Application of inert wastes in the construction, operation and closure of landfills: calculation tool

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ABSTRACT: Waste from construction and demolition activities represents one of the highest volumes of waste in Europe. 500 million tonnes are produced throughout the whole EU every year. In some EU members like Spain, approximately 83 per cent of such waste is disposed in landfills. The remaining part is classified and processed in treatment facilities so that it can later be used as recycled aggregates in the construction sector (sand, gravel, aggregates, etc.) but without much commercial success. The aim of this study is to use recycled aggregates from inert wastes (IW) in the different phases of a landfill (construction, operation and closure) with the aid of a new computer tool called LABWASTE.14. This tool incorporates the mathematical relationship among the activities of the landfill and provides as a result the economic viability of using recycled aggregates compared to aggregates from quarries. Therefore, knowing the needs of aggregates in landfills (dams, drainage layers, covering layers, collection wells, etc.) may determine the amount of IW that could be recovered. These

calculations can be obtained from some of the data that is introduced (population, land physiography, etc.). Furthermore, the use of LABWASTE.14 makes it possible to reduce the demand for aggregates from quarries.

1. Introduction

Construction and demolition wastes (CDW) are a growing problem in many countries. They account for large part of the waste generated in cities and they are usually placed in landfills (Ekanayake and Ofori, 2004). CDW represents around 31% of all waste produced in the European Union (EU) (Fisher and Werge, 2009). It is nowadays acknowledged that the consumption of raw materials in the construction industry is a non-sustainable activity. It is thus necessary to reduce this consumption, and the volume of CDW dumped, by using this waste as a source of raw materials for the production of recycled aggregates (Rodrigues et al., 2013). In fact, in many EU countries a very limited amount of CDW is recycled, the greatest portion being deposited or used as fill material (Masood et al., 2002). However, recycling concrete waste will lead to a reduction in valuable landfill space and savings in natural resources (Tabsh and Abdeltatah, 2009). Because of this, in the EU, the strategic plans about waste include CDW. The European Action Plan on the Circular Economy includes a number of actions that will target market barriers in specific sectors or material streams, such as construction and demolition wastes as well as horizontal measures in areas such as innovation and investment (EU, 2015). All these regulations establish the minimum requirements for their production and management, in order to promote prevention, reuse, recycling and recovery. The EU Waste Framework Directive (Directive 2008/98/EC) introduces recycling and recovery targets to be achieved by 2020 for household waste (50%) and construction and demolition waste (70%). Furthermore, recycling CDW makes it possible to achieve considerable savings on energy and scarce or non-renewable natural resources. The potential to increase energy saving is about 20–40% depending on the form of recycling (Thornmark, 2001). The results obtained by Vieira and Horvath (2008) show that the recycling of concrete can have a significant impact on the reduction of the overall environmental burden of buildings. Policies that promote the recycling of concrete from buildings, e.g., increasing the recycling rate from the current 27% to 50% could yield a 2−3% reduction in the greenhouse gas emissions of buildings. Some works collected from the literature indicate that the performance of most recycled aggregates is comparable to that of natural aggregates and can be used in unbound pavement layers or in other applications requiring compaction (Cardoso et al., 2016).

However, many of the aggregates from recycling CDW have no commercial outlet and are landfilled without any alternative utility. On the other hand, the variability of the composition of recycled aggregates is much higher than that of natural aggregates due to the different sources from which recycled aggregates are obtained and furthermore, they can also contain hazardous materials.

Moreover, in recent years, this problem has been exacerbated by the economic situation in Europe. The decline in construction output has resulted in a drop in the amount of this product on the market. A possible application would be its use in the construction and operation of landfills where recycled aggregates could replace aggregates from quarries.

The objective of this study is to determine the technical and economic feasibility of using recycled aggregates from CDW recycling plants, in the construction, operation and closure of landfills. Hence, firstly, the properties of CDW must be analyzed. Secondly, a technical and economic analysis is performed. This analysis determines the characteristics that allow a benefit to be obtained from the recycled aggregates, with respect to the use of aggregates from quarries or natural aggregates. The economic feasibility depends on many factors, which include the cost and transport of the aggregates. This study proposes the creation of a software tool that takes into account those factors. Nevertheless, while the economy is not currently a major factor in recycling concrete in all regions around the world, it may become more important in the future due to the lower transportation costs and energy consumption that are commonly associated with recycled materials (Tabsh and Abdeltatah, 2009).

Therefore, tool presented here, called LABWASTE.14, raises the use of CDW in the construction, operation and closure of landfills to a draft level. Thus, the user (construction company, operator, etc.) could know roughly the amount of material (aggregates) that will be needed for the construction, operation and closure. It also offers the possibility of carrying out a preliminary study of the cost (Figure 1).

