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Pedological approach on sealed soils: impacts of covering materials on soil properties in urban and peri-urban areas

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Abstract
Land consumption represents a growing environmental threat, driven by rapid urbanization and the increasing demand for space for infrastructure and housing. Among its various manifestations, soil sealing is particularly detrimental, contributing to soil degradation and the interruption of critical ecosystem services, thus highlighting the urgent need for the implementation of sustainable land management policies. De-sealing practices, in particular, have gained significant traction in recent years, although preliminary studies are mandatory to evaluate the soil conditions beneath and guide the planning of necessary interventions. Therefore, this study aimed to examine the pedological properties (morphological, physical, chemical, and mineralogical) of sealed soils in urban (Vallemiano neighborhood) and peri-urban (Torrette neighborhood) areas, focusing on the impact of the covering materials' characteristics and uniformity on these traits. Overall, soils at both sites exhibited problems related to soil compaction, exacerbated by fine-texture classes, low nutrient levels (particularly total organic carbon and nitrogen), and the contribution of allochthonous materials. However, variations in the characteristics and uniformity of the covering materials affected the soil properties. At Torrette, the homogeneous and entirely impermeable asphalt covering prevented the interactions between the atmosphere, hydrosphere, and pedosphere, leading to severe anoxic conditions, mainly in the surface soil horizons. In contrast, Vallemiano presented a degraded and heterogeneous soil surface cover. Thus, water infiltration and/or capillary rise, combined with the calcareous nature of the allochthonous material, promoted the translocation and accumulation of secondary carbonates.

Keywords: *Paved soil; pedogenetic processes; anthropogenic factor; impervious cover*

Introduction

Land consumption is a critical environmental challenge that involves the conversion of natural or seminatural land into urban or artificial surfaces (EEA, 2022; Marquard et al., 2020). This process primarily arises from the increasing demand for infrastructure, housing, and transportation as urbanization expands (Msofe et al., 2019; Colsaet et al., 2018). However, while urban growth addresses these needs, it simultaneously imposes irreversible consequences on ecosystems and landscapes. Among the various forms of

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land consumption, soil sealing stands out as particularly detrimental. Soil sealing, which involves covering soil with impervious materials such as asphalt, concrete, or pavers, exacerbates environmental degradation and effectively disrupts interactions between the soil (pedosphere) and other environmental systems (atmosphere, biosphere, and hydrosphere). The environmental, social, and economic consequences of soil sealing are profound, as they undermine ecosystem services that are crucial for urban resilience and quality of life. These services, which include water regulation, stormwater management, and microclimate moderation (Scalenghe and Ajmone Marsan, 2009), are essential in addressing climate change-related challenges, particularly in urban and peri-urban environments (Hanna et al., 2023; Tobias et al., 2018). Soil sealing represents a significant environmental concern in Europe. According to the European Environment Agency's *State of the Environment in Europe* report (EEA, 2020), total land take in the European Union increased by over 1.1 million hectares between 2000 and 2018, with an average of around 5 hectares of land consumed every hour. In response, the European Commission has proposed policies such as the *Green Deal* and the *European Biodiversity Strategy for 2030*, aiming to reduce net land consumption and promote sustainable land use by encouraging urban regeneration and the protection of natural areas (European Commission, 2020). Several strategies have been proposed across Europe to reverse the trend of soil sealing, focusing on the recovery and regeneration of sealed soils. A key approach is the use of de-sealing techniques, which aim to restore the soil's natural permeability by replacing impermeable surfaces like asphalt and concrete with sustainable materials, such as permeable pavements or urban green spaces. These measures improve water infiltration and groundwater recharge, mitigate the urban heat island effect, and enhance overall environmental quality (Vieillard et al., 2024). When combined with strong legal frameworks and economic incentives, these strategies are crucial for addressing the long-term challenges of soil sealing to balance urban growth and environmental preservation (European Commission, 2020). Despite the critical role of urban soils, including sealed soil, in human health and safety, research on these soils is limited due to the relatively recent and fragmented availability of data, with a clear need to standardize soil sampling methodologies (Stevenson, 2025; Cornu et al., 2021), 2021), and laboratory techniques (Binner et al., 2024). Furthermore, research on the layering, morphological properties, and *ekranopedogenesis* of sealed soils is particularly sparse (Howard, 2021; Puskás and Farsang, 2009; Da-Gang et al., 2008). This study seeks to address the existing knowledge gap by analyzing the pedological (morphological, physical, chemical, and mineralogical) properties of sealed soils in urban and peri-urban areas, with a particular focus on how the characteristics and homogeneity of the covering materials affected these properties. Such characterization would facilitate more effective management to enhance the retrieval soil ecosystem services in urban areas. Indeed, the preliminary characterization of these soils forms the foundational step of the REUSES (Restore Urban Sealed Soil for Alternative Ecosystem Services) project, which aims to reclaim abandoned sealed soils and repurpose them as community gardens (Giacomello et al., 2024).

