**Cite this article**
Rakic D, Basaric I, Caki L and Coric S
Contribution to the geotechnical classification of municipal waste landfills in Serbia.
*Environmental Geotechnics*,
https://doi.org/10.1680/jenge.18.00028

**Research Article**
**Paper 1800028**
Received 18/01/2018; Accepted 30/10/2018



**Keywords:** environmental engineering/fabric/structure of soils/strength & testing of materials

**Environmental Geotechnics**

ice publishing

# Contribution to the geotechnical classification of municipal waste landfills in Serbia

1 **Dragoslav Rakic** BSc, MSc, PhD, EGeol
Associate Professor, Department of Geotechnics, Faculty of Mining and Geology, University of Belgrade, Belgrade, Serbia (corresponding author: dragoslav.rakic@rgf.bg.ac.rs) (Orcid:0000-0001-5375-3506)

2 **Irena Basaric** BSc, MSc, CEng
Teaching Assistant, Department of Geotechnics, Faculty of Mining and Geology, University of Belgrade, Belgrade, Serbia (Orcid:0000-0002-6709-1360)

3 **Laslo Caki** BSc, MSc, PhD, EGeol
Associate Professor, Department of Geotechnics, Faculty of Mining and Geology, University of Belgrade, Belgrade, Serbia

4 **Slobodan Coric** BSc, MSc, PhD, CEng
Full Professor, Retired, Department of Geotechnics, Faculty of Mining and Geology, University of Belgrade, Belgrade, Serbia


**The geotechnical classification system presented in this paper utilises municipal waste from two landfills in Serbia. Sorting and separating was performed according to the instructions outlined in the Solid Waste Analysis Tool (S.W.A.-Tool), and the composition of the municipal waste was defined based on the results. The material was grouped according to particle shape, which was identified through visual inspection. Three characteristic particle shapes were isolated: 'three dimensional' (bulky, compact), 'two dimensional' (flat, platy, flakes, foils) and 'one dimensional' (elongated, acicular, fibrous). The separated materials were further grouped according to the dominant influence in relation to the three most important mechanical properties (compressible – C; incompressible – IC; and with a reinforcement function – R), and the results are presented in a triangular diagram.**

## Notation

| | |
|---|---|
| $b$ | particle width |
| $d$ | grain size |
| $h$ | particle thickness–height |
| $l$ | particle length |
| $r$ | equivalent particle diameter |

## Introduction

A general, common classification system cannot be defined for municipal waste by analysing the results of geomechanical laboratory tests. The reason is that waste is highly heterogeneous, and different test methods are used. Hence, it is necessary to find a suitable geotechnical classification system that includes key factors that affect the mechanical behaviour and physical properties of municipal waste. The aim of the present study is to develop a classification system that includes as many components in waste as possible and to identify indicators that can be described and tested in practice. Current municipal waste classification systems are based on the composition of materials (e.g. paper, plastic, metal and glass) or on the proportion of soil and non-soil waste (Gabr and Valero, 1995; Jessberger and Kockel, 1993; Kavazanjian *et al*., 1995; Landva and Clark, 1986; Manassero *et al*., 1997; Siegel *et al*., 1990; Thomas *et al*., 1999). Landva and Clark (1990) proposed a classification system based on waste biodegradability in which a distinction is made between organic and inorganic components (Figure 1).

Grisolia and Napoleoni (1996) grouped components of waste into three different categories: degradable, inert and deformable. On that basis, these researchers classified waste according to the percentage of each group it contained and illustrated the results graphically on a triangular diagram. The advantage of this system is that it provides information on compressibility and degradability of components; therefore, a comparison between different wastes is possible (Rakic *et al*., 2015, 2016). Kavazanijan (2006) presented a classification system in a document developed by GeoSyntec Consultants, 2003 for managing old landfills entitled *Standard Operating Procedures*. Also, specific recommendations for the geotechnical classification of municipal waste were proposed by Zekkos (2005), Zekkos *et al*. (2006) and Fei *et al*. (2013). Geotechnical classification is performed in three phases: geotechnical classification of municipal waste in the field, primary geotechnical classification of municipal waste and secondary geotechnical classification of municipal waste. Zekkos (2005) and Zekkos *et al*. (2006) list a relatively short time for assessment as a basic priority.

## Methods for the geotechnical classification of municipal waste

Geotechnical classification of municipal waste varies according to different situations and is based on the various existing classification schemes that are used for soil. Unlike done for soil, establishing a general geotechnical classification system for

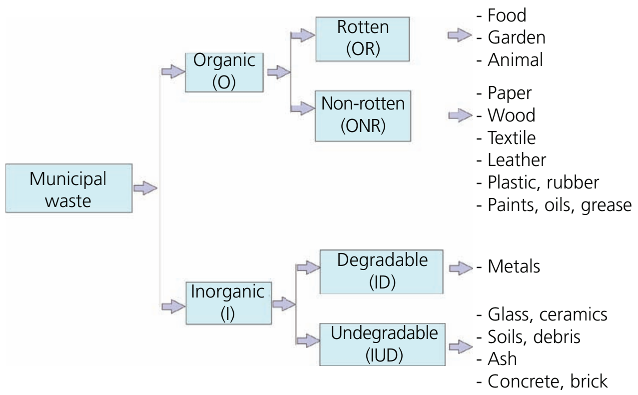



Figure 1. Waste classification system based on biodegradability (Landva and Clark, 1990)

extremely heterogeneous waste is highly complex and is still under development. Therefore, the literature primarily includes geotechnical classification attempts to describe municipal waste that are mostly based on a description of the composition but not the behaviour of the waste (Table 1). The primary reasons for this are (Manassero *et al*., 1997)

- difficulties in obtaining representative samples from municipal waste landfills (there is no generally accepted sampling method)
- significant changes in both the physical and mechanical properties over time
- extreme heterogeneity of municipal waste; the composition varies from location to location within one region, and even more drastic variations occur in different geographic locations
- education and training of staff employed in landfills is not sufficient; staff are not trained to perform measurements and interpret the results.

