Organic and Inorganic Waste for Site Restoration Actions

Maria Rosaria Boni, D.I.T.S., SAPIENZA University of Rome  
Silvia Sbaffoni, D.I.T.S., SAPIENZA University of Rome  
Letizia Tuccinardi, D.I.T.S., SAPIENZA University of Rome

CONTACT
Silvia Sbaffoni  
Department of Hydraulics, Transportation and Roads - SAPIENZA, University of Rome  
Via Eudossiana, 18 – 00184 Rome (Italy)  
Telephone: +39.0644585507  
Fax: +39.0644585015  
Email: silvia.sbaffoni@uniroma1.it

EXECUTIVE SUMMARY

A possible strategy for recovery and valorisation of organic waste is land applications for restoration and rehabilitation of degraded lands whose environmental quality has been compromised by industrial and/or raw materials extraction activities. Based on these considerations, the aim of the present paper is to find an alternative application to waste often landfilled. In particular, the goal was to evaluate the suitability of organic waste, such as compost and stabilized organic fraction (SOF) of municipal solid waste, for restoration activities; tuff and pozzolana, discarded during the extraction activity, were mixed to the organic waste at different percentages, in order to improve their mechanical characteristics.

The materials and the mixtures were characterised in terms of their physical, mechanical and chemical characteristics. The mechanical characterisation was carried out in order to check the suitability of the materials tested for restoration actions, in terms of resistance, response to axial compression, swelling capacity, stability. Thus oedometric test and direct shear test were performed. Tuff and pozzolana exhibited initial void ratio significantly lower (1.76 and 1.16, respectively) than compost (5.03) in correspondence to the beginning of the test (no load applied). Both pozzolana and tuff exhibited a very low void ratio reduction, corresponding to very low compressibility coefficient, with final values equal to 1.02 and 1.31, respectively. On the contrary, compost was characterised by a higher reduction of the void ratio as the vertical load increased (from about 4.45 at 25 kPa to 2.92 in correspondence to 400 kPa); due to such a behaviour compost should not be used alone for site restoration activities. All the compost-based mixtures presented the same behaviour as the inert materials alone, being their response to oedometric compression better than compost one. On the contrary, SOF produced significant worsening in the resistance to compression of both tuff and pozzolana. The friction angle obtained through the direct shear test was almost similar for all the inorganic materials and the compost-based mixture tested, with values typical of granular materials, which guarantee the stability of possible slopes made with the mixtures. Significantly worse performances were shown by the SOF-based mixtures.

Due to the results obtained through the mechanical characterisation, in terms of compressibility and resistance to shear stress, the optimal mixtures selected were checked also in relation to their environmental quality and a seeding test at lab-scale was carried out.

The results obtained allow to conclude the followings:
- the addition of compost in the percentages tested did not affect significantly the mechanical properties of the inorganic waste, in terms of both resistance and mechanical stability;
- the environmental compatibility and the absence of possible phytotoxic effects were proved
through the chemical and leaching characterisation of the mixtures. Thus the mixtures of compost and inert materials, in the percentages investigated in the present work, represent a valid “artificial soil” to be successfully used for cost-effective site restoration. Moreover, the possibility to reuse the waste materials tested allows to reach the economical exploitation of waste materials, the reduction of the waste volumes to be landfilled and the addition of nutritional elements to the soil.