Materials and methods

Study sites

The study was performed in two neighborhoods of the Municipality of Ancona. The city is located on the eastern coast of central Italy, receiving dominant and strong winds from north-northwest (Brecciaroli et al., 2012). According to Köppen-Geiger classification, the climate is humid subtropical, characterized by a mean annual precipitation of 681 mm and a mean annual air temperature of 15.6°C (Peel et al., 2007). July is the warmest month with an average maximum temperature of 28.4°C, while February is the coldest month, with an average minimum temperature of 4.4°C. Precipitation is distributed throughout the year, except for the months of June, July, and August, with an average monthly rainfall below 50 mm (climate-data, 2025). The Municipality covers an area of approximately 125 km^2, with a population of around 99500 inhabitants and a population density of 796 inhabitants per km^2 (Serrani et al., 2022). The two selected study sites are located near partially abandoned structures, with asphalted surfaces that were used as parking lots but are now disused. These sites are settled in the neighborhoods of Torrette and Vallemiano, in peri-urban and urban areas of the municipality, respectively (Fig.1).

Torrette. The neighborhood of Torrette, located in the peri-urban area along the coastal strip, developed from glacis and eluvial-colluvial deposits (ISPRA, 2024). The study area was included in a partially disused structure covering approximately 9,900 m^2.

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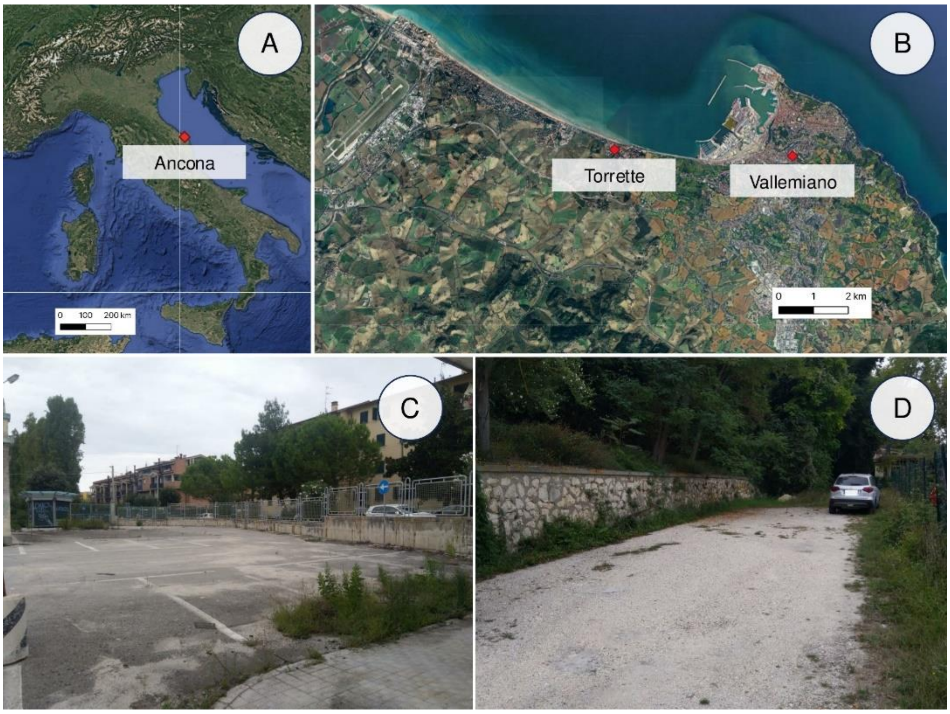

Figure 1
*Schematic map and localization of the neighborhood of Torrette and Vallemiano in the city of Ancona (*A *and* B*). Study sites at Torrette and Vallemiano (*C *and* D*, respectively).*

The soil cover was homogeneous and entirely impermeable, typical of an urbanized and well-maintained environment.

Vallemiano. The neighborhood of Vallemiano, located in the urban area, developed from clays and silty marl clays, gray and dark gray, with intercalated thin layers of whitish calcareous and arenaceous strata (ISPRA, 2024). The study area was part of a structure covering approximately 10,500 square meters and almost entirely in a state of disuse. The area had not undergone maintenance, resulting in a degraded and heterogeneous soil surface cover, characterized by partial permeability and deterioration.

