the pH values were in the range from 6.4 to 6.8. and from 5.9 to 6.8, respectively.

The pH values for Mix A in 2020 before planting ranged from 6.8 to 7.0 for the surface and from 6.3 to 6.8 for the undersurface samples. After harvesting, the pH values were in the range from 6.3 to 6.6 and from 5.8 to 6.2, respectively.

The pH values for Mix B in 2020 before planting ranged from 6.7 to 7.0 for the surface, and from 6.1 to 7.0 for the undersurface samples. After harvesting, the pH values were in the range from 6.4 to 6.7. and from 5.8 to 6.4, respectively.

The pH value from Blank tests started at 4.8 in 2012, increased to 5.0 in 2017 and decreased to 4.9 in 2020. The pH value for all samples was acidic.

When comparing the pH values for Mix A, Mix B and Mix N, the same trend can be observed as for the fluid ash segment for the samples taken in 2012 and 2017, and twice in 2020. For Mix N, the pH value increased in 2017 compared to 2012 for all samples. The increase is slightly larger for samples taken from the surface compared to those taken under the surface. Thus, the grater the depth from which samples are taken, the lower is the appropriate pH value. The pH value for all samples is neutral.

After the year 2017, the pH value instantly decreased for all plant mixes. For Mix A and Mix B, the decrease is more or less the same for all samples. For mix N, the larger decrease of the pH value is observed for samples taken from the surface compared with those taken under the surface. In terms of the decrease of the pH value, Mix A seems to show the best results for samples taken from both the surface and under the surface, followed by Mix B and Mix N. As a result, plant Mix A seems to be the best choice for phytoremediation of the lime+cement mixture binder surrounding ecosystem alkaline inclusion, followed by Mix B and Mix N.

