




Heterogeneity of soil substrate as a factor determining the quality of soils developed on spoil heaps of carbonate raw material mines

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ABSTRACT

In this study we determined the influence of the type of spoil material (clayey and sandy) used in the reclamation process on the course of soil-forming processes as well as on the physical and chemical properties of the developing soils. The study covered 16 reclaimed sites located on the spoil heaps of the “Góraźdże” limestone mine and three reference sites representing forest soils. The physical and chemical soil parameters such as: granulometric composition, pH in KCl, calcium carbonate content and cation exchange capacity (CEC) were determined in accordance with applicable standards and accepted soil science methodology. It was demonstrated that the application spoil material with a clayey granulometric composition promotes the formation of soils with a high nutrient storage capacity, and thus a high potential fertility. Additionally, the elevated calcium carbonate (CaCO₃) content contributes to the development of a stable, near-neutral pH, which is expected to enhance the soils' resistance to acidification over time.

Keywords: technogenic soils, reclamation, post-mining areas.

INTRODUCTION

Human activity, currently recognized as an important soil-forming factor, leads to the development of anthropogenic soils, often strongly modified or formed as a result of industrialization, including mining activities. These soils develop on unconsolidated mineral and organic materials originating, among others, from mining wastes that create new parent materials subjected to soil-forming factors (Strzyszczyk, 2003; Siuta et al., 2012; Cohen-Fernández and Naeth, 2013). Under such conditions, distinguishing between natural and anthropogenic disturbances of pedogenesis is often difficult.

Open-pit mining, despite its considerable economic importance, leads to extensive environmental degradation, including transformations of land relief and destruction of the soil cover (Szopka et al., 2005; Karczewska, 2012; Chodak, 2013). As a result, areas of barren land are formed that require reclamation measures aimed at restoring the functional and natural value of degraded areas

in accordance with applicable legal regulations (Gołda, 2005; Kasztelewicz, 2010; Krzaklewski, 2017). A key element of reclamation is the creation of conditions conducive to vegetation development and the restoration of soil functions.

The character of reclaimed spoil heaps and excavations depends on the type of exploited raw material. In the case of sites after the extraction of carbonate raw materials, particular limitations include a high proportion of rock debris containing calcium carbonate, alkaline soil reaction, and a deficit of biogenic elements, which excludes agricultural reclamation (Kusza and Gołuchowska, 2009; Cohen-Fernández and Naeth, 2013; Kusza, 2015).

The most commonly applied solution is forest-oriented reclamation using spoil materials of varied granulometric composition derived both from overburden layers occurring above the deposit and from raw material processing (Rosik-Dulewska et al., 2008; Kacprzak and Bruchal, 2011).

The aim of this study was to determine the influence of the type of substrate used on the course

of soil-forming processes and on the properties of technogenic soils developing on spoil heaps of carbonate raw material mines.

MATERIAL AND METHODS

Characteristics of the research site

The research plots were established on internal spoil heaps of the “Górażdże” limestone mine located in the south-western part of the country, in the Opolskie Voivodeship, in the village of Górażdże, Gogolin municipality. In the immediate vicinity of the deposit there are state forest areas belonging to the Strzelce Opolskie Forest District and the area of the village of Górażdże (Rosik-Dulewska et al., 2008).

In the central part of the deposit, the “Kamień Śląski” nature reserve is located, for which a protective pillar with a width of 200 m from the reserve boundaries was established on the basis of the decision of the District Mining Office in Gliwice dated 26 March 1977.

The study was conducted on 16 sites located on reclaimed internal spoil heaps (5Z–20Z) and on three reference sites representing forest soils (1RL–3RL) (Figure 1). The research sites differed in the type of reclamation material used (sandy and clayey formations) and in the time elapsed from spoil heap formation to completion of reclamation works.

Soil profile structure of the designated research areas

Fieldwork was carried out in August and September 2022. A total of 19 soil pits were excavated at the selected sites to expose soil profiles. Field investigations included the assessment of basic morphological soil features, such as the number and thickness of soil horizons.