Data related to the mass per cent of extracted components from waste can often be found in the literature. The volume per cent of waste components is rarely analysed, and data pertaining to the size and shape of extracted components are also rare. In the geotechnical classification of municipal waste, information on the physical properties of certain waste components is particularly important (Dixon and Jones, 2005; Pulat and Yukselen-Aksoy, 2013; Rakic *et al*., 2011; Singh, 2008; Sreedeep, 2015; Withiam *et al*., 1995). Therefore, in addition to general knowledge of the composition, geotechnical classification requires determination of the size and shape of extracted components, and based on these data, the structure of the waste inside a landfill body can be determined. This structure is particularly important for the analysis of mechanical characteristics of the waste, since the waste structure affects the mechanical behaviour of the entire landfill body. Therefore, waste composition information should include mass and, if possible, the volume per cent of each component, specific material groups within extracted components and the size and shape of components.

Basic mechanical properties that should be analysed for all extracted elements are shear strength, tension, pressure, strain at failure and deformability. It should be noted that mechanical properties of extracted elements change in time primarily because of changes in the shape and size of components, conditions of waste disposal (e.g. compression and covering), changes in the stress state, deformation of certain particles and degradation process. One potential characteristic that influences the mechanical behaviour of waste is the shape of components. Based on visual observations of the shape of extracted components and their effect on mechanical properties, they can be grouped as one dimensional (1D), two dimensional (2D) with a dominant reinforcing role (e.g. particles of plastic, paper, rubber, fibrous components) and three dimensional (3D). Three-dimensional components can be further grouped as compressible (high

Table 1. Overview of existing systems for the classification of municipal waste (Langer, 2005; Rakic, 2013)

| Author | Basis for separation – distinction | Properties used for separation – distinction |
|---|---|---|
| Sowers (1973) | Mass content | Wet, moist, dry |
| Turczynski (1988) | Waste type | Compaction, shear strength parameters, permeability, plasticity |
| Siegel *et al*. (1990) | Material groups | Mass fraction based on composition |
| Landva and Clark (1990) | Content of organic and inorganic substances | Degradability (fast, slow, undeveloped), shape (hollow, flattened, elongated, massive) |
| Barlaz (1990) | Visual inspection | Chemical composition and possibility of creating methane |
| Westlake (1995) | Comparing the waste characteristics in different countries | Weight ratio and density |
| Grisolia *et al*. (1995) | Degradability, inaction and deformability of extracted groups | Strength, deformability |
| Kölsch (1996) | Material groups | Size, dimension |
| Manassero *et al*. (1997) | Similarity to soil, others | Index characteristics |
| Thomas *et al*. (1999) | Similarity to soil, differences from soil | Material groups |
| Kavazanijan (2006) | Change of waste colour and compaction | Degree of degradation and structure |
| Zekkos (2005) | Phase composition, classification | Composition, age, temperature, moisture content, size and content of soil particles |
| Rakic (2013) | Visual inspection, phase composition, sorting | Material shape, mechanical behaviour mode: content of reinforced, incompressible and compressible fractions |

compressibility – materials that rapidly decompose, plastic packaging in its original form and similar; low compressibility – e.g. cans) and incompressible components that practically do not deform under the effective stresses of the landfill dead load or under compression (e.g. metal parts). One of the important elements of the geotechnical classification of municipal waste is the size of components. According to the research of Kölsch (1996), the highest mass per cent of waste at a landfill is made of components between 40 and 120 mm. This mass per cent includes the so-called heavy components, such as crushed glass, ceramics, metals and pieces of rock, as well as components with 'reinforcing' properties – for example, paper, rubber and plastics.

## Results from the geotechnical classification of municipal waste from landfills in Serbia

At municipal landfills in Serbia, the composition of municipal waste and determination of the percentage share of individual components is rarely registered. Based on data obtained from a project performed by the Department of Environmental Engineering in Novi Sad (2009), the composition of waste in Serbia largely matches the composition of waste elsewhere in the world (Figure 2).

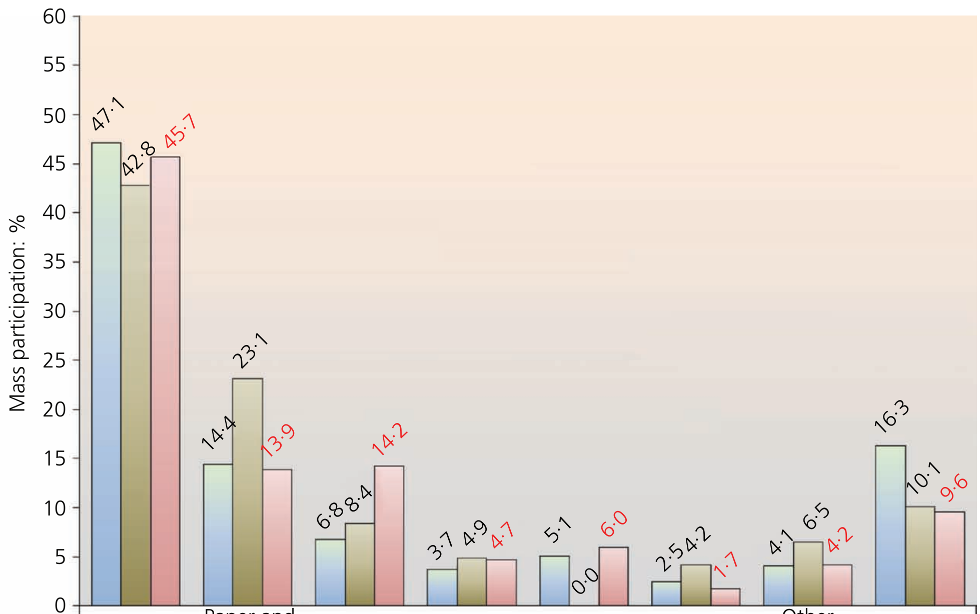
The most common component is organic waste (garden waste and other biodegradable material), which accounts for almost 50% of the mass of municipal waste. There is significant deviation for the content of category PL4 – plastic, which has almost twice the mass percentage of the world average. It should be noted that these data pertain to waste that is directly disposed of to the landfill from its origin.