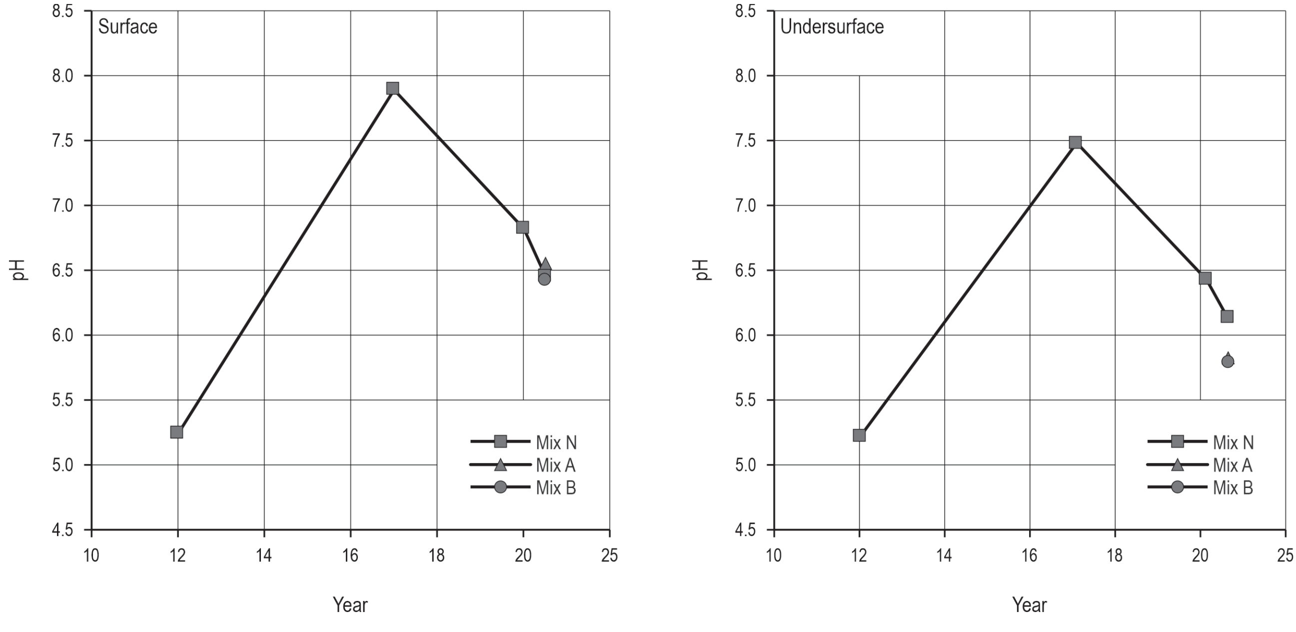

Fig. 6 pH values in years, lime+cement mixture, profile 1 m from road

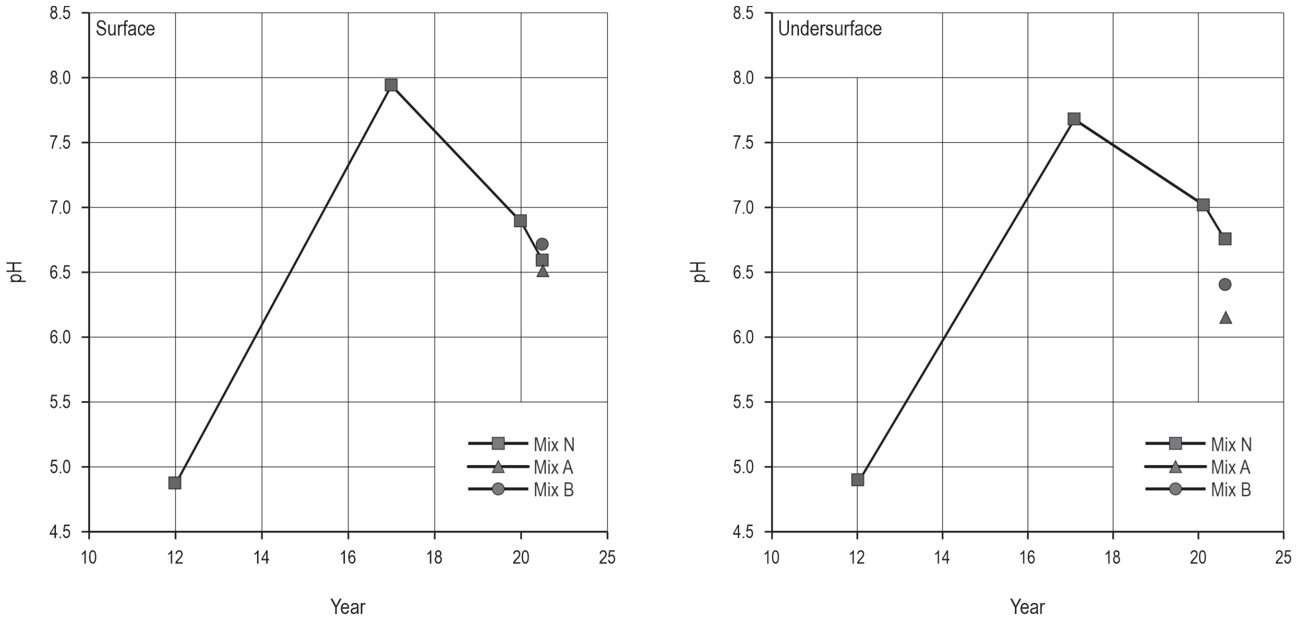

Fig. 7 pH values in years, lime+cement mixture, profile 2 m from road

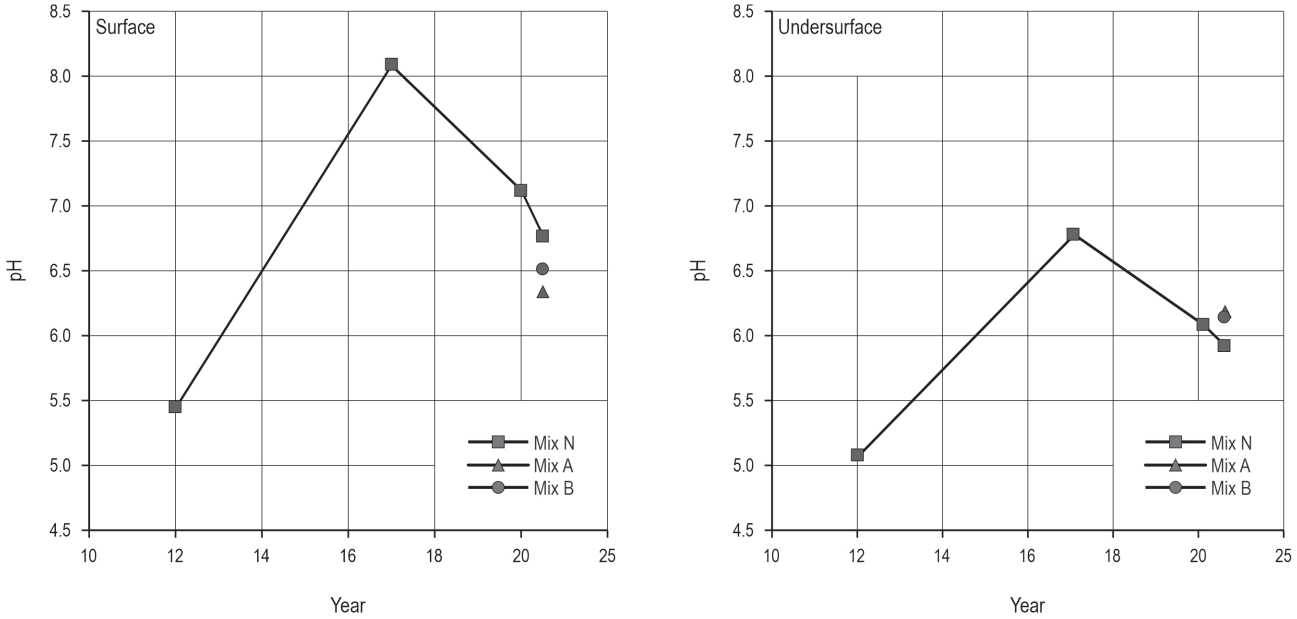

Fig. 8 pH values in years, lime+cement mixture, profile 3 m from road

The results for the carbonate content can be found in Table 2 and Table 4. Carbonate content for Mix N as well as Blank tests is close to zero in 2012 and thus completely insignificant in comparison with the year 2017. In 2017, the carbonate content increased to a maximum of 2.0%, which is more or less 4 times lower than for fluid ash segment. This absolute value can be considered as low and thus insignificant. In the following years, gradual decrease of the carbonate content occurs for all plant mixes. In comparison with the fluid ash binder, the decrease is really gradual and the values in 2020 are close to zero only for samples taken under the surface. For samples taken from the surface, the value up to 1.5% can be observed after phytoremediation process for Mix A, up to 1.3% for Mix N, and up to 0.2% for Mix B.

4. Discussion

The study has shown that the use of hydraulic binders in the forest and rural roads construction leads to alkaline inclusion to the surrounding ecosystem. After the application of hydraulic binders, both in 2012 after the road construction was completed and especially in 2017 after five years of road use, there was an increase of the pH value as well as an increase of the total amount of carbonate in the surrounding ecosystem. As the results show, a greater change of pH values occurs at the surface compared to the pH values under the surface, both for the case of fluid ash and of the lime+cement mixture. In the case of surface alkaline inclusion, its intensity does not seem to be dependent on the distance from the road from which samples were collected. In contrast, undersurface samples taken closer to the road show higher pH values. There were no major differences between the two hydraulic binders analysed in this context.

Surface alkaline inclusion seems to be a result of the pavement construction process and the main factor influencing its intensity is the failure to respect the desired construction technology – e.g. application of hydraulic binders under higher wind intensity, use of inappropriate equipment or machines, etc. – required by the relevant construction standards or codes. Higher pH values are therefore achieved immediately after the road construction is completed.