INTRODUCTION

The landfill is the residual element of the integrated waste management system. Besides, the regulation in force set some limits to the quantity of organic materials to be landfilled. Thus a large amount of biodegradable waste must be diverted from landfills to other organic waste management practices, being recovered and valorised. A possible strategy for recovery and valorisation is land applications for restoration and rehabilitation of degraded lands whose environmental quality has been compromised by industrial and/or raw materials extraction activities. Under the regulations (D.Lgs. 152/06), mine sites and abandoned pits are to be recontoured and topsoil must be replaced. Vegetative cover must be established soon after the end of mining operations to stabilize soils and prevent erosion. In spite of regulations, there is a vast heritage of degraded land left by pit mining that requires restoration, to be achieved as cheaply and as effectively as possible. Organic amendments such as sewage sludge (Haering et al., 2000), compost and stabilized organic fraction from municipal solid waste (Brown et al., 2000) can be used for restoration of abandoned pits or for the reconstruction of topsoil, supplying sufficient organic matter and nutrients to initiate successful soil rehabilitation. With the use of blended residuals to create a manufactured topsoil, it may be possible to restore a vegetative cover directly on mine tailings, providing an alternative to current accepted technologies (Halofsky and McCormick, 2005; Jochimsen, 2001; Cummings et al., 2005). In the last years it was suggested to use organic and inorganic materials alone and mixed in restoration activities (Dudeney et al., 2004; Boni et al., 2004), also in order to find a valid market and a sustainable management strategy for such secondary raw materials, that can be considered as artificial soils. Despite the potential benefits of using the above mentioned materials to recover land disturbed by extraction activities, there are some short and long-term risks involved, linked to their land application. Such risks are associated with the presence of pathogens, heavy metals and organic pollutants (Albiach et al., 2000). Generally the heavy metals content is higher than the one found in soils, but concentrations were generally low, with no reason for concern regarding groundwater contamination (Kaschl et al., 2002; Boni et al., 2006), since the metal concentrations remained below drinking water standards. There are several strategies available to limit heavy metal availability: increasing soil pH and adding organic amendments with high biological stabilization degree (Brown et al., 2003; Boni et al., 2006), which seems to reduce also the amount of pathogens (Dumontet et al., 1999). Besides, the biological stabilization is a successful way and to reduce the negative effects of the unstable organic matter in the soil, such as odour emissions. Finally, also geotechnical problems must be considered, such as the stability of the imported topsoil. Based on these considerations, the aim of the present paper was to find an alternative application to waste often landfilled. In particular, the goal was to evaluate the suitability of organic waste, such as compost and stabilised organic fraction (SOF) of municipal solid waste for restoration activities; inorganic materials (tuff or pozzolana, abundantly present and caved in Italy), with adequate grain size distribution, discarded during the extraction activity, were mixed to the organic waste at different percentages, in order to improve its mechanical and geotechnical characteristics. Thus the experimental activity allowed to determine the optimal percentages of organic waste to be used in the mixture. The feasibility of waste reuse was checked through the physical-chemical and mechanical characterisation of the materials and the mixtures, as well as through the evaluation of their environmental quality in terms of leaching behaviour.
MATERIALS AND METHODS

Materials

The compost used in the present research was collected from a composting plant treating 88 t/d of source-selected waste (about 20 t/d of organic waste from separate collection, 60 t/d of market and food waste and 8 t/d of lignocellulosic waste and green waste). The composting process is carried out in a 26x28 m mixed dynamic horizontal reactor in a close building. SOF was sampled in a biostabilization plant treating about 550 t/d of unsorted municipal solid waste. The biological process is carried out in a 24.5x66 m mixed dynamic horizontal reactor in a close building. In both the plants air is provided through a distribution system at the bottom of the waste pile.

Organic material is an extremely light material, of scarce consistency and density, highly compressible (Boni et al., 2006) even at low vertical loads and able to get its initial volume as the vertical loads are removed. Due to its poor mechanical characteristics, its exclusive use in restoration activities is not feasible. Thus, in this experimental activity compost was mixed to discarded materials from caving of pozzolana and tuff, providing a sort of stony skeleton and a resistant structure. Pozzolana and tuff are natural volcanic materials, collected at the Corcolle cave and at the Riano cave, respectively (both near Rome).

Such materials were mixed, obtaining the “artificial soils” presented in Table 1. The addition of the organic fraction must be defined according to the following criteria:

- geotechnical: the presence of organic waste must not produce a worsening in the resistance and stability performances of the inorganic granular materials, enabling the use of the mixtures;
- physical-chemical: the protection of surface water and groundwater must be ensured avoiding possible contamination events due to the leaching of both organic and inorganic contaminants;
- biological: the organic material should be enough stable from a biological point of view and mature in order to avoid biodegradation processes and phytotoxic effects.