Sampling, description, and soil analyses

In July 2024, three soil trenches per site were opened, within a surface of 100 m^2, to a depth of ≈ 1 m. Soil profiles were morphologically described per FAO guidelines (FAO, 2006) and classified according to IUSS Working Group WRB (2022). Soil samples were collected considering the genetic horizon, air-dried, and sieved at 2 mm to separate the fine earth (<2 mm-fraction) from the skeleton (>2 mm-fraction). The pipette method was adopted to measure the particle-size distribution according to Day (1965). pH and electrical conductivity (EC) were determined in H_2O with a soil:water ratio of 1:2.5. pH was assessed potentiometrically, while EC was measured by a conductivity meter (CO3100L, VWR, USA). Total nitrogen (TN) concentration was measured on Carlo Erba EA1110 combustion analyzer, total organic carbon (TOC) was estimated by K-dichromate digestion, heating the suspension at 180 °C for 30 min (Nelson and Sommers, 1996), while calcium carbonate equivalent (CCE) was determined using titrimetric method through acid neutralization (FAO, 2020). Crystalline minerals were determined by x-ray diffraction with a Bruker D8 Advance diffractometer, using Cu-Kα radiation and operating at 40 kV and 40 mA, in the angular range 2θ=5°-80° (Dixon and Schulze, 2002; Brindley and Brown, 1980). The XRD patterns were analyzed using the DIFFRAC.EVA software package including ICDD—PDF 2 for search/match analysis (Gatto et al., 2025). Based on field survey, the following horizons were selected for the mineralogical characterization to investigate the possible exogenous materials used for land use changes and the conversion of the area for infrastructure purposes: Cr and Cb2 horizons of profile 3 at Torrette and surface horizons (BwC1, BkC, BwkC) of each profile at Vallemiano. The bulk density was measured using soil cylinders. Specifically, a horizontal soil sample was taken from each soil horizon with cylinders of 503 cm³ (height: 10.8 cm; diameter: 7.7 cm), heated at 105°C, and weighed (Camponi et al., 2022, 2023).

Results

Torrette. The morphology of the investigated soils at Torrette are shown in Table 1 and Figure 2, physical

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Table 1. *Morphological properties of de-sealed soils at Torrette, Ancona (Italy). Codes according to FAO (2006). For symbols see the legend.*

Horizon[a]	Depth cm	Thickness cm	Boundary[b]	Colour[c]	Structure[cd]	Roots[e]	Coarse fragments[f]	Observations[g]
Profile 1								
Soil: Ekranic Technosol Siltic Eutric Calcaric Ochric (IUSS Working Group WRB, 2022)								
BT	0-8	7-8	AS	-	-	-	-	-
DS	8-45	27-42	AW	-	-	-	-	-
Cr	45-60	10-20	CI	10Y 3/1	MA	N	V-MC	V-BC mm,cm
2Cb1	60-96	18-36	GW	2.5Y 4/2	MA	N	V-MC	F-BC mm,cm
2Cb2	96-112+	-	-	2.5Y 4/3	MA	N	N	-
Profile 2								
Soil: Gleyic Ekranic Technosol Siltic Eutric Calcaric Ochric (IUSS Working Group WRB, 2022)								
BT	0-19	18-19	AS	-	-	-	-	-
DS	19-45	26-49	AW	-	-	-	-	-
Cr	45-82	23-38	AW	10Y 4/1	MA	N	V-MC	A-RMF 5YR 3/3
2Cb	82-105+	-	-	2.5Y 4/3	MA	N	V-MC	-
Profile 3								
Soil: Gleyic Ekranic Technosol Siltic Eutric Calcaric Ochric (IUSS Working Group WRB, 2022)								
BT	0-8	7-8	AS	-	-	-	-	-
DS	8-38	28-42	AW	-	-	-	-	-
Cr	38-81	36-52	AS	10Y 5/1	MA	N	V-MC	V-RMF 7.5 YR 4/6
2Cb	81-104+	-	-	2.5Y 5/2	MA	N	V-S (brick)	-

[a] master horizons and suffixes according to IUSS Working Group WRB (2022) - [b] A=abrupt, C=clear, G=gradual; S=smooth, W=wavy, I=irregular - [c] moist, according to the Munsell Soil Color Charts (Edition 2022) – [d] MA=massive - [e] N=none.
[f] N=none, V=very few; MC=medium and coarse gravel, S=stones - [g] abundance determined by sight according to "Fig.5 Charts for estimating proportions of coarse fragments and mottles" reported in FAO (2006); V=very few, F=few, A=abundant; BC=black carbon (charcoal); mm= millimetric size, cm=centimetric size; RMFs=redoximorphic features; colors according to the Munsell Soil Color Charts (Edition 2022).