In profiles where it was not possible to clearly distinguish genetic horizons, arbitrary layers were defined at the following depths: 0–10, 10–30, 30–50, 50–70 cm, and below 70 cm. Soil classification was carried out according to the World Reference Base WRB (2022) guidelines.

Soil sampling

Soil samples were collected from organic horizons (in total 11 samples) and mineral layers (in

total 81 samples). The samples were subjected to physical and chemical analyses using standard methods commonly applied in soil science.

Analyses performed in all samples (organic and mineral) included:

- soil pH measured potentiometrically in KCl solution at a mineral soil-to-solution ratio of 1:2.5, and organic soil-to-solution ratio of 1:10; using an ELMETRON CP-411 pH meter with an IJ44A electrode.
- calcium carbonate content determined using the Scheibler volumetric method;
- cation exchange capacity (CEC), determined for all samples as the sum of hydrolytic acidity (Hh) and the sum of exchangeable bases (S). Hydrolytic acidity (Hh) was determined using the Kappen method with 1 M sodium acetate as the extractant. The sum of bases (S) comprised exchangeable cations: Na⁺, K⁺, Ca²⁺, and Mg²⁺. The contents of exchangeable Na⁺, K⁺, Ca²⁺, and Mg²⁺ were determined in 1 M ammonium chloride extracts. Magnesium (Mg²⁺) concentration was measured using atomic absorption spectrometry with a Thermo iCE 3500 atomic absorption spectrometer. Sodium (Na⁺), potassium (K⁺), and calcium (Ca²⁺) were determined using emission spectrometry with a BWB-XP flame photometer manufactured by BWB Technologies UK Ltd.

Analyses specific to mineral samples included:

- particle size distribution, determined using the Bouyoucos hydrometer method modified by Casagrande and Prószyński (PN-04032:1998).

All analyses were performed in triplicate.

Statistical analysis

Statistical analysis of the results was performed using Statistica 13.3 software. For the purposes of statistical analysis, the results were grouped according to the type of reclamation material (sandy and clayey) in order to demonstrate differences in selected soil properties between the analysed substrate types. The statistical analyses focused on determining the variability of selected soil parameters, including selected particle size fractions, soil reaction (pH in KCl), and calcium carbonate (CaCO₃) content.

Due to the non-normal distribution of the data, the non-parametric Mann–Whitney U test