Table 1 Percentages (as volume) of the materials used in the mixtures

<table>
<thead>
<tr>
<th>Mixtures</th>
<th>TC10</th>
<th>TC20</th>
<th>TC30</th>
<th>TF10</th>
<th>TF20</th>
<th>TF30</th>
<th>PC10</th>
<th>PC20</th>
<th>PC30</th>
<th>PF10</th>
<th>PF20</th>
<th>PF30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compost</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>20</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOF</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>20</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Tuff</td>
<td>90</td>
<td>80</td>
<td>70</td>
<td>90</td>
<td>80</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pozzolana</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Methods

**Mechanical characterisation**

The mechanical characterisation was carried out in order to check the suitability of the materials tested for restoration actions, in terms of resistance, response to axial compression, swelling capacity, stability. Thus the following tests were performed:

- oedometric test, to investigate the response to axial compression, simulating the consolidation occurring under the weight of the overhanging soil. The settling rate and the settlements due to the volume changes in the soil samples were measured. The test was performed with increasing vertical loads (25, 50, 100, 200 and 400 kPa), each maintained for 24 h;

- direct shear test. The shear box has a 225 cm² area, enabling to test the materials with a wide range of grain size (70 µm ÷ 60 mm) and to obtain results more similar to the real scale behaviour. Before applying the vertical load the sample was manually packed in the shear box. The static consolidation load was maintained until the vertical deformation remained constant for 60 minutes. Three different normal stresses were applied, equal to 200, 400 and 600 kPa. The angle of internal friction (or friction angle, \( \phi \)) was determined.

Besides, the grain size distribution was determined.

Based on the results of the geotechnical characterisation, the percentages of the organic and inorganic materials to be used were defined, in order to maximise the performance of the mixtures.
from a mechanical point of view, in terms of compressibility (important parameter for land application) and friction angle (important parameter for slopes stability).

Chemical characterisation
The following parameters were measured on the solid matrices: natural pH, water content (U), total organic carbon (TOC), ammonia nitrogen (NH$_4^+$-N), total volatile solids (TVS) and heavy metals (DIVAPRA, 1998). The results obtained were compared to the limits set by regulation in force (D.Lgs. 152/06) for the definition of a potentially contaminated site. Moreover, a compliance leaching test (UNI, 2004) was performed, in order to check the environmental compatibility of the materials, in particular in terms of heavy metals release. The solid matrix was in contact with demineralised distilled water (liquid-to-solid ratio –L/S- equal to 10 l/kg) for 24 hours. Heavy metals were determined by atomic absorption on the eluates obtained. The results obtained were compared to the limits set by the regulation in force (D.M. 03/08/2005) for the hazardousness definition of the waste.

Seeding test
In order to evaluate possible phytotoxic effects of the materials used, a seeding test at lab-scale was carried out on PC30, TC30, PF30 and TF30 (3 samples for each mixture), which resulted suitable for land application in terms of both environmental and mechanical performances. To such an aim wooden pots were used, having the dimensions proper to the direct shear test box were realized: length 15 cm, width 15 cm and height 13 cm. In fact, in order to evaluate the possible influence exerted by roots on the shear resistance of the materials, the samples used for the germination test underwent a shear test about 4 months after the seeding. The friction angle was then compared to the one determined without plant roots during the initial mechanical characterisation. At the end of the experimental phase the plants were characterised in terms of heavy metals content. The seed mixture was made of 20% *Lolium perennis* L., 50% *Festuca arundinacea*, 20% *Festuca rubra* L., 5% *Festuca rubra* fallax, 4% *Poa pratensis*, 1% *Agrostis tenuis* Sibth, usually used in restoration activities.