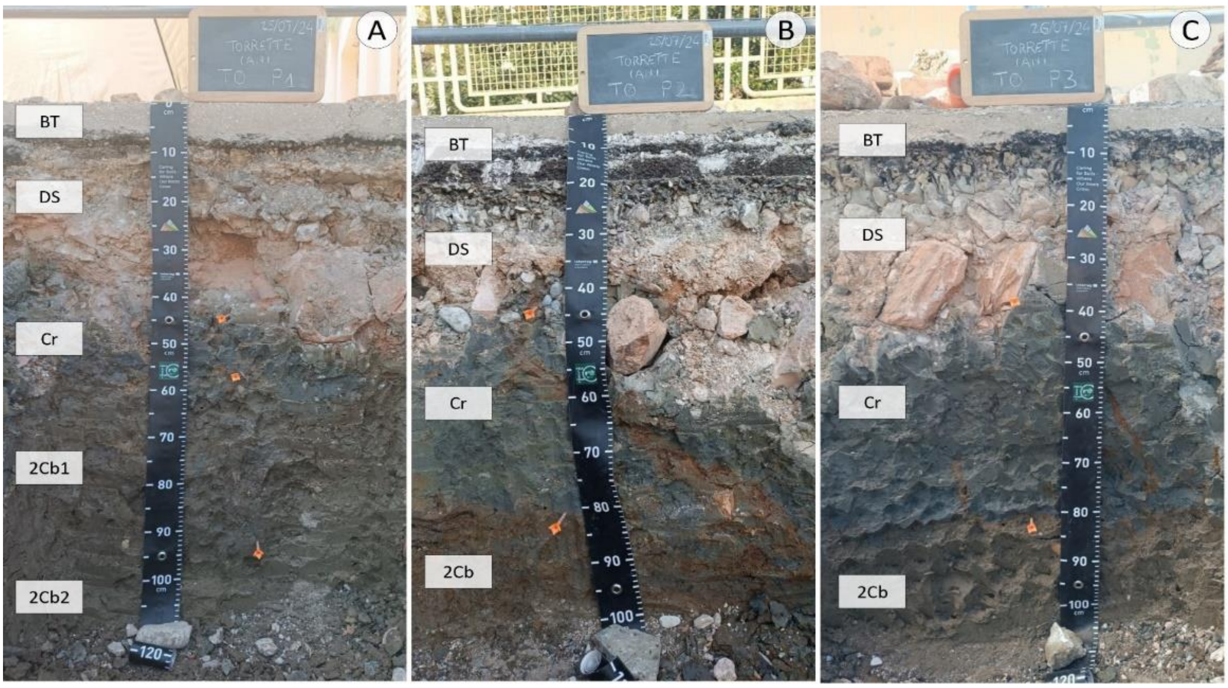

Figure 2. *Soil profile 1 (A), soil profile 2 (B), and soil profile 3 (C) of de-sealed soil at Torrette, Ancona (Italy).*

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properties are graphically represented in Figure 3, while Table 2 reports chemical properties and mineral composition. The soils were classified as Gleyic Ekranic Technosols (IUSS Working Group WRB, 2022) due to the presence of more than 20% artefacts in the upper 100 cm, a layer of technical hard material starting within 5 cm of the surface, and gleyic properties (except Profile 1, as the gleyic properties are confined to a layer <25 cm thick). Overall, under the impermeable soil cover consisting of continuous asphalt and crushed stones, the soils exhibited pedological uniformity: a Cr horizon with strong reduction that lithologically differed from the underlying buried 2Cb horizons. The soils had a massive structure throughout the profile, as confirmed by the consistent bulk density, which ranged from 1.31 to 1.63 g cm³, showing the minimum and maximum values in the deepest horizon of Profile 1 and 3, respectively. Each horizon recorded fine silt content >45%, resulting in a silt-silt loam textural class (Fig. 3). According to the chemical properties in Table 2, soil pH exceeded 8.4 in almost all horizons, except for Cr of Profile 1 and 2, which recorded moderately alkaline reaction. TOC and TN were generally scarce, with values lower than 2% and 0.2%, respectively. Soils were primarily composed of quartz and calcite, with the other mineral components showing the trend: albite>muscovite>kaolinite. Additionally, clinochlore was recorded only in Cr horizon, while microcline was detected in 2Cb horizon (Table 2).

