J Soils Sediments (2010) 10:1246–1254
DOI 10.1007/s11368-010-0206-6

SOILS, SEC 2 • GLOBAL CHANGE, ENVIRON RISK ASSESS, SUSTAINABLE LAND USE • RESEARCH ARTICLE

Early pedogenic evolution of constructed Technosols

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Received: 24 July 2009 / Accepted: 9 February 2010 / Published online: 21 March 2010

Abstract
Purpose Constructed soils are Technosols resulting from the deliberate combination of various artefacts. Similarly to natural soils, technogenic parent materials are transformed by pedogenic factors contributing to their evolution. This work was conducted to study the first stages of the pedogenesis of constructed soils.
Materials and methods Two soils were constructed in lysimetric plots (10 × 10 m) using an engineering process by the combination of paper-mill sludge, thermally treated soil material and green waste compost. Evolution of the soil profiles, composition of soils and leachates were studied for 3 years.
Results and discussion A strong evolution of the profiles was observed over the 3 years with rapid changes in the number and characteristics of the horizons. Significant changes in chemical weathering (decarbonatisation) and physical status (aggregation), i.e. processes similar to those occurring in natural soils were observed. Other processes specific to the technogenic materials were recorded, e.g. massive dissolution of gypsum or drainage of constitutive water. Apart from constructed Technosols classification, prediction was made on their future pedogenic evolution.
Conclusions Constructed Technosols made of finely divided reactive organic and mineral compounds were observed to evolve quickly. Evidences of original pedogenic processes have been highlighted that could be considered as a general diagnostic characteristic of Technosols. Finally, some considerations about the application of the World Reference Base for Soil Resources to the classification of Technosols are proposed, taking into account some aspects of their pedogenesis that have been highlighted by our work.

Keywords Aggregation · Pedogenesis · Technosol · Weathering

Responsible editor: Andreas Lehmann

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1 Introduction

Agriculture, industry and urbanisation induce soil degradation through dramatic physical, chemical and biological transformations but also create new soils characterised by the presence in various proportions of pedological, geological and technogenic materials. Soils developed on non-traditional substrates and largely due to intensive human activity are now referenced as Technosols in the World Reference Base for Soil Resources (WRBSR; Lehmann 2006; Lehmann and Stahr 2007; IUSS Working Group WRB 2006; Rossiter 2007). They are composed of various materials, some of which have no equivalent in nature: technogenic materials, i.e. artefacts.

Following the definition by Simonson (1959), pedogenesis can be classically described as a group of processes of addition, loss, transformation and translocation undergone by an in situ material. The nature, intensity and kinetics of the soil-forming processes are governed by the imbalance between soil parent materials and their environmental factors (Pedro 1964). Both natural and artificial soils are submitted to these environmental factors. However, the composition of the organic and mineral phases of technological materials, their structure and texture, the energy input (e.g. excavation, transportation, crushing, mixing and compaction) may cause original pedogenic processes. The passive soil-forming factors defined by Jenny (1941) are clearly distinctive for Technosols. The parent material is usually deeply marked in its composition by human activity (agricultural wastes, urban wastes, building materials, industrial by-products; Hiller 2000; Lefort et al. 2006; Lorenz and Kandler 2005; El Khalil et al. 2008). Their (1) lithological properties (e.g. extreme pH values, great abundance of calcareous materials, large amounts of organic matter; Bradshaw 1983; Beyer et al. 1996; Lemaire and Rossignol 1999; Lorenz and Kandeler 2005; Morel et al. 2005), (2) hydrological characteristics (extreme permeability, permeable material or paved surface; Nehls et al. 2007), (3) high porosity (i.e. high specific surface) and (4) high temperature and albedo system (Farouki 1986; Baumgartl 1998; Schleuß et al. 1998) cover wider ranges than natural substrates. The pedogenic processes of Technosols have been so far little studied (Payet 2001; Schwartz et al. 2003; Monserié et al. 2009; Badin et al. 2009; Zanuzzi et al. 2009). It has mainly been observed that their transformation is much faster than natural soils and mostly conditioned by the installation of the vegetation (penetration of roots, exudation of organic compounds, water withdrawal; Scalenghe and Ferraris 2009; Scholtus et al. 2009).

This work was undertaken to study the early pedogenesis that affects constructed soils (Séré et al. 2008), as relevant examples of Technosols. The aims were to identify the pedogenic processes, then to evaluate their intensity and kinetics and eventually to compare them with natural soil evolution. Constructed soils were also named after the World Reference Base for Soil Resources (IUSS Working Group WRB 2006).

