

The use of mineral materials for salinity control in roadside soils

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Abstract: This paper presents the results of a field study on using mineral materials (fine-grained sand and medium-grained gravel) to reduce the concentration of readily soluble salts in a roadside environment. The investigated soils were Rendzic Sceleptic Leptosols from an urban area characterized by a shallow humus horizon with a high content of skeletal parts, as well as a lack of homogeneity of the material in the soil profile. All soil samples were taken from five plots located along the main streets in the city of Opole (Southern Poland). It was revealed that the use of fine-grained sand and medium-grained gravel improved the structure of the surface soil layer, and thus favoured the migration of Na^+ and Cl^- ions into the soil profile. In comparison to control surfaces readily soluble salts were reduced with gravel and sand application. Furthermore, the mineral materials introduced on the soil surface for salinity neutralization did not affect the quality of the tested roadside calcareous soils. The results indicate that the use of mineral materials reduces soil salinity caused by NaCl . They also show the need to find new methods of salt neutralization, especially of roadside soils in order to improve and protect the quality of the environment.

Introduction

The harmfulness of chemical substances used for winter maintenance of roads is known as a form of environmental contamination and has been researched since the 1970s (Judd, 1970; Siuta, 1982; Abrol et al., 1988; Turunen, 1997; Koryak et al., 1998), i.e. when many countries began to use substances to reduce the slipperiness of roads and sidewalks. Currently, the most commonly used substances include materials that increase the roughness of the surface, as well as chemical substances, such as chlorides, formate acetates and glycols (Fay and Shi, 2012). Sodium chloride (NaCl) is frequently used mainly due to its low price and high melting efficiency (Berkheimer and Hanson, 2006). Excessive use of NaCl (mainly in urban areas) contributes to the high accumulation of these compounds in surface soil layers, increasing the salinity of areas near roads or sidewalks (Blomqvist and Johansson, 1999; Bryson and Barker, 2002; Green et al., 2008). Research on the range of impact of road salts showed that from 20 to 63% of the salt used on sidewalks and streets can spread great distances by air in the form of aerosols (Blomqvist and Johansson, 1999). Taking into account the systematic – yearly – application of readily soluble salts on roads there can be an excessive accumulation of these substances which can lead to the degradation of soil quality in urban ecosystems. Salt causes negative changes in the physical and chemical properties of roadside belt soils.

An excess of Na^+ may be associated with negatively charged mineral and organic components of soils (clay-humus

complex), which causes the release of Zn, K, Cu, Mn or Ca ions from the sorption complex, thereby changing the soil structure through the formation of large aggregates (Fay and Shi, 2012). In the study of Dmuchowski et al. (2014), the Cl^- ions had a lower impact on the changes of chemical soil properties than sodium ions. Long-term salt accumulation in the soil is also becoming an important factor affecting the health of vegetation along roadside areas. Increased salt concentration in the soil often contributes to excessive uptake of sodium and chloride ions by plants, causing significant damage (Paludan-Müller et al., 2002; Kwasowski and Czyż, 2011; Cekstere and Osvalde, 2013; Łuczak and Kusza 2015), and often causes their premature dying (Dmuchowski et al., 2014). The application of these substances also contributes to groundwater contamination (Ramakrishna and Viraraghavan, 2005; Cunningham et al., 2008; Kelly et al., 2008).

Therefore, it is necessary to find new methods of reducing the negative impact of chemical substances used for winter road maintenance on the roadside environment, in particular on roadside soils and green areas (Anwari et al., 2020; Srivastava, 2020). Currently applied methods (e.g. flushing) cannot always be used in roadside areas due to their location or the expense. Irrigation can decrease the salt concentration in the surface soil, leading to its leaching deeper into the soil profile (Haj-Amor and Bouri, 2019). The disadvantage of this method is the release of important nutrients and salts, limiting their availability to plants. Also, in soils of low permeability, e.g. loamy, ion elution is very limited (Youngs and Leeds-Harrison,

2000). One of the easiest methods to improve the physical properties of salty soils, especially clay soils, is to introduce natural aggregates with a high content of gravel or very coarse sand. Homogenization of this material with the top surface soil (0–30 cm) contributes to loosening the soil structure, and thus increases soil filtration (Maciak, 2003).