## Sample selection and sorting of waste

The present study investigated municipal waste taken from an active landfill that is currently being used for waste disposal (Novi Sad) and from a landfill that is closed (Ada Huja). Waste from the Ada Huja landfill was collected from the exploration boreholes, while the waste from the landfill in Novi Sad was taken from the exploration pits (Figure 3).

After drying at 60°C, the mass of extracted waste groups were measured to define the mass per cent in relation to the total sample mass and the composition of the waste was defined. Thus, the sorted waste is slightly different compared to the composition presented in Figure 2.

In fact, the presented analysis of the composition of waste in Serbia shown in Figure 2 refers to fresh waste that still needs to be disposed of in a landfill, while the waste that was sampled for the present study is older and contains a significant percentage of unsorted and soil material (material used for covering or as a result of the advanced stages of decomposition (Figure 4)). Considering the average period of waste disposal in landfills (over




| | Organic – OR1 | Paper and cardboard – PC3 | Plastics – PL4 | Glass – G5 | Textile – T6 | Metal – M7 | Other category U11 | Fines – F12 |
|---|---|---|---|---|---|---|---|---|
| World (Manassero *et al.*,1997) | 47·10 | 14·40 | 6·80 | 3·70 | 5·10 | 2·50 | 4·10 | 16·30 |
| World (Langer, 2005) | 42·80 | 23·10 | 8·40 | 4·90 | 0·00 | 4·20 | 6·50 | 10·10 |
| Serbia (Rakic, 2013) | 45·70 | 13·90 | 14·20 | 4·70 | 6·00 | 1·70 | 4·20 | 9·60 |

Figure 2. Comparison of the composition of waste in Serbia with that of the rest of the world according to the European Commission catalogue (Rakic, 2013)

Figure 3. Analysed municipal waste from exploration boreholes and exploration pits

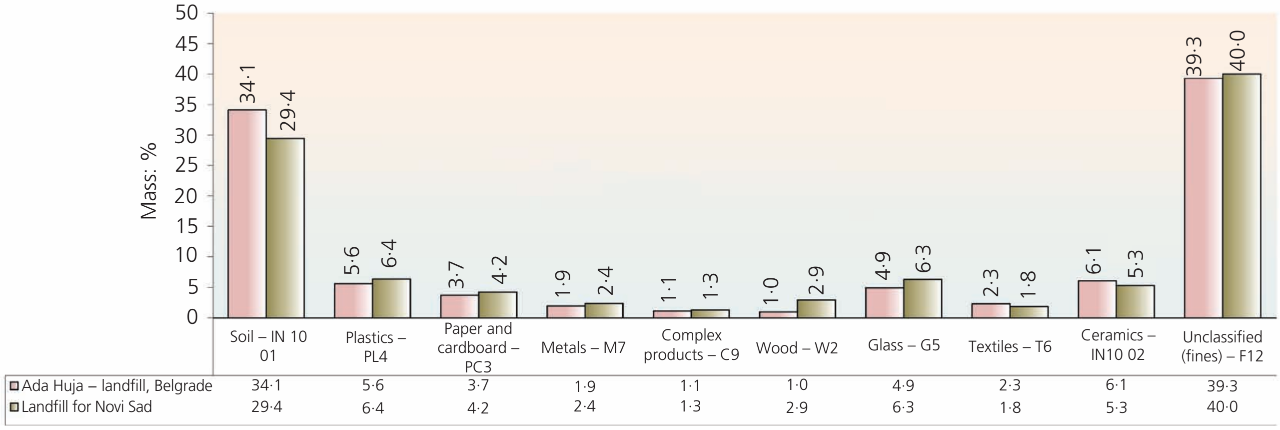



Figure 4. Material composition of municipal waste that was used for testing

30 years in Serbia), the authors suggest that this composition is representative of established landfills.

After defining the composition, sorting of waste was performed according to the partially modified procedure presented in Figure 5 (Rakic, 2013), also known as the Solid Waste Analysis Tool (S.W.A.-Tool) (EC, 2004).

## Recommendation for the geotechnical classification of municipal waste

Unlike soil, waste consists of components that have very different properties, which complicates classification. For this reason, geotechnical classification is difficult and requires a substantial amount of data. Therefore, certain assumptions are necessary regarding waste type, shape, size, homogeneity, influence on mechanical characteristics and potential biodegradability. Typical particle size distribution curves for waste that was used in the geotechnical classification are presented in Figure 6.

The largest diameter of particles used for waste classification was 80 mm, and fractions finer than 10 mm comprise more than 55% of the tested material.

As the shape of particles significantly affects the mechanical characteristics of waste, characteristic shapes were determined by visual inspection for each material group

- ‘3D’ (large, compact)
- ‘2D’ (flattened, laminar, flakes, foil)
- ‘1D’ (elongated, acicular, fibrous).

The first group includes particles with approximately the same length ($l$), width ($b$) and thickness–height ($h$) dimensions (i.e. the ratio of the equivalent particle diameter ($r$) and the characteristic dimension $r/l$, $r/b$ and $r/h$ is about 1). When the ratio of the thickness to the width and length of particle is small ($h/l$ and $h/b$ < 1/100), particles are included in the second group. The third