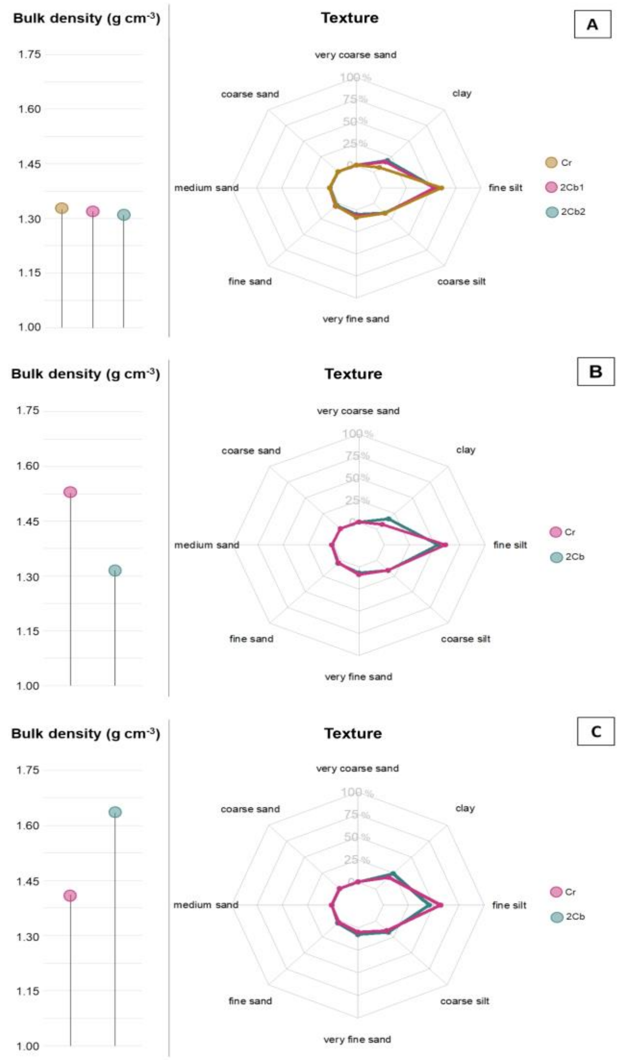

Figure 3. *Physical properties of de-sealed soils at Torrette, Ancona (Italy).*

	pH	EC	TN	TOC	CCE	Mineralogy[a]
		dS m^{-1}		%		
Profile 1						
Cr	8.32	0.37	0.11	1.13	13.29	n.a.
2Cb1	8.52	0.23	0.08	0.81	12.83	n.a.
2Cb2	8.65	0.21	0.09	0.75	11.00	n.a.
Profile 2						
Cr	8.37	0.33	0.09	0.80	14.66	n.a.
2Cb	8.47	0.29	0.11	1.05	11.46	n.a.
Profile 3						
Cr	8.47	0.28	0.10	0.94	11.68	Q, C, A, M, CL, K
2Cb	8.49	0.21	0.09	0.91	9.85	Q, C, A, M, MC, K

EC=electrical conductivity, TN=total nitrogen; TOC=total organic carbon; CCE=calcium carbonate equivalent - n.a.=not available data - [a]Minerals listed in order of abundance: Q=quartz, C=calcite, A=albite, M=muscovite, CL=clinochlore, MC=microcline, K=kaolinite

Table 2. *Chemical properties and mineral composition of desealed soils at Torrette, Ancona (Italy)*

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Vallemiano. Table 3 and Figure 4 present the morphological characteristics of the soils at Vallemiano, physical properties are illustrated in Figure 5, whereas chemical properties and mineral composition are reported in Table 4. The soil profiles showed slight pedological variability, although all were classified as Ekranic Technosols because of the abundance (>20%) of artefacts in the upper 100 cm and the layer of technical hard material found within 5 cm of the surface (IUSS Working Group WRB, 2022). Profile 1 reported a very thin layer of fragmented asphalt (~2cm), overlying crushed stones and BwC horizons with a weakly developed angular and subangular structure and very few roots, ranging from very fine to very coarse. Conversely, the thickness of fragmented asphalt increased in Profile 2 and 3, reaching up to 13 cm. Beneath this layer, soil horizons reported secondary carbonates in the form of concretions with varying abundance, as well as an angular, subangular, and prismatic soil structure of differing grades. Regarding physical properties, bulk density exceeded 1.5 g cm^{-3} (except for the deepest horizon of Profile 3), while particle-size distribution indicated a predominance of fine silt (Fig. 5). Soil reaction was strongly alkaline in Profiles 1 and 3, while the BkC horizon of Profile 2 recorded a pH of 8.31. TOC ranged from 0.23 to 0.58%, with the highest and lowest values in Profiles 1 and 2, respectively. CCE followed the same trend as carbonate concentrations, remaining below 30% only in the horizons of Profile 1 (Table 4). Overall, the soils exhibited the same mineral components despite varying abundances, except for clinochlore, which was absent in Profile 3. Quartz prevailed in Profile 1, contrary to Profiles 2 and 3, in which calcite was the dominant component (Table 4).