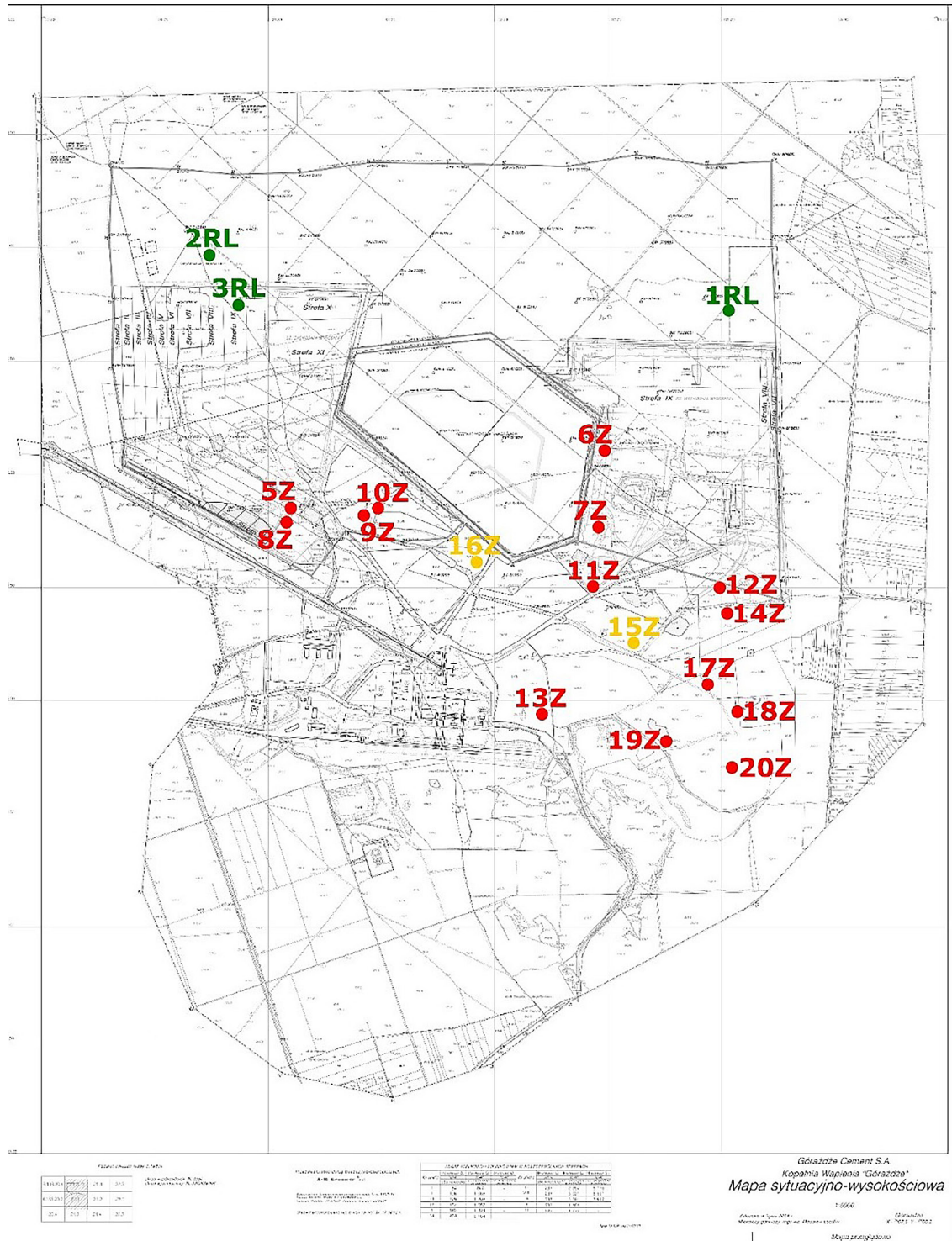


Figure 1. Location of the research sites within the excavation area of the “Góraźdze” mine.
 Source: Own elaboration based on the mining map (2024), where: Z – spoil heap (reclamation);
 Z – spoil heap (natural succession); RL – natural forest

was applied to determine statistically significant differences between soils developed on sandy and clayey reclamation materials. Relationships between selected soil properties were evaluated using Spearman’s rank correlation coefficient. Statistical significance was assumed at $p < 0.05$.

RESULTS

The investigated technogenic soils were characterized by significant variability in particle size distribution resulting from the use of different reclamation materials. Soils developed on sandy

material were dominated by the sand fraction and showed a low content of skeletal, silt, and clay fractions, which favored the formation of light-textured soils. In contrast, soils developing on clayey material were characterized by a higher proportion of silt and clay fractions and often by considerable skeletal content.

A high similarity in particle size distribution was also found between technogenic soils and reference soils, particularly in the case of sites reclaimed with clayey material. Differences in the content of individual particle size fractions between soils formed on sandy and clayey formations were statistically significant, as confirmed by the Mann–Whitney U test ($p = 0.0001$) (Figures 2–4).

The morphological structure of the studied soils showed considerable variability, both between individual sites and within single soil profiles. The characteristics of soil profile structure as well as basic information on soil age and parent material type are presented in Table 1.

The reaction of the studied soils was characterized by considerable variability in pH values in both organic and mineral horizons. In organic horizons, pH values ranged from 4.50 to 6.48. In mineral horizons of technogenic soils developed on sandy material, pH values ranged from 4.55 to 8.37 (median pH = 7.06). Soils formed on clayey

material were characterized by higher reaction values, ranging from pH 6.06 to 8.12 (median pH = 7.68) (Figure 5).