The aim of this paper is to develop the alternative method of improving physical, physico-chemical and chemical properties of the soils of roadside areas using selected mineral materials such as sand and gravel.

Concerning the use of mineral materials mixed with the surface soil (M), we hypothesized that the soil structure would be improved by loosening since there would be free migration of Na⁺ and Cl⁻ ions in the soil profile (Tan et al., 2018).

Materials

In our study natural aggregates were used, namely, sand and gravel, due to their availability and low purchase costs. The first finely-grained material was sand, with a fraction of 0.1–0.25 mm. The second material was a medium gravel, with a fraction of 5–20 mm. As a result of sifting, admixtures of sands and clays, i.e. smaller aggregate particles, were removed from the gravel.

Study area

The study was carried out on five permanent areas on the main streets of the city of Opole (Southern Poland). The climate of Opole is mesothermal, with low temperature amplitudes, an average amount of precipitation, the dynamic occurrence of thermal seasons in the first half of the year followed by mild winters in the second half of the year, which results in a long growing season (Skowera et al., 2016). During the research period (2016–2017), the average monthly air temperature in the coldest month (February) was -5.3°C, while in the warmest month (July) it was 20.6°C. Precipitation was slightly lower than the average recorded for the years 1981–2010. The highest monthly average precipitation was recorded for October 2017. – 63 mm, while the lowest was in April 2017 and amounted to 17 mm. The experimental sites were selected on the basis of the dominant soil type in Opole. There were Rendzic Sceletic Leptosols (WRB) with typical soil profiles for urban areas (Kabała et al., 2019). There are shallow (up to 30 cm) soils developed from marls. In October 2016, a soil transect containing five identical, separate squares 1m x 1m was marked at each experimental site (or plot). These squares were located directly by the side of the road, next to the sidewalk. The road sections selected had intact asphalt surfaces. In this way, we tried to eliminate any uncontrolled splashes of slush or rainwater. They were located a considerable distance from intersections and pedestrian crossings in order to avoid an additional, uncontrolled concentration of readily soluble salt used to remove slippery conditions on pavements. The materials were deposited on the experimental plots in two ways. With the first method the plot was covered freely with the selected experimental material. The purpose was to remove green vegetation (grass) growing on this area. Then the prepared substrate was lined with agrotexile to prevent mixing of sand or gravel with the soil. The used materials (sand and gravel)

were spread out on squares to give a 10 cm thickness. In order to limit the mixing of the used materials with that outside each plot, a 10 cm high dike of the original soil was prepared. The plots were identified using the following abbreviations: S – surface with a top level of sand, G – surface with a top level of gravel. The second method involved mixing the surface level of soil (10 cm) with the mineral material used. Then, soil material from a depth of 0–10 cm was selected from each experimental square and, after homogenization with 10 dm³ of sand or gravel, it was stored in a plastic container. The prepared substrate was laid out on the surface of the marked squares, and identified with the following abbreviations: S–M – soil with sand, G–M – soil with gravel. A control (C) study area was also marked for each experimental plot – soil without mineral materials.

Field Research

The road soils were sampled three times: in October 2016, April 2017, and October 2017, thereby including all seasons. A steel drill was used to take soil samples from two depths: 0–10 cm and 10–30 cm. The samples were placed in plastic containers and transported to the laboratory. The agrotexile was removed before soil sampling. After soil sampling, the 10 cm high dike of the original soil was prepared again. One soil sample consisted of 5 individual collections from the entire surface of the experimental squares.

Laboratory analysis

The soil samples were air-dried at room temperature homogenized and sieved through a 2 mm mesh to separate skeletal parts from the fine earth fraction. According to standard methodology of pedology (Ostrowska et al., 1991; Kabała and Karczewska, 2017) and selected norms, the following were determined: granulometric composition according to the areometric method with additional removal of carbonate; the pH in H₂O and 1M KCl (soil/water weight ratio – 1:2.5); conductivity salinity – by using a method based on EC electrical conductivity (soil/water weight ratio – 1:5); in the water soil extract (soil water weight ratio – 1:5) – the content of cations and anions; magnesium was determined by atomic absorption spectroscopy using a Thermo iCE 3500; sodium, potassium and calcium by emission spectrometry using a BWB XP flame photometer BWB Technologies UK LTD; sulfates by the turbidimetric method; chlorides by the argentometric method, and carbonates by the acidometric method.