2 Materials and methods

2.1 Parent materials

Three different artefacts were used: (1) a green waste compost (g.w. compost) mainly composed of urban tree and grass cuttings, licensed under NF U 44-051 standard; (2) a paper-mill sludge (p.m. sludge), which is a by-product of the paper industry, referenced in European Waste List (EWL) as “de-inking sludges from paper recycling”; (3) a thermally treated industrial soil (treated soil) excavated from a former coking plant site initially heavily polluted with polycyclic aromatic hydrocarbons, referenced in EWL as “solid wastes from soil remediation containing dangerous substances”.

Materials were analysed for agronomic parameters (Table 1). Methods used were similar as for natural soils: texture (three size fractions without decarbonatisation; NF X 31-107), pHwater (ratio soil/solution=1/5; NF ISO 10390), organic matter and organic C (oxidation by heating at 900°C under O_2 flow), total N (Kjeldahl mineralisation; NF ISO 11261), total $CaCO_3$ (reaction with HCl and measurement of the volume of CO_2 evolution with a Scheibler device; NF ISO 10693; AFNOR 2004). Analyses were carried out by the certified laboratory of INRA (Laboratoire d’Analyse des Sols, INRA, Arras). Quality controls for soils, sludges and water samples were assessed by the French Committee of Accreditation.

The main crystallised mineral phases were characterised with X-ray diffraction and scanning electron microscope (SEM S2500 Hitachi) coupled with energy dispersive X-ray analysis (EDS Noran Vantage; Table 2).

2.2 Experimental setup

A field experiment was set up on the experimental site of the French Scientific Interest Group –Industrial Wasteland (GISFI; http://www.gisfi.fr), Homécourt, North-Eastern France. The climate is continental with a mean rainfall of 760 mm year^{-1} and a mean temperature of 10°C (extreme values: 38°C to –22°C). Two basins were constructed (surface, 10 × 10 m; thickness, 1.5 m), and their bottom were lined with geomembrane barriers (high-density polyethylene, 2 mm). Both plots were equipped with a drainage network (polyvinyl chloride plastic pipe) at their bottom and connected to stainless steel tanks to collect drainage water.

In December 2003, they were filled with layers of technogenic parent materials to build two constructed soil

Table 1 Chemical composition of the parent materials

	Granulometric fractions (g kg^{-1})			pH	Organic matter	C/N	Calcite	Gypsum
	<2 µm	2–50 µm	50–2,000 µm		g kg^{-1}		g kg^{-1}	g kg^{-1}
Green waste compost	254	311	435	8.6	376	20	115	ND
Paper-mill sludge	244	687	69	7.9	251	27	478	ND
Treated soil	49	131	820	9.0	94	97	245	3.8

ND non-detected

Table 2 Mineralogy of the parent materials

	Major mineral phases (≥2%)	Minor mineral phases (≤2%)
Green waste compost	Quartz; calcite	Feldspaths
Paper-mill sludge	Calcite; dolomite	Kaolin; talc
Treated soil	Silica; calcite	Gypsum; iron oxides (unidentified)

profiles. They represented two different modalities of constructed soils with different levels of functionalities for derelict lands reclamation. Profile T was a basic reclamation engineering process (treated soil+compost), whereas profile P was designed in a pedological engineering approach with reasoned mixing and superposition of materials (Séré et al. 2008). In the following text, considering the construction process as a pedogenic factor, the term 'horizon' will be used instead of 'layer'. From bottom to top, Profile T (75-cm depth) was filled with (1) a 65 cm-horizon of thermally treated industrial soil and (2) a 10-cm upper horizon of green waste compost (Fig. 1a—t0). From bottom to top, Profile P (115 cm depth) was filled with (1) a 25-cm horizon of pure paper-mill sludge, (2) a 80-cm horizon of treated soil and paper-mill sludge mixture (1:1 volumetric ratio), and (3) a 10-cm horizon of green waste compost (see Fig. 1b–t0).

The surface was initially left unplanted, and spontaneous plants were allowed to develop (*Chenopodium album*, *Taraxacum officinale*, *Cirsum vulgare*). After a 1.5-year period, rye grass (*Lolium perenne* L. var. Tove) and alfalfa (*Medicago sativa* var. Europe) were sown on both plots (seed densities of 240 and 200 kg ha^{-1}, respectively), as they illustrated revegetation practice. These species were selected for their complementary nitrogen fixation, rooting and soil covering. No irrigation was applied.