RESULTS AND DISCUSSION

Mechanical Behaviour
The mechanical characterisation aimed at selecting the best-performing mixture in terms of their compressibility, resistance and mechanical stability.

Grain-size distribution
Tuff and pozzolana were used at a grain size smaller than 60 mm. It was observed that pozzolana and PC30 showed almost overlapping granulometric curves, since the addition of compost did not affect the gain size distribution, as also confirmed by the granulometric classes: both pozzolana and PC30 were made of about 50-51% of gravel, 42-3% of sand and 7% of clay+loam. The difference were more significant between tuff and TC30. In fact, the grain size distribution of tuff showed a higher content in gravel (about 20% higher than pozzolana) and the addition of compost, rich in fine fraction, led to a non-negligible change in granulometric characteristics of the materials: gravel content decreased of about 10% (from 70.2% for tuff to 60.5% for T30), while sand and clay+loam content increased of about 7% and 3%, respectively. Despite that, PC30 and TC30 were quite similar in terms of fine fraction content (7.5% and 7.4%, respectively), differing in terms of gravel (51% and 60.5%, respectively) and sand (41.6% and 32.2%, respectively) content. The gravel+sand content was the same for both the mixtures (92.6% for PC30 and 92.7% for TC30). The uniformity coefficient (U.C. = $D_{60}/D_{10}$) was also calculated; the values obtained (38.5 for tuff, 55.1 for TC30, 38.6 for pozzolana and 44.2 for PC30) were typical of well sorted granular materials, with lower uniformity for tuff-based mixtures.
The grain size distribution of the SOF-based mixtures was artificially reconstructed in order to obtain the same distribution the compost-based mixtures had.

**Oedometric test**
The oedometric test was carried out on all the mixtures and the materials alone, allowing to choose the best-performing mixture in terms of response to axial compression. Tuff and tuff-based mixtures presented very similar behaviour as the porosity reduction is concerned. In fact, the variations were in the range 4-5% for these materials. Compost and SOF had the maximum reduction of about 10% in correspondence to 200 kPa. Compost and SOF addition did not seem to affect the behaviour of the inorganic materials in terms of porosity for the vertical load range investigated.

In Figure 1 the results obtained by the oedometric test for all the materials are shown; in particular the oedometric curves (void ratio vs. vertical load) are presented. Tuff and pozzolana exhibited initial void ratio significantly lower (1.76 and 1.16, respectively) than compost (5.03) in correspondence to the beginning of the test (no load applied). In the case of both pozzolana and tuff, a very low void ratio reduction can be observed, corresponding to very low compressibility coefficient, with final values equal to 1.02 and 1.31, respectively. On the contrary, compost was characterised by a higher reduction of the void ratio as the vertical load increased (from about 4.45 at 25 kPa to 2.92 in correspondence to 400 kPa).

During the loading phase the compost curve is almost linear, confirming the high compressibility of the material; due to such behaviour compost should not be used alone for site restoration activities.
As the vertical load decreased, the materials did not exhibit a significant swelling with a negligible void ratio increase. All the mixtures presented the same behaviour as the inert materials alone, being their response to oedometric compression better than compost: the compost addition in the fixed percentages seemed not to influence significantly the pozzolana and tuff behaviour in terms of compressibility. The tuff-based mixtures presented almost the same behaviour as the pozzolana-based ones, despite the different initial void ratio, and in general their oedometric curves did not differ significantly by the inorganic materials alone.

In general, it can be observed that the organic material was the most compressible matrix. The inorganic materials showed similar behaviour as well as void ratio values. The same can be said also for the mixtures, which in general presented oedometric curves more similar to the inert materials than to the organic fraction, with good response to the edometric load. It can be concluded that the addition of compost in the percentages used in the present experimental activity did not affect significantly the compressibility properties of the inorganic waste. In fact, the tuff-based and the pozzolana-based mixtures presented oedometric curves almost overlapping, not depending on the different content of organic waste.