All physicochemical and chemical analyses were performed in triplicate and the interpreted results are the mean of these measurements.

Statistical analysis

Statistical analysis was done using the Statistica 13.1 program (StatSoft Polska), the non-parametric Friedman test and Spearman correlation test. P <0.05 was calculated as statistically significant.

Results and discussion

Salinity associated with anthropogenic activity is a global and ever-increasing hazard, which can be environmentally devastating, especially in urban areas. The use of de-icing

salts, primarily NaCl, for the maintenance of winter roads has become a common practice in many countries (Cekstere et al., 2008; Czarna, 2014b; Daliakopoulos et al., 2016; Asensio et al., 2017). The necessity of salinity reduction has led to the search for a substance or dosing method which will decrease the negative impact of readily soluble salts entering the soil environment. Currently, many research is being conducted throughout the world to determine the essential features of such a universal and environmentally friendly material, characterized by: naturalness, physical and chemical stability, as well as low costs (de Santiago-Martín et al. 2016). The results presented in this paper are a continuation of an environmental study initiated by Kochanowska and Kusza (2010), which dealt with changes of the physico-chemical properties of soils as a result of readily soluble salts used in the winter maintenance of streets in the city of Opole. Based on their study conducted in 1994 and 2009, the authors (Kochanowska and Kusza 2010) indicated that the concentration of hazardous ions, coming from substances used for melting snow on roads, depended on the amount, type and frequency of use, the localization and busyness of communication routes, and also on the specific properties of different soil types. In this paper it was emphasized that the chemicals currently used in winter road maintenance contribute to the progressive degradation of roadside soils.

Therefore, it is necessary to develop new methods of protecting roadside soils against excessive concentrations of readily soluble salts introduced into the environment. It was assumed that this would decrease the salinity of roadside soils. Our results suggest to reject of the above assumption. We observed changes or texture – the skeletal parts increased to 37% in the 0–10 cm level (GM) (Fig. 2) and the sand fraction increased to 10% in the 0.1–0.25 mm level (SM) (Fig. 1). At the same time, a significant decrease of the salinity in the soil profile was not observed. Comparing both materials, it is important to highlight that better soil parameters of gravel objects (G) may result from the grain size of this material.

Analyzing the chemical properties the ranges of Na⁺ and Cl⁻ ions in the studies are notable. The ranges obtained were in agreement with other studies (Bryson and Barker, 2002; Cekstere et al., 2008; Cunningham et al., 2008). This may indicate a similar, global scale of this problem with salinity of street soils. However, the intensity of this process depends on the texture of the soil (Garakani et al., 2018). In terms of mineralogy the tested soils consisted mainly of quartz (0–10 cm layer), but the parent rock was calcite. This measurably affected the properties of the soils, including: neutral or slightly alkaline pH, the dominance of the Ca²⁺ among other exchangeable cations and a low concentration of calcium carbonate (Licznar,

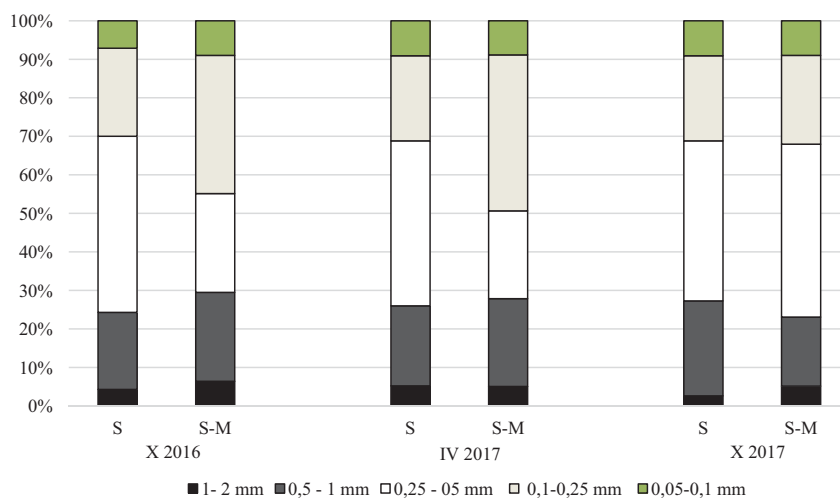


Fig. 1. Diversity of the percent of sand fraction (0.05–2 mm) in soil material taken from objects S and S-M (0–10 cm)