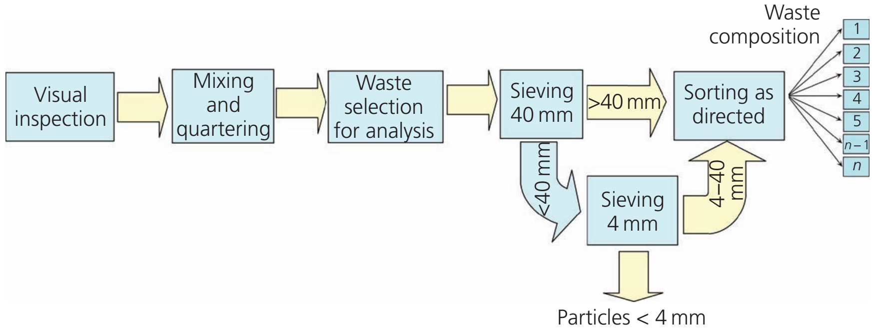



**Figure 5.** Applied procedure for sorting municipal waste (EC, 2004; Rakic, 2013)

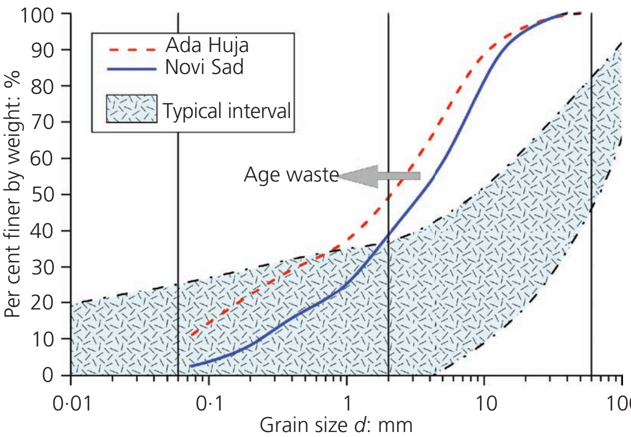


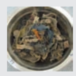
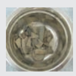
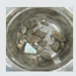
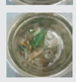
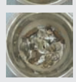
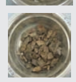

**Figure 6.** Particle size distribution curves of waste that was used for geotechnical classification

group includes particles that have small thickness and width-to-length ratios ($h/l$ and $b/l < 1/100$). The shape of particles is taken into account for two reasons: first, because of practicality reasons for separating particles and, second, because the identified shapes affect the mechanical characteristics of waste (Rakic *et al*., 2013). This classification method cannot be performed based on the particle size distribution. Therefore, the percentage of each material group is estimated visually, and the results are presented in Table 2.

These data and material type data were used to sort further the waste based on the three most important mechanical behaviour characteristics: materials with reinforcing characteristics, compressible materials and incompressible materials. With this approach to the classification of municipal waste, specific mechanical characteristics can be considered, primarily strength and deformability. Characteristic reinforcing properties are important for understanding the shear strength of municipal waste. For the same material, some of determined mechanical characteristics overlap (e.g. textile, rubber and paper can have reinforcing properties and can be compressible/incompressible; unclassified material can be incompressible or compressible). An indication of the dominant influence is given in the form of a triangular diagram, an example of which including all extracted materials is presented in Figure 7 and Table 3 (Rakic, 2013).

Figure 7 shows that the dominant function of plastic materials is reinforcement, while solid components (such as small fragments of wood, pieces of metal and glass) are included in the incompressible material group. These materials do not change their shape and do not deform under the effective load of the

**Table 2.** Visual estimation of the particle shapes of extracted materials (Rakic, 2013)

| Material type | Analysed sample view | Percentage of extracted shapes: % | | |
|---|---|---|---|---|
| | | 3D | 2D | 1D |
| Plastic |  | 5 | 85 | 10 |
| Textile |  | 5 | 70 | 25 |
| Wood |  | 20 | 50 | 30 |
| Rubber |  | 20 | 70 | 10 |
| Ceramics + rocks |  | 65 | 30 | 5 |
| Glass |  | 45 | 50 | 5 |
| Metal |  | 30 | 50 | 20 |
| Paper + cardboard |  | 25 | 70 | 5 |
| Unclassified |  | 70 | 20 | 10 |
| Soil |  | 90 | 5 | 5 |

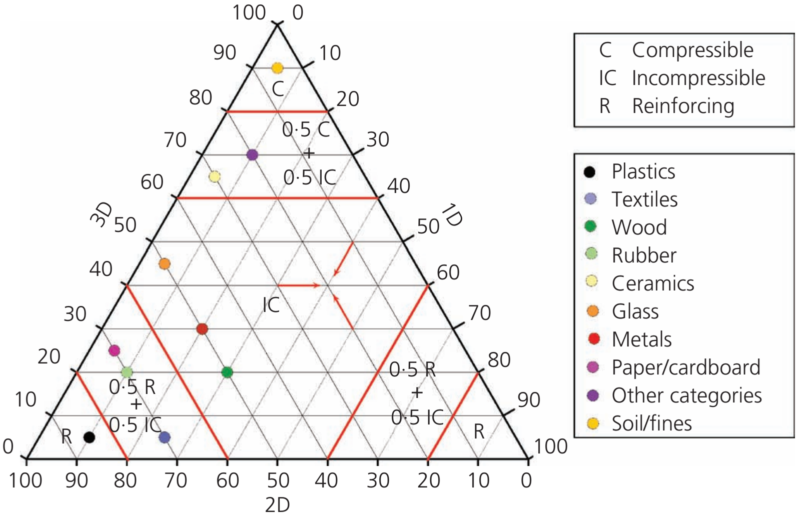



**Figure 7.** Triangular diagram of material shapes with an evaluation of mechanical behaviour

**Table 3.** Classification of materials according to aspects of mechanical behaviour

| Mechanical characteristic | Material type – mass participation: % |
|---|---|
| Reinforcing components – R | 1 × plastic |
| | 0·5 × textile |
| | 0·5 × rubber |
| | 0·5 × paper |
| Incompressible materials – IC | 1 × wood |
| | 1 × metal |
| | 1 × glass |
| | 0·5 × textile |
| | 0·5 × rubber |
| | 0·5 × paper |
| | 0·5 × unclassified |
| | 0·5 × ceramics + gravel + rock |
| Compressible materials – C | 1 × soil + fine fraction |
| | 0·5 × unclassified |
| | 0·5 × ceramics + gravel + rock |

landfill (Rakic, 2013). Compressible materials can be classified in such a way that extremely compressible and poorly compressible materials are separated. However, this limit is difficult to quantify. One of the methods is estimation based on visual inspection of the waste material. For example, thin packaging materials, such as plastic foil or paper, can have a 3D shape when they are wrinkled, and these materials would be classified as highly compressible. In contrast, the materials' original appearance would be classified as poorly compressible or even incompressible if their orientation is perpendicular to the load. This finding means that the boundary between extremely compressible and poorly compressible material differs from case to case; therefore, to simplify the process, they are not determined. This classification recommendation is applied to the predefined composition of the studied Serbian landfills, and the results are presented in Table 4 (Rakic, 2013).