The alkaline inclusion to the surrounding ecosystem under the surface is delayed in time after the surface alkaline inclusion as a result of water erosion, i.e. the result of the binder leaching from the improved subgrade. The alkaline inclusion intensity depends on a number of factors. First and foremost is the influence of the binder type used and the subgrade type, because their interaction determines how tightly they are bound and thus how successful is the soil improvement. If it is successful, leaching by water erosion is lower than otherwise. The self-evident consequence is that there is less alkaline inclusion to surrounding ecosystem in the first case and more alkaline inclusion in the second one. Another factor is the influence of the natural ecosystem, and in particular the influence of the water erosion intensity and the groundwater level. In the case of a higher intensity or a higher groundwater level, even in the case of successful application of hydraulic binders, the leaching to the surrounding ecosystem is higher.

When comparing the results obtained with the results from other areas where phytoremediation has been used, some similarities could be found. For example, in the paper »Phytoremediation: an alternative to eliminate pollution« (Delgadillo-López et al. 2011), where the application of phytoremediation for the stabilization of heavy metals pollutants, radioactive metals, organic compounds and compounds derived from petroleum, is described. The plants used were *Helianthus annuus* L., *Brassica napus* L., *and Cichorium intybus* L. Their use had a positive effect on soil improvement, as shown by the presented results. In a similar study (Ling Ma et al. 2015) describing rehabilitation of acidic mines drainage sites, the above obtained results were confirmed. Different plant mixtures and single plants were used to demonstrate their ability to survive in acidic ecosystems. It was shown that most of the plant species mixtures grown in moderately acidic soil could not survive at pH 2.0 or lower, while 13 plant species were identified as strongly acidic tolerant. In another phytoremediation study (Cai et al. 2021), phytoremediation was used to improve the mine waste ecosystem as well as to solve contamination problems in the subgrade around mine waste and to initiate ecological subgrade restoration. Although the results obtained in our study were not so ultimate, they are in agreement with the results of the above mentioned studies. In all cases, the obtained results of observed parameters show decreasing trends after the initial increase, depending on the hydraulic binder used for soil improvement and the vegetation mixture used for phytoremediation process. At the same time, it should be pointed that our results do not provide any generalizable rule confirming a significantly higher influence of one of the studied mixtures compared to other.

It should also be noted that the influence of carbonates on vegetation as well as on different subgrade characteristics varies and should also be positive. The positive effect, among others, can be seen in increasing pH value, which consequently positively influences the plants growth due to the optimum plant nutrient supply. The optimum supply and maximum nutrient availability for plants is reached under the neutral pH value in the interval 6.0 – 7.5 (Gazey 2018, Miller 2016). Also. there is better particle and structure aggregation, improved soil aeration and water movement, reduction of Al, Mn and Fe toxicity as well as the improvement and development conditions for microorganisms growth (Goulding 2016).

5. Conclusions

The use of hydraulic binder materials for pavement subgrade improvement has many implications for subgrade, secondary for vegetation and generally for the surrounding ecosystem as a whole. These materials are capable to alter the subgrade chemistry in the immediate vicinity of the road, and to start changing the surrounding subgrade affected by alkaline inclusion from the original quality.

After reaching the maximum alkaline inclusion level and the maximum subgrade pH value, the alkaline inclusion starts to decrease. A different trend can be observed for surface and undersurface samples. It is characteristic for both types of hydraulic binders analysed that the decrease is faster for higher pH values, i.e. for samples taken at the surface. It is also characteristic that the success of phytoremediation for Mix A and Mix B does not differ much from Mix N for samples taken on the surface for both hydraulic binders. For undersurface samples, phytoremediation success can be observed for both Mix A and Mix B. Mix B appears to be the best for fluid ash binder and Mix A for lime+cement mixture binder. It is worth noting that the native natural vegetation in Mix N also contributes to phytoremediation process and that appropriate plant selection – e.g. plant Mix A and plant Mix B – can accelerate this process.

It is also necessary to note the undoubted influence of the surrounding natural ecosystem, in particular the influence of the water erosion intensity and the groundwater level, on the alkaline inclusion intensity. The higher the water erosion intensity or the higher the groundwater level, the greater the leaching into the surrounding ecosystem, even in the case of successful application of hydraulic binders. At the same time, however, the alkaline inclusion is spread over a larger area, thus reducing its intensity in the closer vicinity of roads.

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Received: October 05. 2023
Accepted: January 28. 2024

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