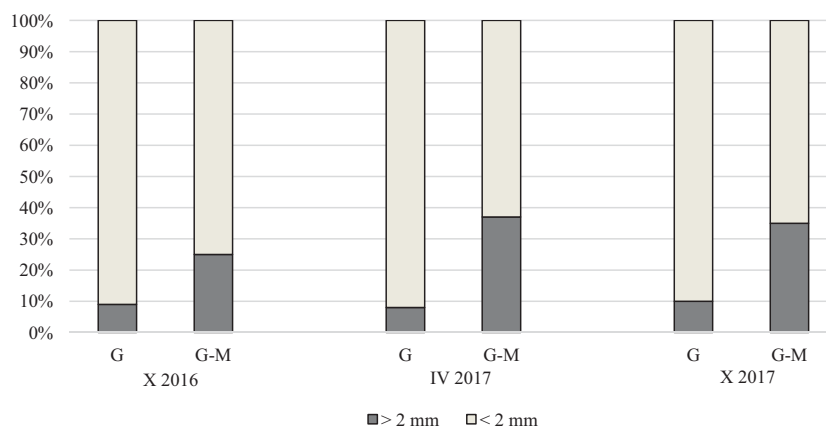


Fig. 2. Changes in the grain size distribution of soil samples taken from G and G-M objects (0–10 cm); skeletal parts (> 2mm), clay (<2mm)

1976; Kochanowska and Kusza, 2011). Therefore, one should individually approach the problem of salinity in correlation with the type of soil, especially the interpretation of the content of separate ions of readily soluble salts. Despite the carbonate nature of the parent rock, no alkaline pH was found in the tested soils. Both measurements in H_2O and in KCl indicated neutral or slightly alkaline pH (in $H_2O = 6.8-7.4$, in 1M KCl = 6.6–7.1). It was noticed that a seasonal increase of soil salinity (after a period of winter use of readily soluble salts) did not cause changes in pH. These observations were confirmed by Licznar (1976).

The content of sodium and chloride ions showed a significant increase immediately after the use of salt for winter road maintenance in all tested surfaces and in each level of the soil profile. In the analyzed research periods, G–M objects were characterized by the lowest sodium ion content within the entire soil profile. The loosening of the surface soil level after gravel application positively affected the migration of ions into the profile, and helped to decrease the salinity of the surface. In the second and third research periods (April and October 2017), the average values of Na^+ at G–M objects were 24% lower than in other objects (Fig. 3). This is another premise for the possibility of using gravel to improve the chemical properties of saline soils.

Chloride ions, as anions, undergo different processes in soil than cations. This ion is washed relatively quickly by rainwater

deeper into the soil profile and migrates to groundwater (Howard and Maier 2007). In the study in Opole loosening of the soil of the 0–10 cm level did not change the Cl^- value in the analyzed layers during all research periods. In the second experimental period, the average values for all objects were $37 \text{ mgCl}^- \cdot 100\text{g}^{-1} \text{ d.m.}$ and in the third – $22 \text{ mgCl}^- \cdot 100\text{g}^{-1} \text{ d.m.}$ However, in the 10–30 cm level, the Cl^- concentration was almost twice as high, especially in the period after the winter use of readily soluble salts (for SM and GM, the average values ranged from 53.7 to 54.2 $\text{mgCl}^- \cdot 100\text{g}^{-1} \text{ d.m.}$) (Fig. 4). This parameter exhibited seasonal variation, by a two-fold decline of the content of this ion during the following 6 months. Comparing the Cl^- content of the surface soil layer (0–10 cm) with mulch application (S and G) and mixed mineral material (SM and GM), loosening the soil structure contributed to the free migration of chlorides into a deeper soil profile. Therefore, it would be beneficial to use mineral materials with larger diameters mixed with saline soil. Based on the results of our experiment, the application of mineral materials on the surface of objects did not clearly decrease hazardous salt concentrations in the studied soils. A significant increase of the of Na^+ and Cl^- ions in the soil profile was observed after the winter period, as a result of the application of readily soluble salts during the winter. In the surface level of soil, the Na^+ content after the winter period (April 2017) was about $250 \text{ mg} \cdot 100\text{g}^{-1} \text{ d.m.}$, with