Since an analysis of particle shape does not consider particle size, it is proposed that size be defined based on the particle size distribution. The results presented in Tables 3 and 4 were used to obtain frequency curves – that is, particle size distribution curves of extracted groups of materials. Based on these curves, the effect of particle size was analysed and also included in the waste classification, and the two following criteria were adopted (Rakic, 2013).

- Particles with a reinforcing function only apply to particles with over 10 mm size, and finer particles were included in the incompressible materials group, which is considered to have no reinforcing effect.
- Particles measuring 2 mm are compressible, and finer particles were included in incompressible materials group.

These criteria are recommended for waste with a maximum particle diameter of 80 mm. This characteristic is defined in the laboratory. In the case where classification is performed in the field, and materials with significantly larger dimensions are extracted, these criteria should be changed.

Cumulative particle size distribution curves with the adopted criteria and per cent curves of individual particles within the groups of extracted material are presented in Figures 8–10, and apply to the Ada Huja landfill in Belgrade.

A similar analysis was performed for the Novi Sad landfill, and the results are presented in Figures 11–13.

Thus, calculated values were corrected in relation to the total mass participation of extracted groups. Based on these data and the data provided in Table 4, waste classification was performed in relation to the basic forms of mechanical behaviour. In Table 5,

Table 4. Classification of materials according to the content of reinforcing, compressible and incompressible components

| Material type | Ada Huja | | Novi Sad | |
|---|---|---|---|---|
| | Mass fraction: % | Frequency | Mass fraction: % | Frequency |
| Reinforcing components – R | | | | |
| 1 × plastic | 5·59 | 61·5 | 6·35 | 63·5 |
| 0·5 × textile | 1·15 | 12·6 | 0·91 | 9·1 |
| 0·5 × rubber | 0·55 | 6·1 | 0·64 | 6·4 |
| 0·5 × paper | 1·80 | 19·8 | 2·10 | 21·0 |
| Σ | 9·09 | 100·0 | 10·00 | 100·0 |
| Compressible materials – C | | | | |
| 1 × soil + fine fractions | 34·17 | 60·0 | 29·43 | 56·5 |
| 0·5 × unclassified | 19·69 | 34·6 | 20·05 | 38·5 |
| 0·5 × ceramics + gravel + rock | 3·05 | 5·4 | 2·66 | 5·0 |
| Σ | 56·91 | 100·0 | 52·14 | 100·0 |
| Incompressible materials – IC | | | | |
| 1 × wood | 0·98 | 2·9 | 2·92 | 7·7 |
| 1 × metal | 1·94 | 5·7 | 2·38 | 6·3 |
| 1 × glass | 4·85 | 14·3 | 6·24 | 16·5 |
| 0·5 × textile | 1·15 | 3·4 | 0·91 | 2·4 |
| 0·5 × rubber | 0·55 | 1·6 | 0·64 | 1·7 |
| 0·5 × paper | 1·80 | 5·3 | 2·10 | 5·5 |
| 0·5 × unclassified | 19·69 | 57·9 | 20·01 | 52·9 |
| 0·5 × ceramics + gravel + rock | 3·05 | 8·9 | 2·66 | 7·0 |
| Σ | 34·01 | 100·0 | 37·86 | 100·0 |

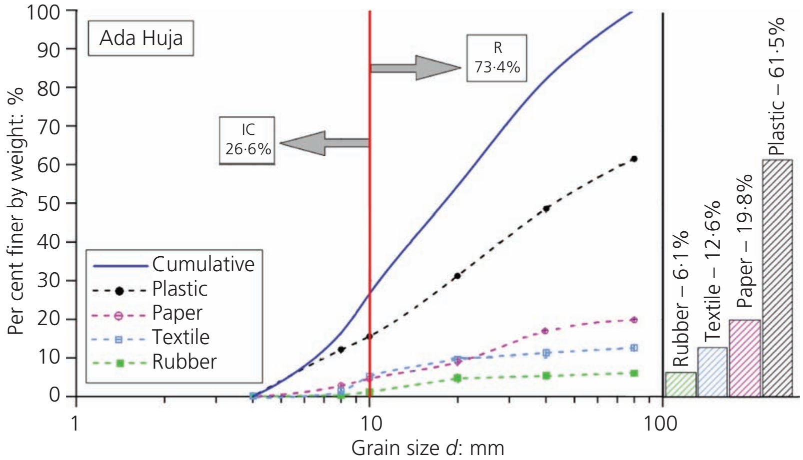



Figure 8. Cumulative particle size distribution curve and per cent curve for material with reinforcing characteristics – Ada Huja landfill

the results are presented for waste from the Ada Huja landfill and from the Novi Sad landfill (Rakic, 2013).

The results were used to perform a geotechnical classification of municipal waste, and the outcome is presented in a triangular diagram (Figure 14).

Results of the present classification indicate that wastes from the Ada Huja and Novi Sad landfills differ somewhat. Waste from the landfill Ada Huja is older; therefore, the content of compressible components is slightly lower. Also, the content of reinforcing components is lower, which may be related to the age of the waste.

An estimation of biodegradation (i.e. degradation of certain materials) was not analysed in the present study. However, it should be noted that the condition of waste components is affected by time and changes through three phases of landfill construction: the initial state (corresponds to the characteristics of waste that is transferred to the landfill), the state occurring a certain time after disposal and the state during long-term decomposition and degradation. Therefore, information

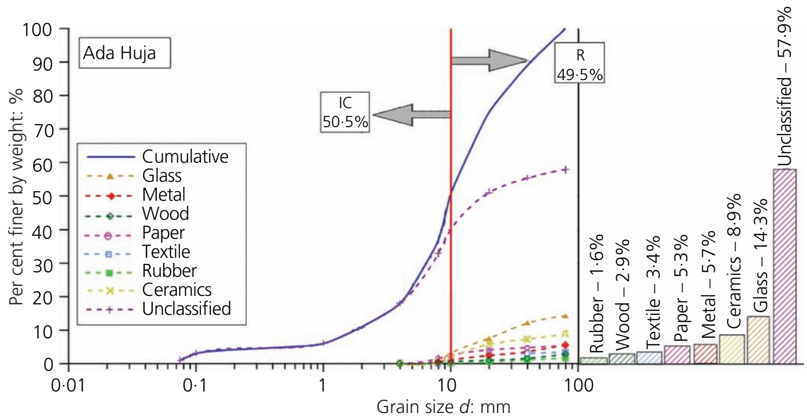



**Figure 9.** Cumulative particle size distribution curve and per cent curve for material with incompressible components – Ada Huja landfill