2.3 In situ description, measurements and characterization

Campaigns were driven each year in May from 2004 to 2006 by digging a pit (1-m^2 surface area) on each plot. The soil profiles were described. Horizons were identified according to their colour (Munsell code) on dried samples; structure (form of aggregates), biological activity and root development were observed. The redox potential was determined in situ with a redox combination electrode (MC201Au-8). Bulk density was estimated from the volume and weight of the total soil material excavated from the pits. For each horizon (or sub-horizon), three sub-samples were collected to form a mean sample analysed for pHwater, organic C, total N and texture (same protocols than Section 2.1). Water content of soil samples was measured by weight difference after 16-h drying at 105°C.

Water-retention data were determined on a pressure plate apparatus for two water potentials (–10 and –15,800 kPa)

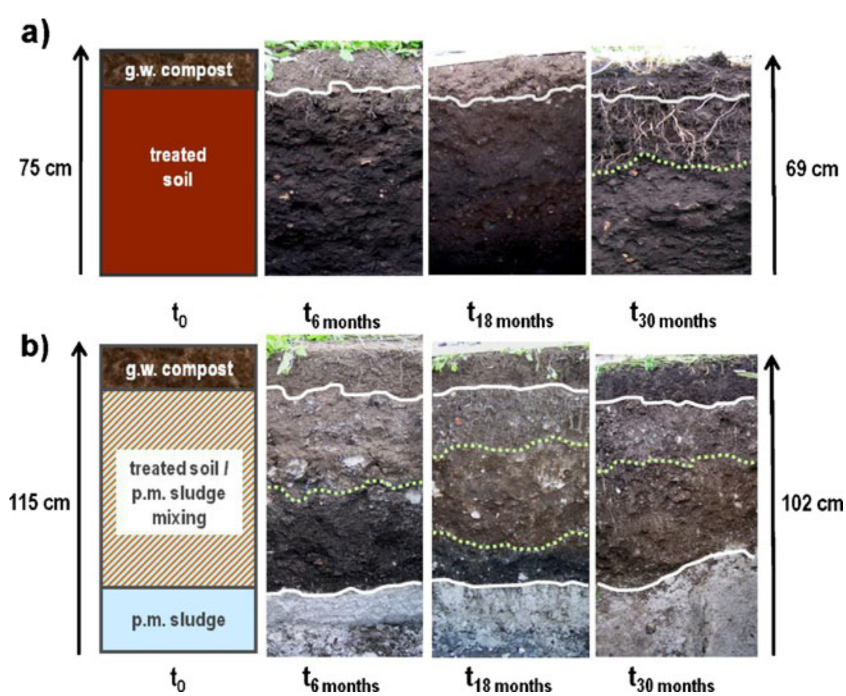

Fig. 1 Evolution of the constructed soil profiles over time; **a** profile T; **b** profile P

according to the methods described by Bruand et al. (1996). Available water storage (AWS), i.e. water disposable for plant growth, has been calculated by the following equation:

$$\mathrm{AWS} = (\mathrm{Wfc} - \mathrm{Wwp})$$

where AWS represents the available water storage (gramme per 100 g), Wfc is the water content at field capacity (gramme per 100 g; water potential –10 kPa) and Wwp is the water content at permanent wilting point (gramme per 100 g; water potential, –15,800 kPa).

Available water content (AWC), i.e. quantity of water disposable for plant growth in the soil, has been calculated by the following equation (Cousin et al. 2003):

$$\mathrm{AWC}_i = \mathrm{AWS}_i\, d_i\, \mathrm{th}_i$$

where AWC_i represents the available water quantity of horizon i (millimetre per centimetre), AWS_i is the available water storage of the horizon i (gramme per 100 g), d_i is bulk density of the horizon i (gramme per cubic centimetre) and th_i is the thickness of the horizon i (centimetre).

Soil aggregation was assessed by observation at ultra-structural scale of fine fractions (<2 mm) of the different horizons. For this, samples were fixed in osmium tetroxide, then dehydrated in graded acetones, and embedded in epoxy resin (Epon 812) until complete polymerisation. Then, ultra-thin sections (80–100 nm) were cut with a diamond knife on a Leica Ultracut S ultramicrotome, stained with uranyl acetate and lead citrate and examined in a JEOL 1200 EX II transmission electron microscope operating at 80 kV (Villemin et al. 2007).

Both the volume and composition of representative aliquots of drainage water collected and homogenised in the tanks were monitored monthly (as a function of rainfall). Samples were filtered at 0.45 μm and analysed for pH and major ion (notably Ca^{2+}, Mg^{2+}, SO_4^{2-}) composition by ionic chromatography (Dionex). In addition to that analysis, HCO_3^- was calculated to reach chemical charges equilibrium.