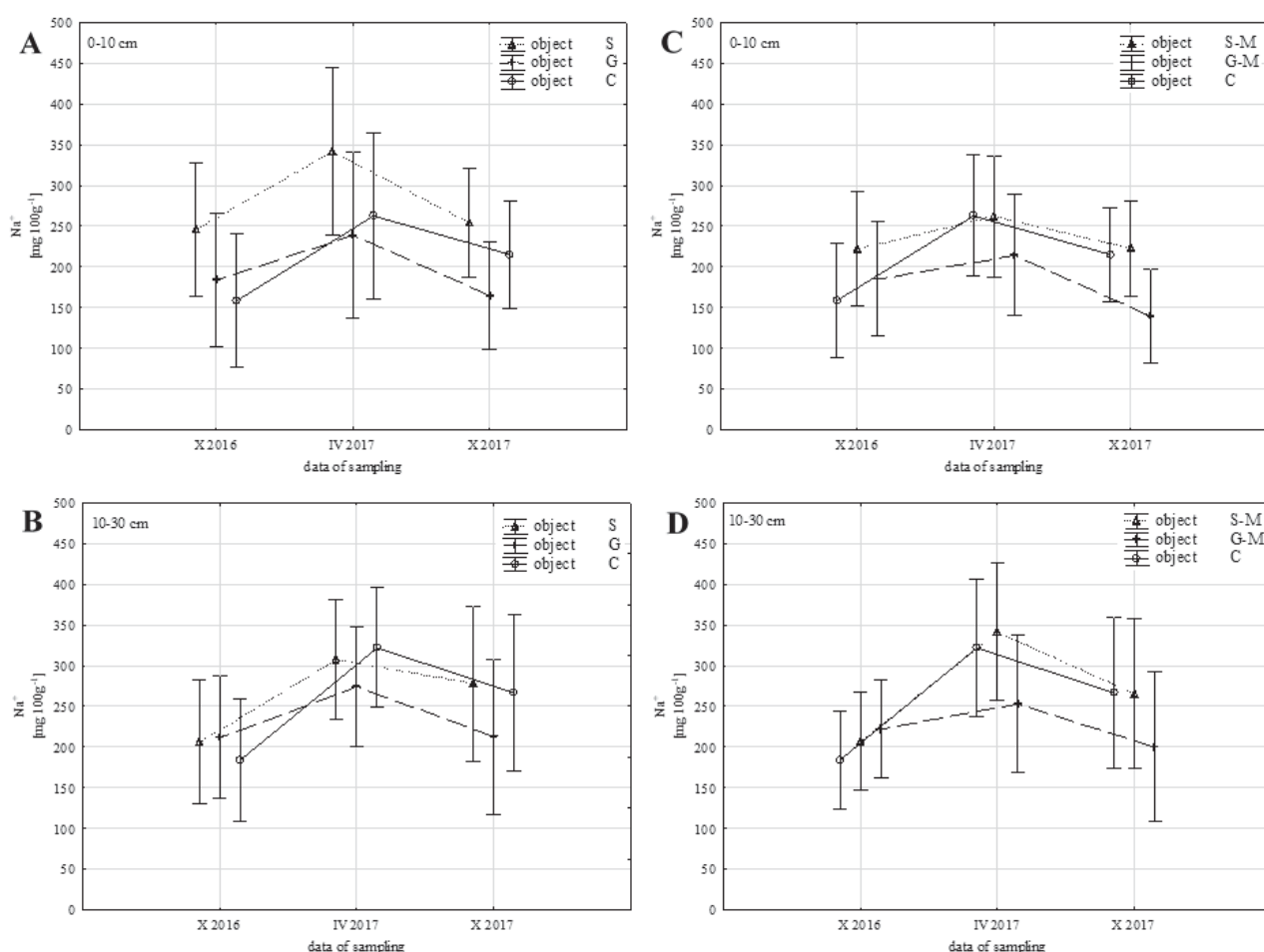


Fig. 3. The rate of changes of sodium ion content in the analyzed research periods. (A) – 0–10 cm level on objects S, G and C; (B) – 10–30 cm level on objects S, G and C; (C) – 0–10 cm level on objects S–M, G–M and C; (D) – 10–30 cm level on objects S–M, G–M and C.