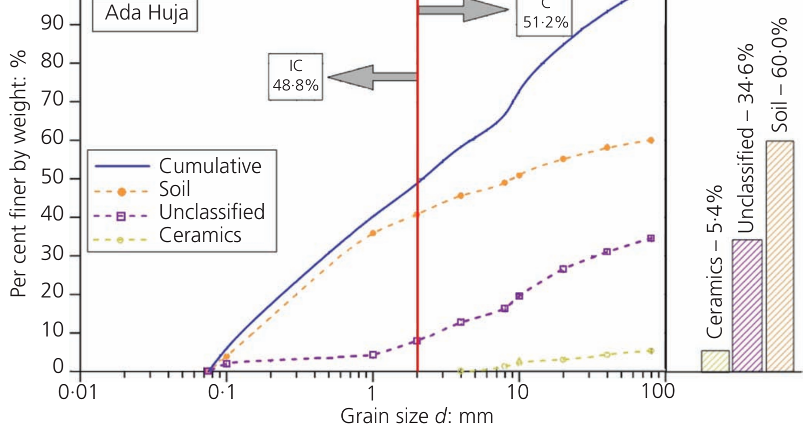



**Figure 10.** Cumulative particle size distribution curve and per cent curve for material with compressible components – Ada Huja landfill

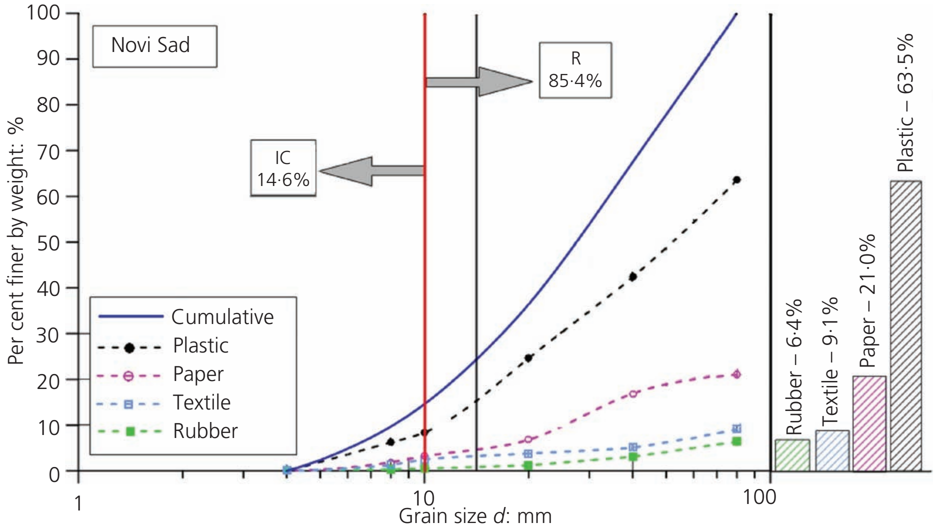



**Figure 11.** Cumulative particle size distribution curve and per cent curve for material with reinforcing components – Novi Sad landfill

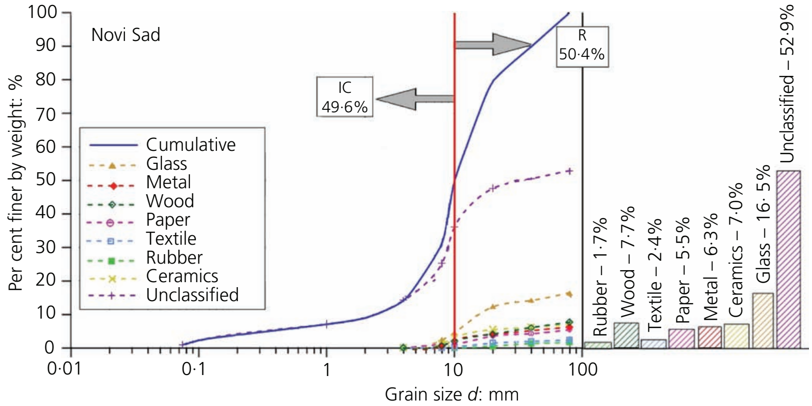



**Figure 12.** Cumulative particle size distribution curve and per cent curve of material with incompressible components – Novi Sad landfill

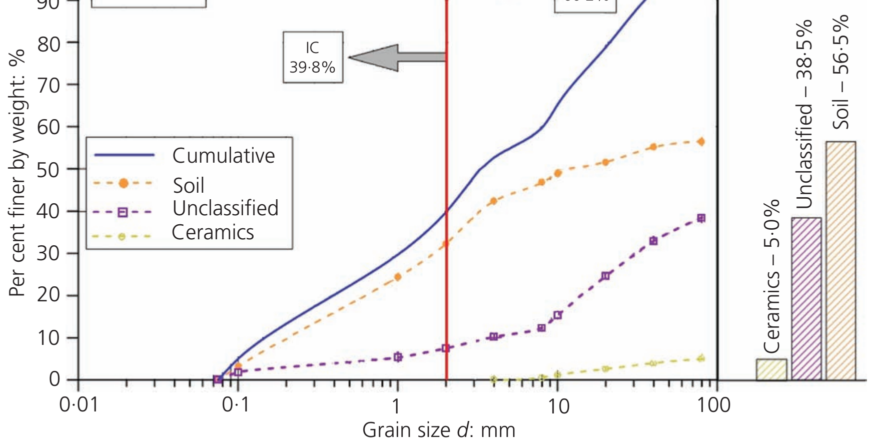



**Figure 13.** Cumulative particle size distribution curve and per cent curve for material with compressible components – Novi Sad landfill