3 Results

3.1 Profile description

Both soils exhibited a reduction in volume over the 3 years. Profile T shrank from a 75-cm depth at 6 months to a 69-cm depth at 30 months (see Fig. 1a). Profile P lost 13 cm during the same period (from 115 to 102 cm; see Fig. 1b). Bulk densities of the parent materials of the constructed soils were low compared to natural soils (≤1 Mg m^{-3}). Increase in the bulk density was recorded in all horizons (Fig. 2), except in the paper-mill sludge horizon. The most significant increase was observed in the treated industrial soil/paper-mill sludge mixing horizon of profile P (0.7 Mg m^{-3} after 6 months to more than 1 Mg m^{-3} after 30 months).

The constructed soil profiles showed clear evidence of a rapid development of new horizons that can be visually distinguished according to their colour (Table 3) and to the root density. Profile T (see Fig. 1a) was originally composed of two horizons, which resulted from the superposition of different parent materials. After 30 months, a sub-horizon appeared between 15 and 35 cm. It was characterised by a higher root density as well as by a more brownish colour (10YR 3/2) than deeper in the profile (2.5Y 3/1; see Table 3). Profile P was made of three constitutive horizons (see Fig. 1b). After 6 months, four different horizons were observed. An additional horizon was observed after 18 months of evolution. Indeed, a temporary stagnic horizon appeared, characterised by the accumulation of stagnant water above the paper-mill sludge horizon, inside the treated soil/paper-mill sludge mixing. Some isolated grey–blue spots (<2% of the total surface) were visible that were associated to this water-saturated episode. It disappeared after 30 months, and four horizons again were recorded. Roots penetration increased with time from the soil surface. Earthworms and rodent burrows were present in the upper parts of the profiles from the 18-month campaign.

3.2 Structure and aggregation

Soils structure also showed a strong evolution. In profile T, the structure evolved slowly from particular (or structureless) at the origin to granular (or crumbly) with small aggregates (1 mm) in both green waste compost and the upper part of the treated soil horizon. The structure of the bottom part of the treated soil did not evolve significantly. In profile P, a granular structure's evolution was also observed in green waste compost. In the mixed material (treated industrial soil/paper-mill sludge), the original structure was blocky–granular (>10-mm diameter) and evolved to a very distinct granular structure (5-mm diameter), especially in the upper part of the horizon. The pure paper-mill sludge horizon evolved from an original blocky–granular structure to a prismatic structure (50–100 mm).

TEM observations conducted on soil samples collected after 30 months of evolution highlighted soil aggregation. Examples of aggregates were visualised as bacterial aggregates in the compost (Fig. 3a): Bacteria-producing exopolymers were surrounded by fine mineral particles and also as close associations between mineral particles of the treated soil and cellulosic fibres of the paper-mill sludge (see Fig. 3b).