In the reference soils, the reaction of organic horizons ranged from pH 5.02 to 7.10. In mineral horizons of reference soils developed on sands, pH values ranged from 4.05 to 6.00. Reference soils developed on clayey limestone weathering material were characterized by higher pH values ranging from 5.92 to 6.91.

CaCO₃ occurred in all investigated technogenic soils, both in mineral and organic horizons. In organic horizons, its content ranged from 0.14 to 10.96%. Mineral horizons of soils developed on sandy material contained CaCO₃ in amounts ranging from 0.09 to 59.05% (median 0.28%), whereas soils developed on clayey formations were characterized by significantly higher and more variable contents of this component, ranging from 0.87 to 74.32% (median 22.05%). These differences were statistically significant ($p = 0.0001$) (Figure 6).

A characteristic feature of profiles with high calcium carbonate content was the simultaneous high content of skeletal, silt, and clay fractions, which was statistically confirmed and expressed by Spearman’s correlation coefficients (respectively: skeletal fraction $r = 0.812$, silt fraction $r = 0.841$, and clay fraction $r = 0.848$).

Table 1. Characteristics of soils located within the excavation area of the “Górażdże” limestone mine

No of profiles	WRB soil name	Soil profile morphology	Parent material
1RL	Calcaric Cambisols	$O_{fh} - A_{caq} - B_{wcaq} - B_{wcaq} C_{caq} - R_{Ca}$	Loamy
2RL	Brunic Arenosols	$O_i - O_{fh} - A - B_v - B_v C - C$	Sandy
3RL	Arenosol	$O_i - A - C_1 - C_2$	Sandy
5Z	Technosols	$C_a 1 - C_a 2 - C_a 3 - C_a 4$	Sandy
6Z	Spolic Technosols	$C_a 1 - C_a 2$	Loamy
7Z	Spolic Technosols	$C_a 1 - C_a 2 - C_a 3$	Loamy
8Z	Technosols	$C_a 1 - C_a 2 - C_a 3 - C_a 4$	Sandy
9Z	Technosols	$O_i - C_a 1 - C_a 2 - C_a 3$	Sandy
10Z	Technosols	$C_a 1 - C_a 2 - C_a 3$	Loamy
11Z	Technosols	$O_f - A - C_a 1 - C_a 2 - C_a 3 - C_a 4$	Sandy
12Z	Spolic Technosols	$C_a 1 - C_a 2 - C_a 3$	Loamy
13Z	Spolic Technosols	C_a	Loamy
14Z	Spolic Technosols	$O_f - A - C_a 1 - C_a 2 - C_a 3$	Loamy
15Z	Technosols	$O_i - A - C_a 1 - C_a 2 - C_a 3$	Sandy
16Z	Technosols	$O_i - A - C_a 1 - C_a 2$	Sandy
17Z	Technosols	$O_f - A - C_a$	Sandy
18Z	Technosols	$A - C_a 1 - C_a 2 - C_a 3$	Sandy
19Z	Technosols	$O_i - A - C_a$	Sandy
20Z	Technosols	$A - C_a$	Sandy