**Table 5.** Waste classification in relation to mechanical characteristics

| Characteristic | Percentage: % | Mass participation: % | Cumulative percentage: % |
|---|---|---|---|
| | | Ada Huja | |
| Reinforcing components – R | R = 73·4 | 9·09 | 6·7 |
| | IC = 26·6 | | 2·4 |
| Incompressible components – IC | IC = 50·5 | 34·01 | 17·2 |
| | R = 49·5 | | 16·8 |
| Compressible components – C | C = 51·2 | 56·91 | 29·1 |
| | IC = 48·8 | | 27·8 |
| Classification | R | IC | C |
| Σ | 23·5 | 47·4 | 29·1 |
| | | Novi Sad | |
| Reinforcing component – R | R = 85·4 | 10·00 | 8·5 |
| | IC = 14·6 | | 1·5 |
| Incompressible components – IC | IC = 49·6 | 37·86 | 18·8 |
| | R = 50·4 | | 19·1 |
| Compressible components– C | C = 60·2 | 52·14 | 31·4 |
| | IC = 39·8 | | 20·7 |
| Classification | R | IC | C |
| Σ | 27·6 | 41·0 | 31·4 |

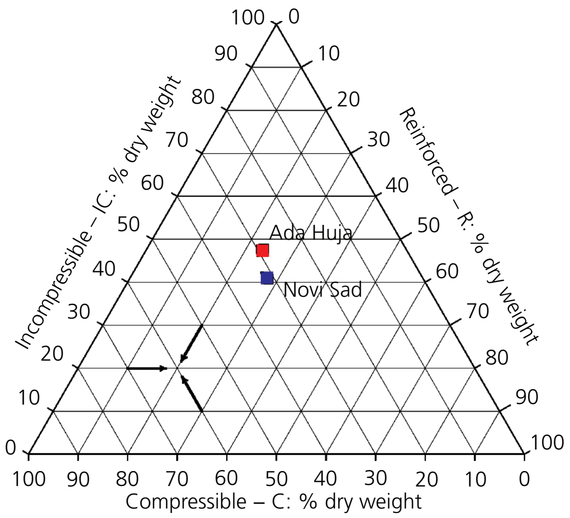



Figure 14. Classification of landfill material according to various aspects of the mechanical behaviour of municipal waste (Rakic, 2013)

concerning the potential degradation of certain materials can be used to determine the eventual state of components through the phases of disposal. This finding is particularly important for determining long-term conditions and the complete decomposition and degradation of waste (Rajesh *et al*., 2015).

Langer (2005) presented a draft recommendation using certain assumptions about the potential degradation of waste components to define the state of the component in relation to the disposal phase. A partial upgrade of this recommendation could be performed by introducing the effects of particle size and shape changes (Rakic, 2013). By performing the current analysis of two landfills in Serbia, the authors conclude that there is a general trend related to differences in the initial phase of waste disposal and after a certain period of time. Initially, waste has large compressibility (over 40% contains compressible components), and the quantity of reinforcing components increases over time and ultimately becomes the largest component. In the final stage of the waste disposal cycle, there are no longer any compressible components, and they are replaced by reinforcing and incompressible components. This finding means that the percentage of compressible components decreases, and the content of incompressible and reinforcing components increases, over time at municipal waste landfills.

## Conclusions

Information on the composition, shape and size of particles in a landfill can be of great importance for analysing the mechanical characteristics of municipal waste. Therefore, these properties form the basis of a new geotechnical classification system for municipal waste, which is presented in this paper. This study was completed in several phases starting from analysing the composition of waste, sorting and classifying waste into groups and classifying material by particle shape by visual inspection. Based on the information obtained, the key factors that affect the mechanical behaviour of municipal waste are defined. These factors are primarily the content of compressible and incompressible particles and the presence of reinforcing components. The effect of the shape and size of particles is defined based on an analysis of particle size distribution by adopting certain criteria. Furthermore, geotechnical classification was performed according to the basic mechanical characteristics and presented as triangular diagrams. Geotechnical classification of municipal waste is recommended and may facilitate long-term analysis of the state of a landfill, particularly for proposals and solutions regarding landfill closure and future land use at these sites.

## Acknowledgement

This paper was completed under project number TR36014 funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia for the period 2011–2018.

### REFERENCES

Barlaz MA, Ham RK and Schaefer DM (1990) Methane production from municipal refuse: a review of enhancement techniques and microbial dynamics. *CRC Critical Reviews in Environmental Control* **19(3)**: 557–584, https://doi.org/10.1080/10643389009388384.

Dixon N and Jones DRV (2005) Engineering properties of municipal solid waste. *Geotextiles and Geomembranes* **23(3)**: 205–233, https://doi.org/10.1016/j.geotexmem.2004.11.002.

EC (European Commission) (2004) *Project: S.W.A.-Tool, Development of a Methodological Tool to Enhance the Precision & Comparability of Solid Waste Analysis Data*. 5th Framework Programme, EU, Vienna, Austria.

Fei X, Zekkos D and Raskin L (2013) A laboratory landfill simulator for physical, geotechnical, chemical and microbial characterization of solid waste biodegradation processes. In *Proceedings of the International Symposium, Coupled Phenomena in Environmental Geotechnics* (Manassero M, Dominijanni A, Foti S and Musso G (eds)). Taylor & Francis, London, UK, pp. 321–327.

Gabr MA and Valero SN (1995) Geotechnical properties of municipal solid waste. *Geotechnical Testing Journal* **18(2)**: 241–251, https://doi.org/10.1520/GTJ10324J.

GeoSyntec Consultants (2003) *Geosyntec Project Number ME0250: Waste Characterization Report, Cherry Island Landfill Expansion Project, Wilmington, Delaware, Columbia, Maryland, USA.*

Grisolia M and Napoleoni X (1996) Geotechnical characterization of municipal solid waste: choice of design parameters. In *Environmental Geotechnics, Volume 2: Proceedings of the Second International Congress, IS-Osaka '96, Osaka, 5–8 November 1996* (Kamon M (ed.)). Balkema, Rotterdam, the Netherlands, pp. 641–646.

Grisolia M, Napoleoni Q and Tancredi G (1995) Contribution to a technical classification of municipal solid waste. In *Sardinia '95: 5th International Landfill Symposium* (Christensen TH, Cossu R and Stegmann R (eds)). Cisa, Cagliari, Italy, pp. 703–710.