The same considerations can be done as the graph settlements-time are concerned. The maximum and minimum settlements were observed for compost and pozzolana, respectively. Settlements for compost are due to the water migration in the sample, as well as to the deformation of the organic components (plants fibers, wooden parts, plastics, etc.).

The lowest compressibility of pozzolana and PC30 was also linked to the higher content of finer fractions; besides the higher uniformity of the grain-size distribution, as calculated through the U.C., influenced the lowest compressibility of both the T-based and P-based mixtures.

The oedometric test allowed to calculate the oedometric modulus, defined as follows:

\[ E = \frac{\Delta \sigma}{\Delta H / H_0} \]

where \( \Delta \sigma \) is the load increase, \( \Delta H \) is the variation in the sample height and \( H_0 \) is the initial height of the sample.

The oedometric modulus of the mixtures in correspondence to 200 kPa was always higher than 2 MPa: such values can be considered suitable for restoration actions.

**Direct shear stress test**

Through the direct shear test the maximum shear stress (\( \tau_{\text{max}} \)) value can be determined for each step of the test in correspondence to each normal load applied. Such value represents the maximum shear stress admissible for the material before the breaking. The profile of the shear stress as a function of the horizontal displacements was typical of the granular materials: at the beginning the materials density increased slightly, due to the grains repositioning, corresponding also to a higher material resistance. Beyond the maximum shear stress causing the material breaking, a decrease in the shear resistance was observed: the deformation continues without volume and resistance variations. The residual resistance reached at the end of the test is generally higher than 50% of \( \tau_{\text{max}} \). It was observed that the behaviour of the mixtures did not differ significantly from the tuff and pozzolana ones in terms of \( \tau_{\text{max}} \) value, especially when the minimum (200 kPa) and the medium (400 kPa) normal loads are concerned. As the organic material’s content increased, the time needed to reach \( \tau_{\text{max}} \) increased with respect to tuff and pozzolana alone, and it occurred in correspondence to higher horizontal displacements.

The friction angle was obtained as the slope of the straight lines obtained in a Mohr plane, where the horizontal and the vertical axis represent the normal stress and the shear stress, respectively. The friction angle is almost similar for all the materials and mixture tested, with values typical of granular materials, which guarantee the stability of possible slopes made with the mixtures (Dixon and Jones, 2005), as shown in Table 2. All the materials tested presented friction angle values higher than 50°, except for SOF-based mixtures. The higher the SOF percentage, the lower the friction angle with reduction of about 23% and 45% for PF30 and TF30, respectively.

Due to the results obtained through the mechanical characterisation of the materials, in terms of
compressibility and resistance to shear stress, the optimal mixtures selected were PC30 and TC30, in order to ensure a good organic content for revegetation without worsening the mechanical performance of the inorganic waste. Such mixtures were checked also in relation to their environmental quality.

Table 2 Friction angle for the materials investigated and correlation coefficient of the fitting straight lines

<table>
<thead>
<tr>
<th>P</th>
<th>T</th>
<th>PC10</th>
<th>PC20</th>
<th>PC30</th>
<th>TC10</th>
<th>TC20</th>
<th>TC30</th>
<th>PF10</th>
<th>PF20</th>
<th>PF30</th>
<th>TF10</th>
<th>TF20</th>
<th>TF30</th>
</tr>
</thead>
<tbody>
<tr>
<td>θ (°)</td>
<td>58.54</td>
<td>50.25</td>
<td>56.38</td>
<td>56.73</td>
<td>57.15</td>
<td>52.89</td>
<td>52.40</td>
<td>54.44</td>
<td>40.05</td>
<td>37.24</td>
<td>31.79</td>
<td>33.35</td>
<td>27.09</td>
</tr>
<tr>
<td>R²</td>
<td>0.96</td>
<td>0.93</td>
<td>0.95</td>
<td>0.99</td>
<td>0.99</td>
<td>0.97</td>
<td>0.99</td>
<td>0.99</td>
<td>0.82</td>
<td>0.91</td>
<td>0.95</td>
<td>0.99</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Chemical-Physical and Leaching Behaviour