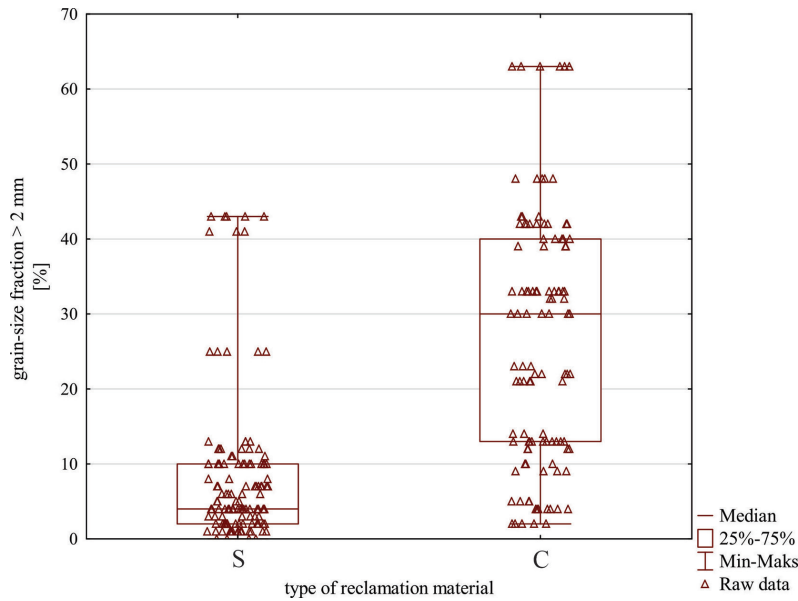


Figure 2. Distribution of the >2 mm particle size fraction (skeletal fraction) in mineral samples collected from the studied sites, distinguished by the type of reclamation material used (S – sandy formations, C – clayey formations)

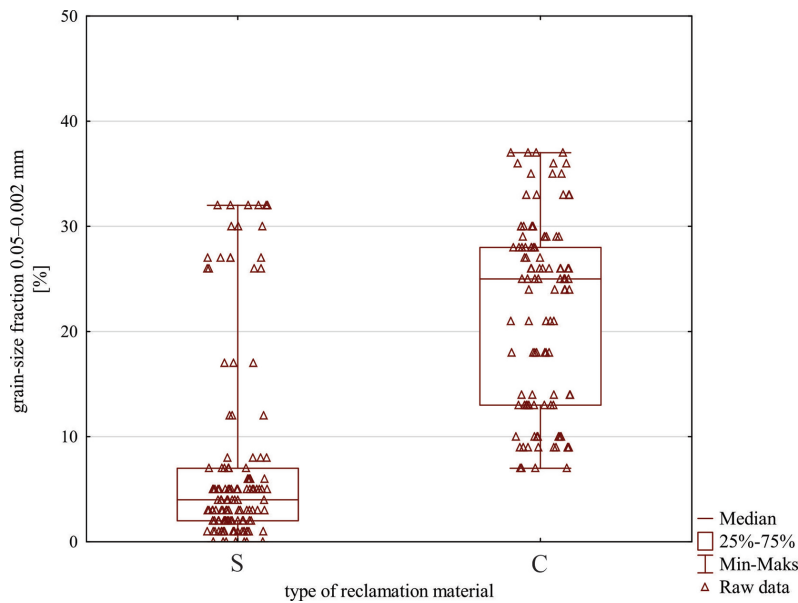


Figure 3. Distribution of the 0.002–0.05 mm particle size fraction (silt) in mineral samples collected from the studied sites, distinguished by the type of reclamation material used (S – sandy formations, C – clayey formations)

Cation exchange capacity (CEC) reached the highest values in the organic horizons of the studied soils, where it ranged from 34.44 to 77.01 $\text{cmol}(+)\cdot\text{kg}^{-1}$. In mineral horizons of technogenic soils developed on sandy material, CEC values ranged from 1.92 to 28.45 $\text{cmol}(+)\cdot\text{kg}^{-1}$ (median 4.27 $\text{cmol}(+)\cdot\text{kg}^{-1}$). Soils developed on clayey formations were characterized by significantly higher cation exchange capacity values, ranging

from 12.76 to 31.13 $\text{cmol}(+)\cdot\text{kg}^{-1}$ (median 20.73 $\text{cmol}(+)\cdot\text{kg}^{-1}$). The statistical significance of these differences was confirmed using the Mann–Whitney U test ($p = 0.0001$) (Figure 7).