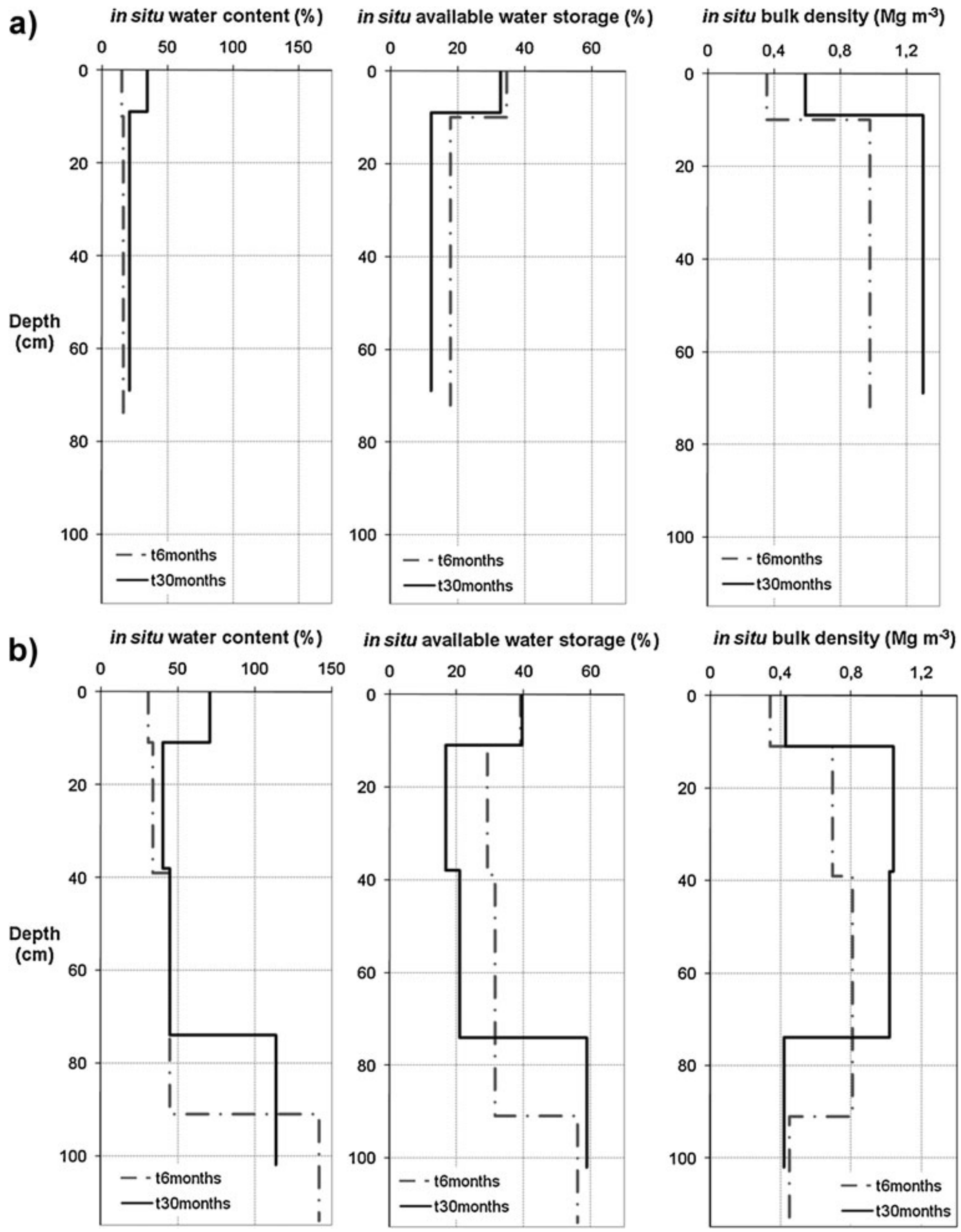

Fig. 2 Evolution of water content; available water storage; bulk density of **a** profile T, **b** profile P

Table 3 Evolution of the colour of the constructed soil horizons (dried samples)

		Colour/Munsell code		
		6 months	18 months	30 months
Profile T	Green waste compost	10YR 2/2	10YR 2/2	10YR 3/3
	Treated soil	7.5YR 2/1	10YR 2/1	10YR 3/2 2.5Y 3/1
Profile P	Green waste compost	10YR 2/2	10YR 2/2	7.5YR 3/2
	Treated soil/paper-mill sludge mixing	2.5Y 4/1	7.5YR 4/2	10 YR 5/2
		2.5Y 6/2	10YR 4/3 2.5Y 3/3	2.5Y 4/2
	Paper-mill sludge	N 8/0	2.5GY 8/1	7.5Y 8/1

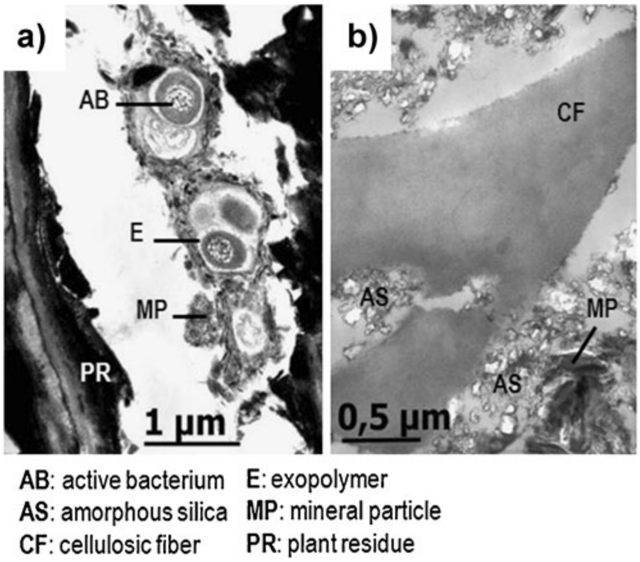

Fig. 3 Microscopic structures (TEM) on profile P material sampled 30 months after soil construction in, respectively, **a** g.w. compost and **b** treated soil/p.m. sludge mixing

3.3 Water status

Considering that the climatic conditions were similar before each campaign, it is possible to compare qualitatively the measurements. The water contents were constantly lower in profile T than in profile P for all horizons (see Fig. 2). In profile T, the water content was always higher in the compost horizon than in the treated soil horizon. On the contrary, in the profile P, the water distribution was located mainly in both the upper part (the compost horizon) and the lower part (the paper-mill sludge horizon) of the constructed soil.