the highest values found in surface levels with sand application (about $342 \text{ mgNa}^+ \cdot 100\text{g}^{-1} \text{ d.m.}$). This may indicate a lack of effectiveness of sand mulching of soils exposed to periodic salinity. This tendency is confirmed by Gan et al. (2008) and Zare et al. (2015). At the level of 10–30 cm in the soil profile, the values of this parameter were lower, in the range of $275\text{--}322 \text{ mgNa}^+ \cdot 100\text{g}^{-1} \text{ d.m.}$ This may indicate a basic accumulation of sodium ions in the surface level of soil and its slower migration into deeper levels of the soil profile. However, from a practical point of view, the objects with gravel application are very interesting for research. The lowest values of sodium ions in all research periods in the surface level, compared to objects with sand were observed. In the third research period (October 2017), the Na^+ values for G objects were about 23% lower than the values of this parameter at S objects. The reason for this phenomenon can be seen in the possibility of limiting the water flow up to the pores between the gravel, which leads to a reduction of evaporation (Xie et al., 2006; Yuan et al., 2008). Studies have shown that thicker layers of gravel are able to prevent evaporation more effectively (Qiu et al., 2014; Feng et al., 2018).

After winter the chloride ion content was doubled both in the surface level and the deeper level (10–30 cm) of the tested object. However, it cannot be definitely confirmed which of the analyzed materials used as mulch, can decrease the content

of this parameter in the soil profile. This may result from the individual properties of this ion (Howard and Maier, 2007). Electrical conductivity (EC) showed great seasonal diversity, similar to the content of Na^+ and Cl^- ions. After winter, the values of EC increased significantly, regardless of the depth in the soil profile. But the value of EC for the objects with a mixture of sand or gravel was lower (in the 0–10 cm layer) than analogous objects with a mulch and control (Fig. 5). This situation was particularly evident in the second experimental period. At the 10–30 cm level of analyzed soil profiles, the reverse trend could be observed. Therefore, it is difficult to clearly indicate which type of test application showed the best properties for decreasing electrical conductivity.

To determine the relationship between electrolytic conductivity and the content of selected ions found in the aqueous extracts of the studied soils, the Spearman correlation coefficients were calculated, for both the 0–10 cm and 10–30 cm levels. In the studied soils, a strong positive relationship between EC and Na^+ and Cl^- ions was observed in all research objects. For Na^+ content, the highest statistically significant correlation coefficient was calculated in the range 0.493–0.944 (10–30 cm layer). A similar relationship was found for the content of chloride ions in this same level and ranged from 0.508 to 0.979 (Table 2). In addition, a positive effect of the content of Ca^{2+} , K^+ and Mg^{2+} ions on the EC values in the