In the reference soils, the highest cation exchange capacity values were also found in the organic horizons (44.39–61.21 $\text{cmol}(+)\cdot\text{kg}^{-1}$). In mineral horizons, these values varied depending on the particle size distribution of the

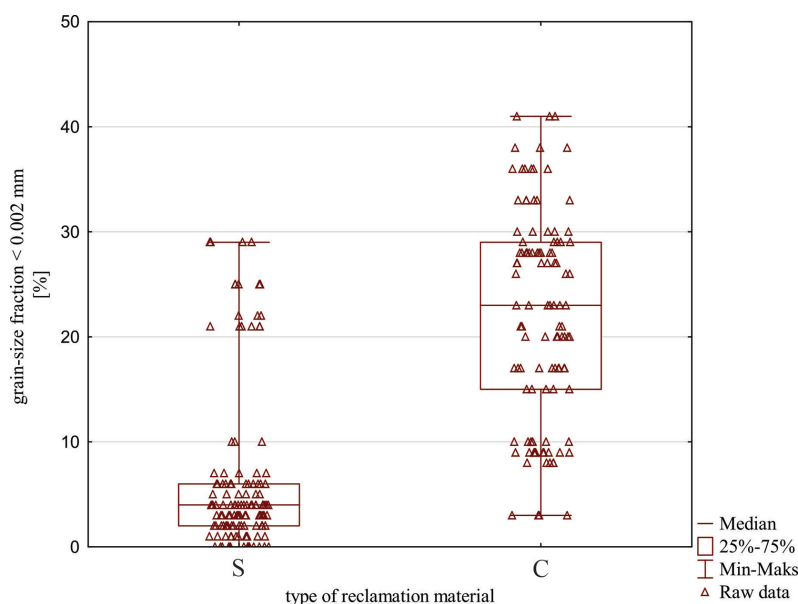


Figure 4. Distribution of the <0.002 mm particle size fraction (clay) in mineral samples collected from the studied sites, distinguished by the type of reclamation material used (S – sandy formations, C – clayey formations)

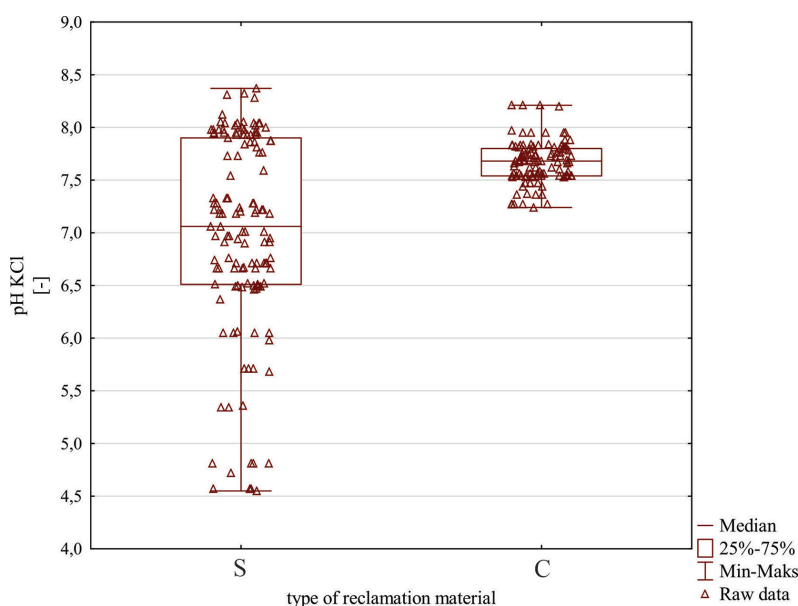


Figure 5. Distribution of pH (KCl) values in mineral samples collected from the studied sites, distinguished by the type of reclamation material used (S – sandy formations, C – clayey formations)

parent material and ranged from 1.88 to 16.59 $\text{cmol}(+)\cdot\text{kg}^{-1}$ in sandy soils and from 13.03 to 21.10 $\text{cmol}(+)\cdot\text{kg}^{-1}$ in clayey soils.

DISCUSSION

Reclamation of post-mining areas initiates soil-forming processes that lead to the development of technogenic soils whose properties are

largely determined by the nature of the reclamation material used and the method of its application. In the study area, a key role was played by substrate heterogeneity resulting from the use of sandy and clayey formations characterized by different physical and chemical properties. The observed variability may also be influenced by the time elapsed since reclamation, which affects the intensity of soil-forming processes and the degree of soil profile development.