The chemical characterisation of the materials investigated is reported in Table 3. The values of the parameters analysed for compost and SOF were below the limit set by the regulation in force for their possible reuse in environmental restoration activity (D.C.I. 27/07/1984). Only pH is slightly higher than the limit, but it should not be of concern, depending on natural pH of the sites to be restored (e.g. in case of tuff or pozzolana caves, natural pH can be quite higher than 9, as also determined in this experimental research). Besides, compost and SOF ensured a good organic as well as nutrient content to the mixtures, allowing an efficient revegetation of the site. All the materials resulted suitable for land application; in fact, the heavy metals concentrations were below the threshold concentration of contamination (D.Lgs. 152/06) for both industrial and residential destination use.

Table 3 Chemical characterisation of the materials investigated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>compost</th>
<th>PC30</th>
<th>TC30</th>
<th>SOF</th>
<th>PF30</th>
<th>TF30</th>
<th>D.C.I. 27/07/84</th>
<th>D.Lsg. 152/06</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td></td>
<td>8.87</td>
<td>9.26</td>
<td>9.05</td>
<td>7.90</td>
<td>8.28</td>
<td>8.40</td>
<td>6-8.5</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>%</td>
<td>9.59</td>
<td>2.16</td>
<td>4.56</td>
<td>14.52</td>
<td>5.20</td>
<td>3.79</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>TVS</td>
<td>%</td>
<td>68.53</td>
<td>22.08</td>
<td>25.47</td>
<td>51.37</td>
<td>7.13</td>
<td>12.47</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>TOC</td>
<td>%</td>
<td>39.03</td>
<td>7.89</td>
<td>7.88</td>
<td>20.21</td>
<td>1.64</td>
<td>2.16</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>NH₄⁺-N</td>
<td>mg/kg</td>
<td>575.76</td>
<td>219.41</td>
<td>262.44</td>
<td>255.34</td>
<td>6.90</td>
<td>10.73</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>mg/kg</td>
<td>22.86</td>
<td>11.56</td>
<td>15.13</td>
<td>17.44</td>
<td>9.81</td>
<td>7.60</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td>Cu</td>
<td>mg/kg</td>
<td>168.11</td>
<td>91.73</td>
<td>66.50</td>
<td>113.86</td>
<td>58.89</td>
<td>19.95</td>
<td>2500</td>
<td>600</td>
</tr>
<tr>
<td>Pb</td>
<td>mg/kg</td>
<td>126.82</td>
<td>170.35</td>
<td>114.95</td>
<td>579.67</td>
<td>244.91</td>
<td>140.63</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>Cd</td>
<td>mg/kg</td>
<td>&lt; d.l.</td>
<td>&lt; d.l.</td>
<td>&lt; d.l.</td>
<td>&lt; d.l.</td>
<td>&lt; d.l.</td>
<td>&lt; d.l.</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Zn</td>
<td>mg/kg</td>
<td>343.23</td>
<td>206.64</td>
<td>259.75</td>
<td>329.18</td>
<td>114.04</td>
<td>84.00</td>
<td>600</td>
<td>1500</td>
</tr>
<tr>
<td>Cr</td>
<td>mg/kg</td>
<td>47.19</td>
<td>18.36</td>
<td>25.35</td>
<td>19.27</td>
<td>5.61</td>
<td>8.08</td>
<td>100</td>
<td>800</td>
</tr>
</tbody>
</table>

The leaching test performed aimed at verifying the environmental compatibility of the materials, allowing to define their leaching behaviour. This allowed to check the possible risk of contamination coming from a possible leaching of pollutants to groundwater due to rainwater. The results of leaching test UNI-EN 12457-2 were used in order to check the non-hazardousness of the materials; to such an aim, the heavy metals concentrations detected in the eluates were compared to the limits set by the regulation in force (D.M. 03/08/2005) for waste classification. In particular, the materials alone were non-hazardous waste, while the mixtures, except for lead and zinc, can be considered inert waste, as shown in Table 4 (Boni et al., 2006). Thus it can be concluded that the mixtures are suitable to be applied to the land for restoration activities of degraded areas or abandoned pits from an environmental point of view. The leached quantities are generally very low, representing only a small fraction of the initial heavy metals content of the materials. In some cases the heavy metals concentrations in the eluates were compatible to the limit set by the regulation in force (D.Lgs. 152/2006) for groundwater contamination.