Taking into account the whole soil thicknesses, the AWC was significantly lower in profile T (12 mm cm^{-1}) than in profile P (26 mm cm^{-1}). AWS was similar for both green waste compost horizons and varied only slightly with time (35% to 39%; see Fig. 2). It was constant and very high in the paper-mill sludge horizon (>55%). It has decreased in treated soil horizon from profile T (18% to 12%) and treated soil/p.m. sludge mixing horizon from profile P (30% to 18%); this can be correlated with the increase of the bulk densities.

There was a continuous and significant increase of the redox potential in both soil profiles (Fig. 4). After 6 months, reducing conditions (–37.5 mV) were detected in the treated industrial soil horizon of profile T which disappeared after 30 months of evolution. In profile P, significant differences were noticed between the upper sub-horizon and the lower sub-horizon of the treated soil/paper-mill sludge mixing.

3.4 Chemical weathering

All parent materials were calcareous, and their pH was alkaline (see Table 1). In profile T, pH decreased with time in the compost (8.6 to 8.1), contrary to the treated soil horizon which exhibited an increase in pH (9.0 to 9.4; see Fig. 4a). This sensible increase could be either explained by the exposition of new mineral phases (e.g. CaO) or by a sampling bias. In profile P, loss of alkalinity was observed in the upper horizon of compost (8.6 to 8.0); in the other horizons, the pH varied perceptibly with a small decrease in the lower part of the mixing horizon (8.5 to 8.3; see Fig. 4b).

Breakthrough curves of the major elements in the drainage water of profile T showed a simultaneous decrease in SO_4^{2-} and Ca^{2+} concentrations from 25 to about 10 meq L^{-1}