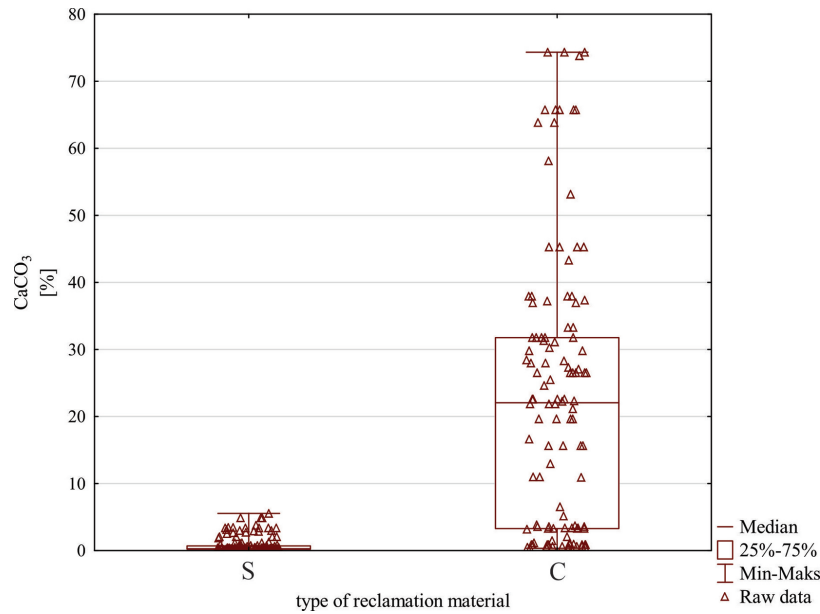


Figure 6. Distribution of calcium carbonate content in mineral samples collected from the studied sites, distinguished by the type of reclamation material used (S – sandy formations, C – clayey formations)

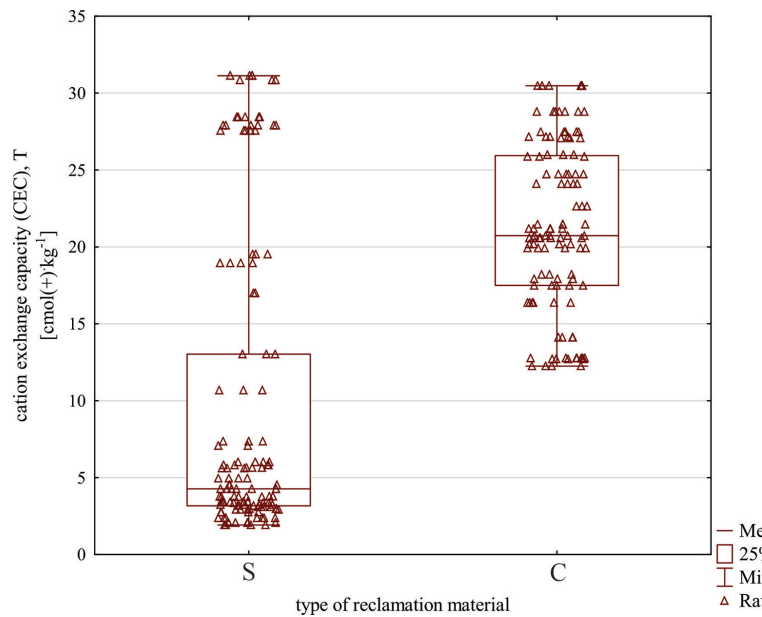


Figure 7. Distribution of soil sorption capacity values (mineral samples) collected from the studied sites, distinguished by the type of reclamation material used (S – sandy formations, C – clayey formations)

The particle size distribution of the studied technogenic soils clearly reflected the properties of the parent material. Soils developing on sandy formations were dominated by the sand fraction and contained low proportions of fine fractions, whereas soils formed on clayey material were characterized by a higher content of silt and clay fractions and more pronounced profile differentiation. This type of variability is typical of post-mining soils and results from the non-selective

dumping of overburden and the diverse lithological origin of reclamation materials, as confirmed by studies of other authors (Gilewska and Otremba, 2004, 2007, 2011; Stachowski et al., 2005;).