Seeding test

The seeding test was carried out for the mixtures PC30, TC30, PF30 and TF30. The plants were periodically pruned in order to maintain an approximately constant height of about 5-6 cm. After the first month, the grass began to turn yellow and fungi as well as moulds appeared.
Consequently, several seeds were added and the pots were placed outdoor, exposing the grass to natural sunlight and rain cycle.

Table 4 Characterisation of the eluates produced in leaching tests UNI-EN 12457-2 (values are expressed as mg/l)

<table>
<thead>
<tr>
<th></th>
<th>Tuff</th>
<th>Pozzolana</th>
<th>TC30</th>
<th>PC30</th>
<th>TF30</th>
<th>PF30</th>
<th>D.M. 03/08/2005 (non-hazardous waste)</th>
<th>D.M. 03/08/2005 (inert waste)</th>
<th>D.Lgs. 152/06 (groundwater contamination)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>&lt; 0.0005*</td>
<td>&lt; 0.0005*</td>
<td>0.01</td>
<td>&lt; 0.0005*</td>
<td>&lt; 0.0005*</td>
<td>&lt; 0.0005*</td>
<td>0.02</td>
<td>0.004</td>
<td>0.005</td>
</tr>
<tr>
<td>Cr</td>
<td>&lt; 0.002*</td>
<td>&lt; 0.002*</td>
<td>0.02</td>
<td>&lt; 0.002*</td>
<td>&lt; 0.002*</td>
<td>&lt; 0.002*</td>
<td>1.0</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Cu</td>
<td>&lt; 0.0005*</td>
<td>&lt; 0.0005*</td>
<td>0.06</td>
<td>0.28</td>
<td>0.2</td>
<td>0.2</td>
<td>5.0</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Ni</td>
<td>&lt; 0.002*</td>
<td>&lt; 0.002*</td>
<td>0.02</td>
<td>&lt; 0.002*</td>
<td>0.07</td>
<td>0.05</td>
<td>1.0</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Pb</td>
<td>&lt; 0.002*</td>
<td>&lt; 0.002*</td>
<td>0.09</td>
<td>0.13</td>
<td>0.10</td>
<td>0.27</td>
<td>1.0</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>Zn</td>
<td>0.04</td>
<td>0.03</td>
<td>0.52</td>
<td>0.44</td>
<td>0.094</td>
<td>0.09</td>
<td>5.0</td>
<td>0.4</td>
<td>3</td>
</tr>
</tbody>
</table>

* detection limit

About 1 month later, an evident improvement in terms of both hardiness and pigmentation was observed: the grass resulted profuse and well adapted to the substrate; besides, the periodical pruning ensured a better development of the radical apparatus and in general of the whole plant (Figure 2). No phytotoxic effect seemed to occur (Dudeney et al., 2004), also due to the low content of heavy metals in the mixtures used (Table 3).

![Figure 2 Seeding test](image)

At the end of the experimental activity the grass was characterised in terms of heavy metal content. A significant Zn content was detected, due to the high Zn concentration in the matrices used as well as to its high availability. Also Cu, Pb and Cr were measured, even if at lower concentrations (Table 5).

Moreover, all the samples underwent the direct shear test, each for one vertical load (200, 400 and 600 kPa), in order to evaluate the mechanical properties of the system mixture-vegetative topsoil. The roots interested only the first 4-6 cm of the soil and the predominance of horizontal roots was observed; the limited development of deeper root systems (even if some species as *Lolium perennis* can develop up to 100 cm long roots) can be ascribed to:
- the small height of the pots;
The presence of coarse grains of pozzolana and tuff, enabling the roots deepening;
- the predominance of *Festuca arundinacea*, characterised by horizontal roots.