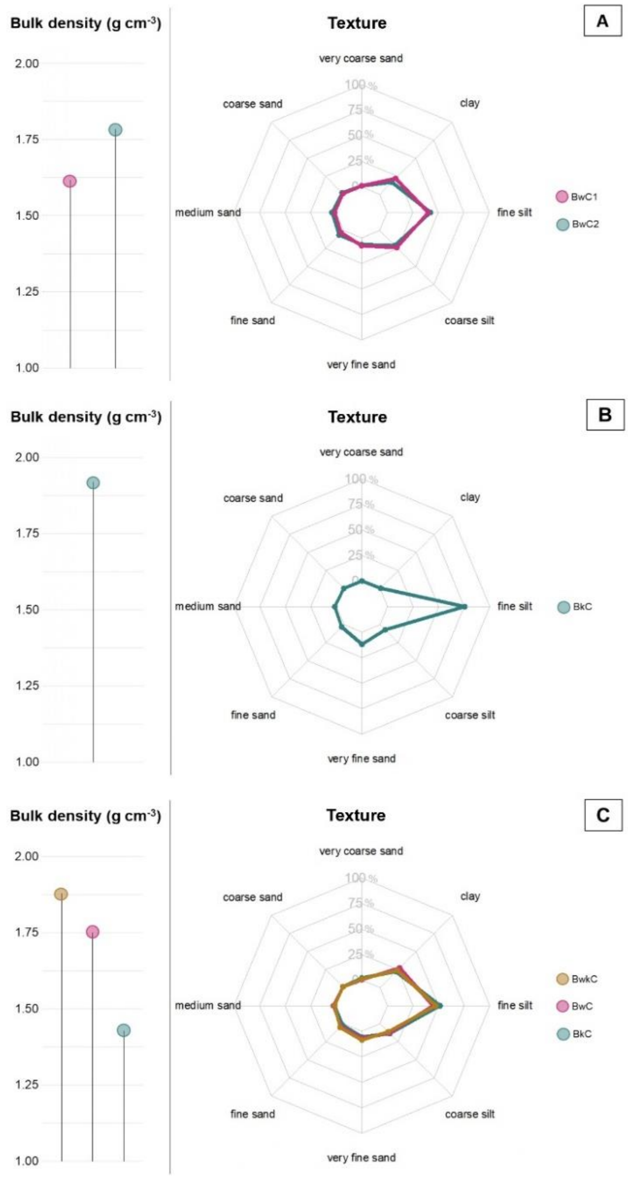

Figure 5. *Physical properties of de-sealed soils at Vallemiano, Ancona (Italy).*

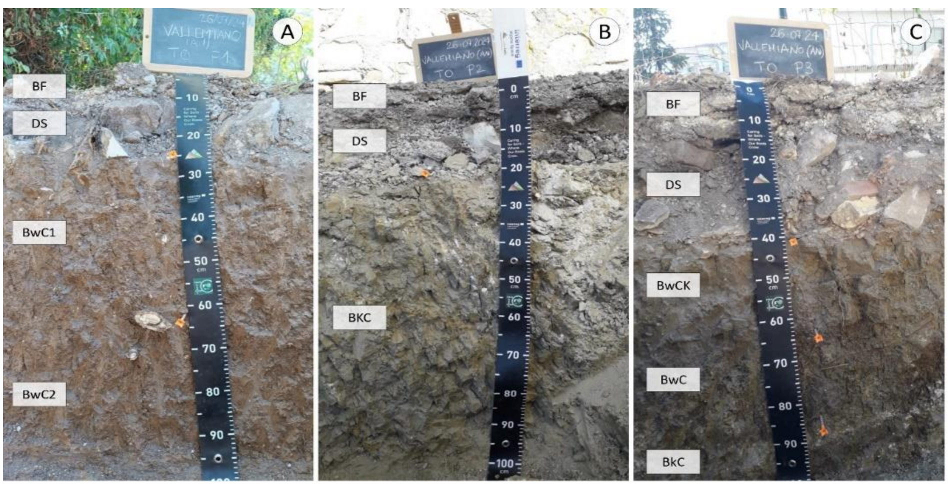

Figura 4.
Soil profile 1 (A), soil profile 2 (B), and soil profile 3 (C) of de-sealed soil at Vallemiano, Ancona (Italy).

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Table 3. *Morphological properties of de-sealed soils at Vallemiano, Ancona (Italy). Codes according to FAO (2006). For symbols see the legend.*

Horizon[a]	Depth cm	Thickness cm	Boundary[b]	Colour[c]	Structure[d]	Roots[e]	Coarse fragments[f]	Observations[g]
Profile 1								
Soil: Ekranic Technosol Siltic Eutric Cambic Calcaric Ochric (IUSS Working Group WRB, 2022)								
BF	0-2	1-2	AS	-	-	-	-	-
DS	2-24	20-27	AW	-	-	-	-	-
BwC1	24-61	32-37	CW	10YR 5/4	WE-VF,FI,ME,CO,VC-AS	VF,F,M, CO-V	C-MC	-
BwC2	61-99+	-	-	10YR 5/4	WE-VF,FI,ME,CO,VC-AS	VF,F,C O,VC-V	F-M	-
Profile 2								
Soil: Ekranic Technosol Siltic Eutric Calcaric Ochirc (IUSS Working Group WRB, 2022)								
BF	0-5	4-5	AW	-	-	-	-	-
DS	5-20	14-18	AW	-	-	-	-	-
BkC	20-99+	-	-	2.5Y 6/4	ST-VF,FI,ME,CO,VC-AS; ST-VF,FI,ME,CO-PR	VF,F,M,C O-V	N	M-RMF 10YR5/6 and 2.5Y 6/3; FDM; V-SCC
Profile 3								
Soil: Ekranic Technosol Siltic Eutric Cambic Calcaric Ochric (IUSS Working Group WRB, 2022)								
BF	0-13	12-13	AW	-	-	-	-	-
DS	13-41	11-29	AW	-	-	-	-	-
BwkC	41-64	11-29	CW	2.5Y 5/4	MO-F,FI,ME,CO,VC-AS; MO-I,ME,CO,VC-PR	VF,F-V	F-M	V-SCC
BwC	64-85	24-26	CW	2.5Y 6/4	MO-F,FI,ME,CO,VC-AS; MO-I,ME,CO,VC-PR	VF,F,M-V	N	V-SMC on ped
BkC	85-101+	-	-	2.5Y 6/3	WE-VF,FI,ME,CO-AS	F-V	N	M-SCC