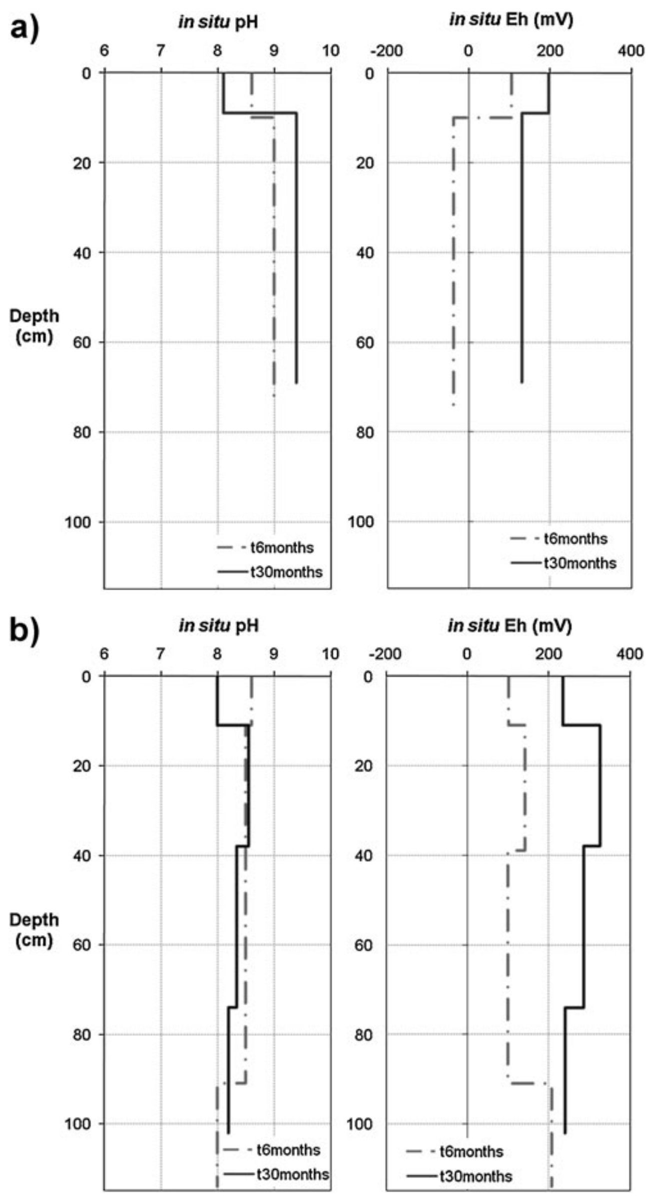

Fig. 4 Evolution of redox potential and pH of **a** profile T, **b** profile P

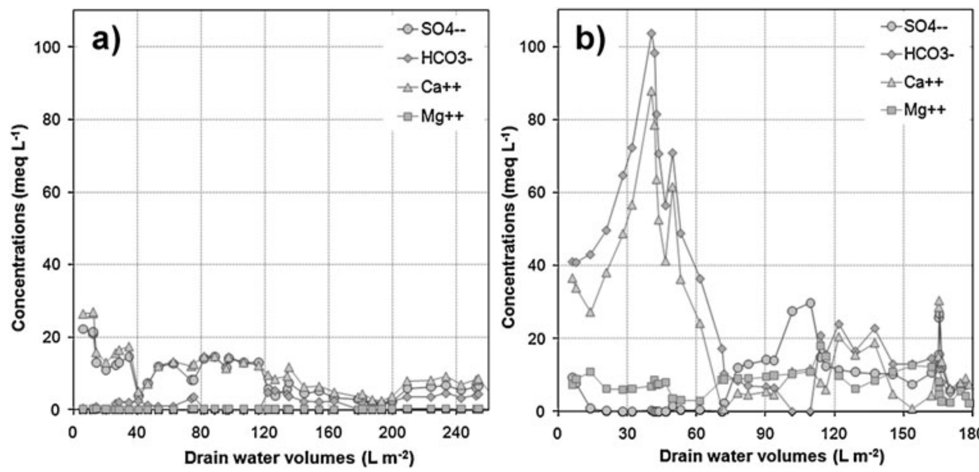

Fig. 5 Evolution of the composition in major elements of the leachates from **a** profile T, **b** profile P

until 120 L m^{-2} (Fig. 5a). Then, until 240 L m^{-2}, SO_4^{2-}, HCO_3^- and Ca^{2+} concentrations remained steady at around 10 meq L^{-1}. In profile P, a concentration peak of HCO_3^- and Ca^{2+} reaching 105 meq L^{-1} above calcite solubility was observed in the first 70 L m^{-2} (see Fig. 5b). Then, an increase in the output of SO_4^{2-} and Mg^{2+} followed with the next 100 L m^{-2}. In the end, all ion concentrations decreased, especially SO_4^{2-}. The concomitant outputs of SO_4^{2-} and Ca^{2+} indicated gypsum ($CaSO_4$) dissolution, whereas the coupled output of HCO_3^- and Ca^{2+} was dissolution of calcite ($CaCO_3$). The mass balance calculations on the two profiles indicated that 0.05% of the total calcite in profile T and 0.35% in profile P had been dissolved, and Gypsum dissolution reached 5% in both soil profiles (see Table 2).

The leachates from profile P, notably in the first 70 L m^{-2}, were very loaded in soluble ions. The very high concentrations in Ca^{2+} and HCO_3^- with significant amount of Mg^{2+} attest of the presence of a complex equilibrium between different carbonated minerals, with complex reprecipitation kinetics inside the soil. Our assumption is that this chemical composition resulted of the drainage of constitutive water that was already present in the parent materials (especially paper-mill sludge) before the soil construction.

4 Discussion

4.1 Early pedogenesis of constructed Technosols

Constructed soils are the result of a deliberate combination of materials to create specific soil functions. Such raw materials undergo strong transformations during the early stages. The resulting soil profiles exhibit two distinct phases of pedogenesis, as shown by our work. During the first phase, the technogenic parent materials are subjected to dramatic physical and chemical changes such as compaction, evacuation of constitutive water and intense weathering of soluble minor minerals. The reactions taking place during this early period of soil life have a distinctive feature, due to the anthropogenic origin of the materials that have no strict equivalent in natural soils. The second phase is characterised by pedogenic processes similar to those happening in natural soils, in similar pedoclimatic conditions, i.e. the dominant chemical reaction of decarbonatisation and the bio-physical reaction of the formation of aggregates. Indeed, significant evolutions of the macrostructure, the water-retention properties as well as the evidence of a micro-structuring have been highlighted.

The work was based on an in situ lysimetric experiment to study the evolution of the constructed soils under conditions as close as possible to the reality of the implementation of the technology. No repetition was done considering the large size of plots (100 m^2). The time of study (3 years) could be considered as short, but general trends of evolution have been highlighted. However, additional studies are of course needed to understand the further evolution of the constructed Technosols. Another point would be to take into account the role of parameters such as biological factors (plants, soil fauna).