Jessberger HL and Kockel R (1993) Determination and assessment of the mechanical properties of waste materials. In *Waste Disposal by Landfill: Green '93* (Sarsby RM (ed.)). A.A. Balkema, Rotterdam, the Netherlands, pp. 313–322.

Kavazanjian E Jr (2006) Waste mechanics: recent findings and unanswered questions. In *Advances in Unsaturated Soil, Seepage, and Environmental Geotechnics* (Lu N, Hoyos LR and Reddi L (eds)). American Society of Civil Engineers, Reston, VA, USA. GSP 148, pp. 34–54.

Kavazanjian E Jr, Matasovic N, Bonaparte R and Schmertmann GR (1995) Evaluation of MSW properties for seismic analysis. *Proceedings of the*

*Specialty Conference on Geotechnical Practice in Waste Disposal, New Orleans, LA, USA*, part 1, pp. 1126–1141.

Kölsch F (1996) *Der Einfluss der Faserbestandteile auf die Scherfestigkeit von Siedlungsabfall.* PhD thesis, Technische Universität Braunschweig, Braunschweig, Germany (in German).

Landva AO and Clark JI (1986) Geotechnical testing of waste fill. *Proceedings of the 39th Canadian Geotechnical Conference, Ottawa, ON, Canada*, pp. 371–385.

Landva AO and Clark JI (1990) Geotechnics of waste fill. In *Geotechnics of Waste Fill – Theory and Practice* (Landva A and Knowles GD (eds)). ASTM International, Philadelphia, PA, USA, STP 1070, pp. 86–103.

Langer U (2005) *Shear and Compression Behaviour of Undergraded Municipal Solid Waste*. PhD thesis, Loughborough University, Loughborough, UK.

Manassero M, Van Impe WF and Bouazza A (1997) Waste disposal and containment. *Proceedings of the 2nd International Congress on Environmental Geotechniques, Osaka, Japan*, pp. 1425–1474.

Pulat HF and Yukselen-Aksoy Y (2013) Composition and degradation effects on the compaction characteristics of municipal solid waste. In *Coupled Phenomena in Environmental Geotechnics: from Theoretical and Experimental Research to Practical Applications* (Manassero M, Dominijanni A, Foti S and Musso G (eds)). CRC Press, Boca Raton, FL, USA, pp. 341–346.

Rajesh S, Hanumantha RB, Sreedeep S and Arnepalli DN (2015) Environmental geotechnology: an Indian perspective. *Environmental Geotechnics* **2(6)**: 336–348, https://doi.org/10.1680/envgeo.14.00047.

Rakic D (2013) *Constitutive relations of Landfill Municipal Waste in Serbia*. PhD thesis, University of Belgrade, Belgrade, Serbia.

Rakic D, Caki L and Ljubojev M (2011) Deformable characteristics of the old municipal solid waste sites with Ada Huja, Belgrade – Serbia. *Technics Technologies Education Management* **6(1)**: 52–60.

Rakic D, Caki L and Coric S (2013) Shear strength of municipal waste materials from two landfills in Serbia. In *Coupled Phenomena in Environmental Geotechnics: from Theoretical and Experimental Research to Practical Applications* (Manassero M, Dominijanni A, Foti S and Musso G (eds)). CRC Press, Boca Raton, FL, USA, pp. 347–354.

Rakic D, Caki L and Basaric I (2015) Phase relations and indicators of municipal waste physical condition. *Proceedings of the 4th International Conference: Regional Waste Management, Ohrid, Macedonia*, pp. 211–220.

Rakic D, Basaric I, Berisavljevic Z and Berisavljevic D (2016) Geotechnical characteristics of industrial waste slag and sludge from Smederevo steel mill Serbia. *Journal of Environmental Protection and Ecology* **17(2)**: 512–522.

Siegel RA, Robertson RJ and Anderson DG (1990) Slope stability investigations at a landfill in southern California. In *Geotechnics of Waste Fill – Theory and Practice* (Landva A and Knowles GD (eds)). ASTM International, Philadelphia, PA, USA. STP 1070, pp. 259–284.

Singh MK (2008) *Characterization of Stress-Deformation Behaviour of Municipal Solid Waste*. PhD thesis, University of Saskatchewan, Saskatoon, SK, Canada.

Sowers GF (1973) Settlement of waste disposal fills. *Proceedings of the Eighth International Conference on Soil mechanics and Foundation Engineering, Moscow, Russia*, vol. 2, pp. 207–210.

Sreedeep S (2015) Vision ahead for environmental geotechnics. *Environmental Geotechnics* **2(5)**: 255–256, https://doi.org/10.1680/envgeo.13.00101.

Thomas S, Aboura AA, Gourc JP *et al.* (1999) An in situ waste mechanical experimentation on a French landfill. In *Sardinia '99: 7th International Landfill Symposium* (Christensen TH, Cossu R and Stegmann R (eds)). Cisa, Cagliari, Italy, pp. 445–452.

Turczynski U (1988) *Geotechnical Aspects of Building Multicomponent – Landfills*. PhD thesis, Technische Universität Bergakademie Freiberg, Freiberg, Germany.

Westlake K (1995) *Landfill Waste Pollution and Control*. Woodhead, Cambridge, UK.

Withiam JL, Tarvin PA, Bushell TD, Snow RE and German HD (1995) Prediction and performance of municipal landfill slope. In *Geoenvironment 2000: Characterization, Containment, Remediation, and Performance in Environmental Geotechnics* (Acar YB and Daniel DE (eds)). American Society of Civil Engineers, New York, NY, USA. GSP 46, pp. 1005–1019.

Zekkos DP (2005) *Evaluation of Static and Dynamic Properties of Municipal Solid Waste.* PhD thesis, University of California–Berkeley, Berkeley, CA, USA.

Zekkos DP, Bray JD, Kavazanjian E *et al.* (2006) Unit weight of municipal solid waste. *Journal of Geotechnical and Geoenvironmental Engineering* **132(10)**: 1250–1261, https://doi.org/10.1061/(ASCE)1090-0241(2006)132:10(1250).

## How can you contribute?

To discuss this paper, please submit up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial board, it will be published as a discussion in a future issue of the journal.