[a] master horizons and suffixes according to IUSS Working Group WRB (2022) - [b] C=clear; W=wavy - [c] moist, according to the Munsell Soil Color Charts (Edition 2022) - [d] WE=weak, MO=moderate, ST=strong; VF=very fine, FI=fine, ME=medium, CO=coarse, VC=very coarse; AS=angular and subangular blocky, PR=prismatic - [e] VF=very fine, F=fine, M=medium, CO=coarse, VC=very coarse; V=very few - [f] N=none, F=few, C=common; M=medium gravel, MC=medium and coarse gravel - [g] abundance determined by sight according to "Fig.5 Charts for estimating proportions of coarse fragments and mottles" reported in FAO (2006); V=very few, M=many; RMF=redoximorphic features; colors according to the Munsell Soil Color Charts (Edition 2022); FDM=finely disseminated manganese; SCC=soft carbonate concretions; SMC=soft manganese concretions.

	pH	EC dS m^{-1}	TN %	TOC %	CCE %	Mineralogy[a]
Profile 1						
BwC1	8.54	0.27	0.07	0.58	16.80	Q, C, A, M, D, CL, K
BwC2	8.60	0.21	0.06	0.52	14.97	n.a.
Profile 2						
BkC	8.31	0.54	0.05	0.23	41.85	C, Q, M, A, CL, K, D
Profile 3						
BwkC	8.49	0.28	0.09	0.44	31.46	C, Q, D, A, M, K
BwC	8.56	0.26	0.08	0.42	34.21	n.a.
BkC	8.60	0.24	0.07	0.36	35.74	n.a.

EC=electrical conductivity, TN=total nitrogen; TOC=total organic carbon; CCE=calcium carbonate equivalent - n.a.=not available data-[a]Minerals listed in order of abundance: Q=quartz, C=calcite, A=albite, M=muscovite, D=dolomite, CL=clinochlore, K=kaolinite

Table 4
Chemical properties and mineral composition of de-sealed soils at Vallemiano, Ancona (Italy).

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Discussion

The soils from both study sites were identified as Technosols due to the materials covering the surface. However, variations in the characteristics of the asphalt, completely impervious and semi-impervious surfaces, influenced different pedological processes, resulting in distinct classifications for each site.

Torrette. The investigated profiles consisted of two distinct C horizons (Soil Survey Staff, 2024) with varying soil origins. As indicated by the abrupt color boundaries, the original soil (2Cb horizon) was located at depths ranging from 60 to 80 cm, overlain by a horizon developed through anthropogenic aggradation resulting from construction activities in the area (Norra et al., 2008). This is further supported by the distinct presence of microcline in the 2Cb horizon, which is absent in the surface Cr horizon, the latter being characterized by the presence of clinochlore. Despite these mineralogical differences, the shared composition of minerals between the two horizons (Quarzt < Calcite < Albite < Muscovitee < Kaolinite), aligned with other studies on soils from the same neighborhood (Serrani et al., 2022), led to similar chemical properties throughout the profile, including an alkaline soil reaction and an average Calcium Carbonate Equivalent (CCE) of 12.11%, with a standard deviation of 1.60%. Similarly, the physical characteristics of the soils revealed that all horizons contained a high percentage of fine-sized particles, which occluded interstitial pores. This, in conjunction with the very low organic matter content [ranging from a maximum of 1.13% to a minimum of 0.75% Total Organic Carbon (TOC)], led to the formation of massive pedological structures and contributed to soil compaction across all depths (Jim and Ng, 2018; Jim, 1998). This is supported by the bulk density values ranging from 1.31 to 1.63 g/cm³, which are considered the threshold beyond which physical limitation to potential root growth occurs (Fini et al., 2017; Nyéki et al., 2017). In this anthropogenically influenced pedogenic context, the characteristics of the surface cover played a significant role as a pedogenetic factor. Asphalt, with its low albedo, absorbed a substantial amount of solar radiation, which increased soil surface temperatures and reduced temperature fluctuations both seasonally and diurnally (Li et al., 2013; Fini et al., 2017). Consequently, soil biological activity may increase due to elevated temperatures, particularly during the initial stages following surface coverage, resulting in greater oxygen consumption in the telluric air (Piotrowska-Długosz and Charzyński, 2015; Zong-Qiang et al., 2014; Wei et al., 2013; Zhao et al., 2012). As oxygen levels continued to decline, the restricted atmospheric exchange fostered a gradual accumulation of CO_2 in the soil, which drove the transition to an anoxic environment. In addition, the reducing conditions were exacerbated by the physical properties that significantly affected soil water movement and retention (Kaczmarek et al., 2015; Namdar-Khojasteh et al., 2012). Within this soil, water primarily moved upward through capillarity and evaporation, as vertical infiltration from precipitation was impeded by the impermeable asphalt layer (Scalenghe and Ajmone Marsan, 2009). Equally, the impermeable cover disrupted the natural exchange processes between the atmosphere and soil, inhibiting vapor diffusion into the atmosphere (Piotrowska-Długosz and Charzyński, 2015). Consequently, water condensed upon contact with the impermeable layer and underwent precipitation (distillation process), progressively accumulating within the soil pores (Yao and Wang, 2019; Morgenroth and Buchan, 2009). Thus, the downward movement of water primarily occurred through interpedal cracks, which, due to their larger size, retained air longer than surrounding pores. This condition promoted the development of redoximorphic features along these cracks, particularly evident in the Cr horizons of Profiles 2 and 3 (Vepraskas et al., 2012).