### Table 5 Heavy metals in the plants at the end of the experimental period

<table>
<thead>
<tr>
<th></th>
<th>TC30 mg/kg S.S.</th>
<th>PC30 mg/kg S.S.</th>
<th>TF30 mg/kg S.S.</th>
<th>PF30 mg/kg S.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>3.81</td>
<td>2.37</td>
<td>&lt; d.l.</td>
<td>&lt; d.l.</td>
</tr>
<tr>
<td>Cr</td>
<td>18.32</td>
<td>6.72</td>
<td>5.64</td>
<td>9.50</td>
</tr>
<tr>
<td>Cu</td>
<td>29.74</td>
<td>24.9</td>
<td>56.93</td>
<td>109.76</td>
</tr>
<tr>
<td>Ni</td>
<td>2.18</td>
<td>&lt; d.l.</td>
<td>4.51</td>
<td>6.86</td>
</tr>
<tr>
<td>Pb</td>
<td>14.69</td>
<td>23.32</td>
<td>99.20</td>
<td>257.52</td>
</tr>
<tr>
<td>Zn</td>
<td>145.1</td>
<td>203.16</td>
<td>269.98</td>
<td>276.52</td>
</tr>
</tbody>
</table>

The internal friction angle obtained was slightly lower than the one exhibited by the mixtures alone. Such a behaviour was probably due to the following differences in the procedure adopted during the direct shear stress test with respect to the same test performed for P30 and T30:
- P30+plants and T30+plants were not dry: it was not possible to eliminate the water within the samples and the equipment used did not allow to control the interstitial fluids drainage;
- the filling of the shear cell was not performed in layers (as done for P30 and T30), which would have ensured an initial compaction and consolidation, as achieved for P30 and T30;
- as P30+plants and T30+plants were extracted from the pots, the deeper layers were disturbed, since they were not interested by the roots deepening (roots were about 6 cm deep).

However, despite that, $\phi$ values obtained made it possible to use the mixtures selected for slopes realization, with no concerns for their mechanical stability.

### CONCLUSIONS

The results obtained allow to conclude the followings:
- the addition of compost in the percentages tested in the present research did not affect significantly the mechanical properties of the inorganic waste; the response to oedometric compression, the compression coefficient and the internal friction angle of the mixtures are quite similar to those obtained for tuff and pozzolana alone; the mechanical characteristics of the mixtures are quite good in terms of both resistance and mechanical stability;
- SOF addition led to a worsening in the inorganic material’s performances, especially in terms of friction angle;
- the chemical and leaching characterisation of the mixtures TC30, PC30, TF30 and PF30, chosen as the optimal materials in terms of both mechanical properties and organic content for revegetation ensured their environmental compatibility and the absence of possible phytotoxic effects, due to the low content and negligible availability of the heavy metals;
- a fertile substrate ensuring a good potential revegetation can be provided.

Thus the mixtures of organic amendments and inert materials, in the percentages investigated in the present work, represent a valid “artificial soil” to be successfully used for cost-effective site restoration.

Moreover, the possibility to reuse the waste materials tested allows to reach the following goals: the economical exploitation of waste materials; the potential for an abatement of the costs of restoration activities; the reduction of the waste volumes to be landfilled; the addition of nutritional elements to the sites to be restored.

### ACKNOWLEDGEMENTS

Authors wish to thank Giancarlo De Casa for carrying out the mechanical characterisation tests and the Italian Ministry of Education, University and Research for the financial support.
REFERENCES


UNI (2004): UNI-EN 12457-2:2004 Characterisation of waste, leaching: Compliance test for leaching of granular waste materials and sludge – Part 2: one stage batch test at a liquid to solid ratio of 10 l/kg with particle size below 4 mm (without o with size reduction)