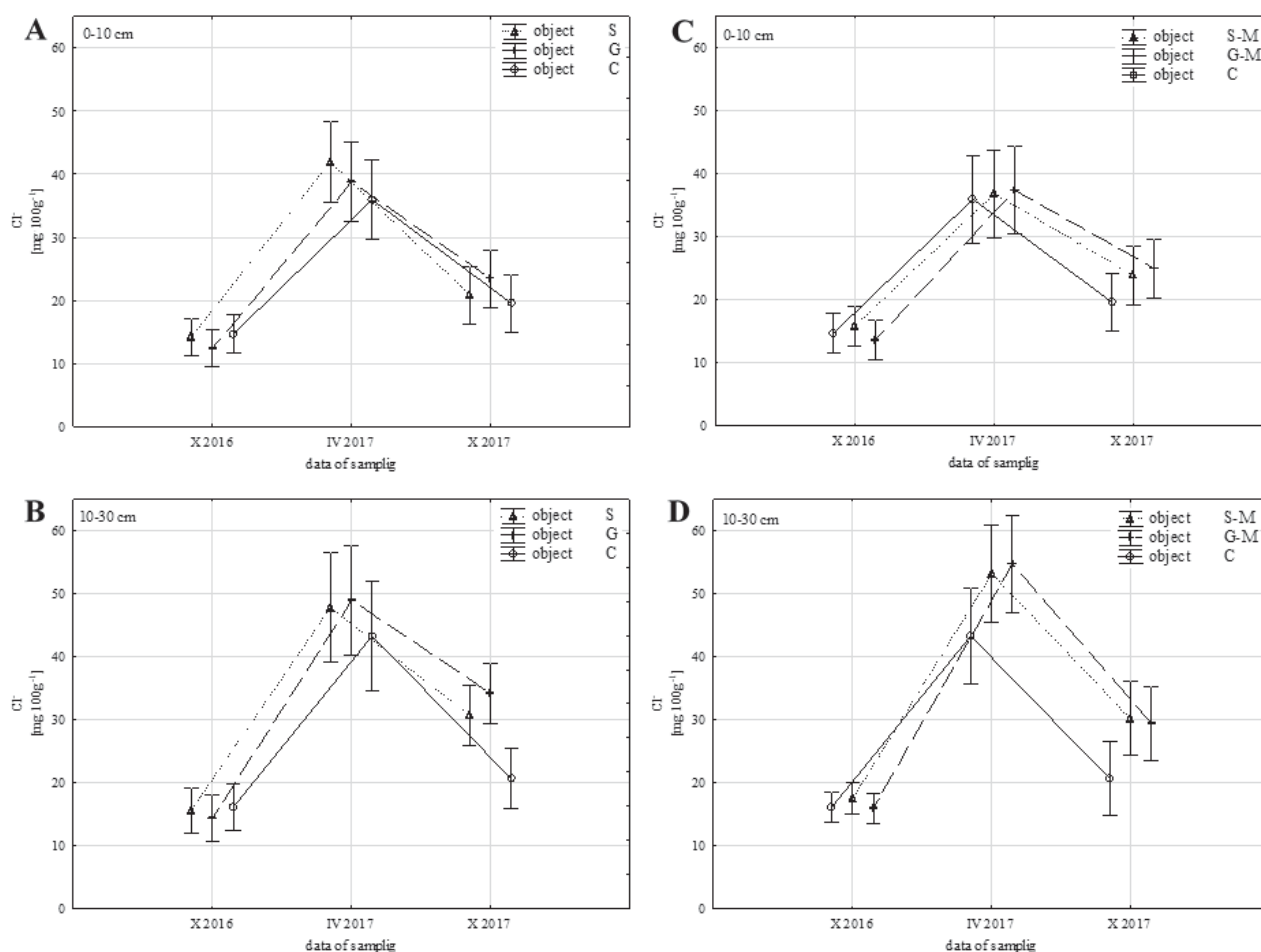


Fig. 4. The rate of changes of chloride ion content in the analyzed research periods. (A) – 0–10 cm level on objects S, G and C; (B) – 10–30 cm level on objects S, G and C; (C) – 0–10 cm level on objects S–M, G–M and C; (D) – 10–30 cm level on objects S–M, G–M and C.

0–10 cm layer was shown (Tab. 1). The amount of these ions may be a result of the homogenization of soil material, and thus a significant effect of the parent rock on the entire soil profile. In the deeper level to 30 cm the effect of the concentration of potassium and magnesium ions was eliminated to benefit the ions of HCO_3^- content – which strongly affected the EC values ($r = 0.294$). The observed tendency was a result of the features of the parent rock (Licznar 1976). This can be a result of significant changes in the soil sorption complex, especially in a situation where other ions of readily soluble salts enter the soil environment.

The best parameters were found in soils of G and G–M objects, however, applying gravel and gravel mixed with soil or separately applied on the surface may not help decrease the ion content of readily soluble salts in analyzed soils of

Opole. Therefore, the possibility of using mineral materials with a larger diameter for soils with low salinity can be recommended, especially in areas with large amounts of atmospheric precipitation (Xie et al., 2006).

Conclusions

Based on results, it can be concluded that selection of materials applied to the surface layers of road soils can reduce the negative impact of excessive amounts of readily soluble salts on the soil environment the soil environment as a result of winter road maintenance.