The reaction of the studied soils was largely dependent on the calcium carbonate content of the reclamation material. Soils formed on clayey formations, often rich in CaCO_3 , were characterized by a stable alkaline reaction. In contrast, soils developing on sandy material showed

greater variability in pH values and a reaction close to neutral. Similar relationships have been observed in other studies of soils developing on carbonate substrates (Licznar, 1976; Kusza and Gołuchowska, 2009; Kusza et al., 2016).

An important factor modifying the reaction of surface layers was also the immission of limestone dust associated with ongoing mining activity. The deposition of dust rich in calcium carbonate contributed to increased pH values in organic horizons and limited soil acidification processes.

Cation exchange capacity in young technogenic soils was primarily determined by particle size distribution and the content of fine fractions. Higher sorption capacity values were recorded in soils developed on clayey formations, whereas sandy soils were characterized by very low sorption capacity. This relationship is consistent with the results of previous studies conducted on post-mining soils (Pietrzykowski, 2006; Gilewska and Otremba, 2007, Smólczyński and Orzechowski, 2010).

The obtained results indicate that substrate properties play a dominant role in shaping the physicochemical characteristics of technogenic soils; however, their evolution is a dynamic process influenced by both initial conditions and ongoing environmental factors.

A limitation of the study is the relatively small number of sampling sites and the spatial heterogeneity of the reclaimed materials, which may influence the variability of the obtained results. Further research should include a larger number of sampling sites and a more detailed analysis of temporal changes in soil properties to better understand the long-term development of technogenic soils in post-mining areas.

CONCLUSIONS

This study demonstrates that soil substrate heterogeneity is a primary factor controlling the development, variability, and functional quality of technogenic soils in post-mining environments. The use of reclamation materials differing in granulometric, mineralogical, and chemical composition resulted in significant differences in soil properties and pedogenic pathways.

Soils developed on sandy materials were characterized by simplified profile structure, low content of fine fractions, and limited sorption capacity, with cation exchange capacity (CEC) ranging from 1.92 to 28.45 $\text{cmol}(+)\cdot\text{kg}^{-1}$ (median

4.27 $\text{cmol}(+)\cdot\text{kg}^{-1}$). In contrast, soils formed on clayey materials showed greater profile differentiation, higher proportions of silt and clay fractions, and substantially higher sorption capacity, with CEC values ranging from 12.76 to 31.13 $\text{cmol}(+)\cdot\text{kg}^{-1}$ (median 20.73 $\text{cmol}(+)\cdot\text{kg}^{-1}$), i.e. up to five times higher than in sandy soils.

Substrate-related differences were also reflected in soil reaction and calcium carbonate content. Soils developed on sandy materials exhibited a wide range of pH values (4.55–8.37), indicating unstable chemical conditions, whereas soils formed on clayey substrates maintained more stable and predominantly alkaline conditions (pH 6.06–8.12). Calcium carbonate content was markedly higher and more variable in clayey soils (median 22.05%) compared to sandy soils (median 0.28%), confirming the dominant role of parent material composition in shaping soil chemistry. The results indicate that the physicochemical properties of the parent material determine both the rate and direction of technogenic soil development, influencing key soil functions such as nutrient retention and buffering capacity. Among the analyzed materials, clayey till proved to be more suitable for reclamation due to its higher sorption capacity and greater potential to support the development of more stable and fertile soils.

However, the relatively high content of coarse fragments in clayey materials may limit vegetation establishment, indicating that effective reclamation strategies should balance the advantages and constraints of different substrate types. Where technically feasible, controlled mixing of sandy and clayey materials may enhance soil physicochemical properties and improve long-term ecosystem functionality.

Overall, the study highlights that the deliberate selection and management of reclamation materials should be considered a critical factor in designing sustainable post-mining landscapes, with direct implications for soil quality, ecosystem stability, and long-term land use potential.

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