All observed pedogenic processes are characterised by fast kinetics and high intensity, a situation probably caused by the fine division and the high specific surface area of the materials favouring a strong mineral weathering (Anderson et al. 2002). For example, weathering rates of calcite were higher in the constructed soils under a continental climate—around 240 g m^{-2} $year^{-1}$—than in the calcareous parent rocks, e.g. from 10 g m^{-2} $year^{-1}$ in chalk rock under the same climatic conditions to 200 g m^{-2} $year^{-1}$ on a würmian calcaric terrace under humid mountain climatic conditions (Duchaufour 1983). Beside physical changes (compaction and water drainage), other processes were recorded leading to the multi-scale structuring of the constructed soils. It is noticeable that such a pedogenic process as aggregation resulted from both a natural factor as the biological activity (Morel et al. 1991) and an anthropogenic factor like the initial parent materials' settlement and the particle mixing.

Intrinsic reasons relating to the artefacts' origin of the parent materials inevitably induce a remarkable intensity in the pedogenic processes of constructed soils. Disequilibria between the parent materials and the environmental forcing factors that lead to an internal chemical response induced a high-energy state of the constructed soil system, as suggested by Chadwick and Chorover (2001).

4.2 Classification of constructed Technosols

Using the new WRBSR (IUSS Working Group WRB 2006), profile T is classified as Spolic Folic Technosols (Calcaric), due to the presence of treated soil as an industrial waste and the content of calcite (2.5%). Green waste compost horizon is less than 20 cm thick; it is therefore named 'folic' instead of 'garbic'. The profile P is classified as Spolic Garbic Hydric Technosols (Calcaric) due to the presence of treated soil, the content in green wastes compost and paper-mill sludge as organic waste materials and the water-retention properties of the paper-mill sludge at its bottom; its content in calcite is >2%. In both cases, the suffix Gypsiric could not be used as they contain less than 5% of gypsum.

Considering the stagnic episode during the second campaign, profile P could have been temporarily named Spolic Garbic Endostagnic Hydric Technosols (Calcaric). Taking into account the significant organic matter mineralization and global evolution in the compost horizon (Séré 2007), it can be considered that the garbic origin of the material will quickly be undetectable. This will lead to a fast evolution (within 10 years) of profile P to Spolic Folic Hydric Technosols (Calcaric). Step by step, the technic properties of the different artefacts will less and less influence the pedogenic evolution. Furthermore, our assumption is that later, constructed soils' pedogenesis will bring them to acquire characteristics and properties of natural soils such as Cambisol. It can be assumed that—in about a century—the constructed Technosol will become with time a Technic Cambisol, considering that evidences of the anthropogenic origin of the parent materials could still be visible.

5 Conclusions

Constructed soils clearly appear to be relevant examples of the recently created reference Technosol. Soils are four-dimensional natural bodies with the key characteristic of spatio-temporal variation in state properties and processes (Sommer 2006) and so are constructed Technosols. The results suggest that they are submitted to a dynamic evolution as far as transfer by leaching, aggregation, organic matter transformation and mineral weathering are concerned. Some pedogenic processes appear to be similar to what happens in natural soils like aggregation and decarbonatisation. On the other hand, some processes are different and characteristic of Technosols such as the initial hydric drainage and the significative dissolution of gypsum. In all cases, the kinetics of the reactions is very fast, and this is explained by the disequilibria between the artefacts and the environmental conditions. Constructed Technosols are extreme examples of Technosols; however, such a distinctive and dynamic evolution could be considered as a diagnostic characteristic of this soil reference.

The classification that has been developed for Technosols is mainly based on criteria such as the nature and origin of the artefacts or technogenic parent materials. On contrary to the classification of natural soils and horizons, this choice was made, in a certain way, to the detriment of genetic criteria. Our work showed that it was difficult to take the genetic into account because of the fast pedogenic evolution of young Technosols—considering pedological time scale. Indeed, the results presented here illustrate the fact that in constructed Technosols, a pedoclimax could not be reached in the early stages. The present classification of Technosols is hardly able to describe the precocious evolution already observed: the plurality of origin and composition of the parent materials (garbic, spolic, calcaric) as well as its evolving properties (hydric, stagnic). These examples speak in favour of a more dynamic approach. Finally, concerning their further evolution, one can formulate the hypothesis that, in certain cases (permeable environment, development of vegetation and biological activity), Technosols might only be a step in the evolution of anthropised soils to becoming natural soils.

Acknowledgements This project is supported by the GISFI programme (www.gisfi.fr); it was financed by the Etat Français (ANRT), Région Lorraine (CPER), ADEME and received technical support from Etablissement Public Foncier de Lorraine and Arcelor-Mittal Real Estate France. The authors wish to thank Stéphane Colin, Alain Rakoto and Jean-Claude Bégin for their precious technical help.

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