The loosening of the structure of the topsoil or uppermost part of soil after gravel application favoured the free migration of Na^+ and Cl^- ions into the soil profile, consequently reducing

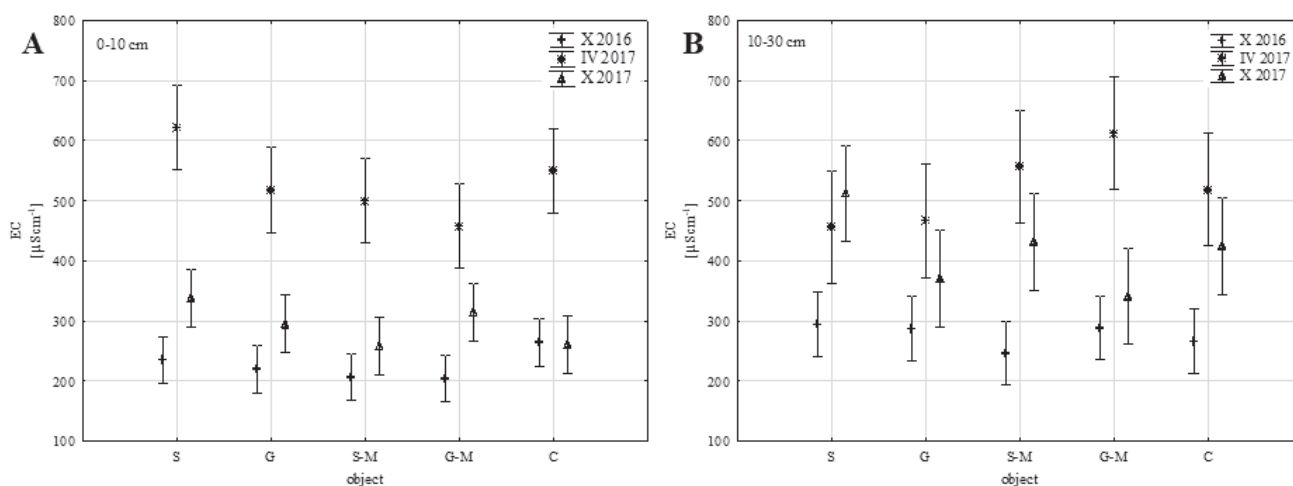


Fig. 5. Values of electrical conductivity (EC) in the analyzed research periods. (A) 0–10 cm; (B) 10–30 cm.

Table 1. Spearman's correlation coefficients calculated between EC and Na^+ , K^+ , Ca^{2+} , Mg^{2+} , HCO_3^- , Cl^- , SO_4^{2-} values determined in the water extract of soil material taken from a depth of 0–10 cm in the soil profile ($p < 0.05$), * significant values were determined statistically

Objects	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	SO_4^{2-}
Total	0.758*	0.745*	0.794*	0.424*	0.175	0.783*	-0.007
S	0.421*	0.865*	0.873*	0.707*	-0.169	0.590*	-0.452
S–M	0.917*	0.628*	0.839*	0.502	0.320	0.936*	0.075
G	0.923*	0.597*	0.492	-0.415	0.369	0.936*	0.010
G–M	0.673*	0.395	0.211	-0.035	0.453	0.637*	0.837

Table 2. Spearman's correlation coefficients calculated between EC and Na^+ , K^+ , Ca^{2+} , Mg^{2+} , HCO_3^- , Cl^- , SO_4^{2-} values determined in the water extract of soil material taken from a depth of 0–30 cm in the soil profile ($p < 0.05$), * significant values were determined statistically

Objects	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	SO_4^{2-}
Total	0,915*	0,187	0,602*	0,034	0,294*	0,938*	0,120
S	0,944*	0,032	0,687*	0,628*	0,402	0,979*	0,667
S–M	0,901*	0,285	0,840*	0,700*	0,209	0,894*	-0,052
G	0,768*	0,061	0,212	-0,681*	0,010	0,777*	-0,416
G–M	0,493*	0,301	0,316	-0,180	0,357	0,508*	-0,038

the salinity in the topsoil. However, sand application did not measurably improve the chemical properties of the analyzed soils throughout the entire profile.

We believe that our findings can be useful for development of new methods of neutralizing the salinity of roadside soils, and to improve the quality of the environment.

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