Vallemiano. The study site at Vallemiano showed higher pedological variability, as evidenced by horizons with distinct properties. Although limited in some cases, all Profiles displayed a certain degree of development, as indicated by the presence of BC horizons with subsurface soil structure (Soil Survey Staff, 2024). The degraded and heterogeneous soil surface cover facilitated partial exchange between the hydrosphere, atmosphere, and pedosphere, while tree roots explored the surrounding soil, contributing to soil horizons differentiation (Scalenghe and Ajmone Marsan, 2009; Gessner et al., 214; Wang et al., 2024). Although the soils had a similar mineral composition, the relative proportions of quartz and calcite differed between Profile 1 and the other two soils, suggesting a more calcareous nature for Profiles 2 and 3. Soils in urban environments are subject to continuous changes driven by management practices and the introduction of allochthonous materials, resulting in spatial heterogeneity (Jim, 1998; Burgos Hernandez et

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al., 2021; Riddle et al., 2022). Profiles 2 and 3 recorded accumulations of secondary carbonates at varying depth, manifesting as concretions with differing abundances. Water infiltration and percolation through the soil profile led to the solubilization and downward movement of soil carbonates (primarily calcite) into deeper horizons. As the solution became supersaturated and/or soil moisture decreased due to evapotranspiration, the dissolved ions re-precipitated, forming secondary carbonate concretions (Zamanian et al., 2016). Additionally, Washbourne et al. (2012), investigated the origin of carbonates in urban soils attributing their formation to chemical reaction between carbon dioxide (CO_2) and soil cations. CO_2 in the soil may dissolve in water and react with calcium, magnesium, or other metal ions to form insoluble carbonate minerals, such as calcite (Washbourne et al., 2012; Prokof'eva et al., 2020). The accumulation of pedogenic carbonates primarily occurs in areas with a mean annual precipitation of less than 600 mm (Lintern et al., 2006). Although the study site received higher precipitation (~700 mm), surface cover may reduce water infiltration in soil, promoting lateral flow (Scalenghe and Ajmone Marsan, 2009). Wessolek (2008) reported that approximately 10% of precipitation infiltrates into soils beneath asphalt pavement. At Vallemiano, cracks and discontinuities in the soil cover increased water infiltration, which promoted carbonate accumulation, also due to the calcareous nature of the construction material (Kida and Kawahigashi 2015; Burgo Hernandez et al., 2021). Variations in the thickness of the asphalt layer (ranging from 5 to 13 cm in Profiles 2 and 3, respectively), may have influenced water infiltration differently, resulting in the formation of carbonate concretions at different depths. However, the absence of such morphologies in the BwC horizon of Profile 3 suggests that the formation of pedogenetic carbonates in the deepest horizon (BkC) is likely due to a process other than the downward movement of water. Chemeri et al. (2025) monitored hydrogeochemical changes in groundwater at various sites in Ancona. At Vallemiano, water levels varied between 1.94 m and 5.29 m below ground level, with the composition of anions and cations dominated by bicarbonate (HCO_3^-) and calcium (Ca^{2+}), respectively. Thus, the ascending capillary rise of water rich in Ca-HCO_3^- may have reached the BkC horizon, leading to the formation and accumulation of secondary carbonates (Espejo et al., 2008).

Conclusions

This study highlights the significant impact of soil sealing on urban and peri-urban environments, demonstrating how variations in covering materials influence soil properties and degradation processes. The findings reveal that homogeneous and impermeable asphalt layers, induce severe anoxic conditions by completely isolating the soil from atmospheric and hydrological exchanges. Conversely, the heterogeneous and degraded cover allowed for some degree of water movement, leading to carbonate translocation and accumulation. Overall, both sites exhibited common issues, including soil compaction, low nutrient levels, and the presence of allochthonous materials, further emphasizing the negative consequences of land consumption. Given these challenges, a comprehensive assessment of soil variability in urban areas is mandatory to develop effective site-specific interventions aimed at restoring de-sealed soils ecosystem services. This approach will optimize environmental rehabilitation strategies, promoting the recovery of soil functions and enhancing urban ecosystem sustainability. Future research should focus on evaluating the long-term effects of de-sealing and the potential for soil rehabilitation under different urban planning scenarios.

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