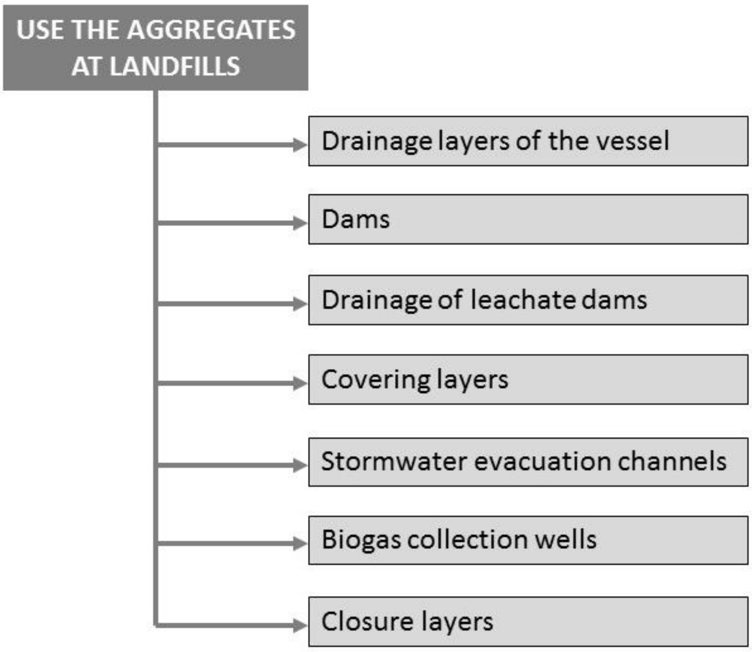

Figure 1. Need for of aggregates in the construction, operation and closure of a landfill

2. Methodology

LABWASTE.14 has been developed by means of Excel® software application. By using the mathematical relationships between the variables in a landfill, it can provide the results required to present a preliminary design and quotation for a draft of a landfill. These variables are defined as follows.

2.1. General data

In this section, the tool requests information regarding the supply of aggregates, both from quarries and recycled, since each activity requires a sort of materials. This information is related to:

- Distance from the landfill to the quarry or to the recycling plant.
- Types of aggregates available with their size and density (sand, graded aggregates, gravel, mixed) and the price of each type of aggregate according to its grain size.
- Cost of transport.

2.2. Construction of the landfill body

In order to dimension the landfill body, it is necessary to introduce information about the main characteristics which define the structure of the different layers. The information required is:

- Type of landfill according to its topography (in an area, in a valley or on a hillside) or according to the type of waste (inert, non-hazardous industrial, municipal or refuse) and the average density of the waste deposited there (D_M) in kg m^{-3}.

– Geometrical data: estimate perimeter in meters, estimated available area (E_{AV}) and estimated average depth (E_D) in meters. With these data, the tool calculates the approximate capacity of the landfill body (C_V) in m^3 and area to be waterproofed (A_W) in m^2.

– Population to be served (P_{AB}) in inhabitants, and waste generation rate (D_{WD}) in kg inhabitant^{-1} day^{-1}. With these data, the tool calculates the annual waste generation rate deposited in the landfill (A_{GR}) in t year^{-1}.

– Climatic data: average monthly temperature (°C), maximum monthly average rainfall, average maximum rainfall in 24 h (L m^{-2}), monthly evapotranspiration (L m^{-2}) and data collection period (years).

– Need (yes or no) of an artificial barrier to waterproof the bottom of the landfill body (if the original layer does not meet the requirements of permeability).

Therefore, by means of Equation 1, from the above data the tool calculates the estimated useful life (UL) of the landfill in years. Above the impermeable layer of the landfill body, it is advisable to apply a layer of drainage gravel in order to evacuate leachates. By means of Equation 2, the tool calculates the amount of gravel (C_{RL}) in tonnes needed for the drainage of the bottom, according to the thickness of the drainage layer (T_{DL}) in m and the density of the gravel (D_{GR}) in t m^{-3}.

$$\mathrm{UL} = \frac{C_V \cdot D_M}{A_{GR} \cdot 1000} \qquad (1)$$

$$C_{RL} = A_W \cdot T_{DL} \cdot D_{GR} \qquad (2)$$

2.3. Construction of dams

The tool shows the geometry of the section of the toe dam. Generally, the structure of the dam is always similar to a scalene trapezium, with different upstream and downstream inclination angle. The construction material must have good mechanical properties in order to construct a safe dam. Thus, very useful materials for these sorts of constructions (earth dams) are graded aggregates, which can be well compacted. Nevertheless, the properties of graded-aggregates must be known and accepted by the regulations of the country (González, 2002; US Department of Transportation, 2009).

Regarding the dimensions of the dam, the tool displays a set of values in order to guide the user on the most common dimensions and below which lower values cannot be entered. For the width of the crest (W_{CR}) in meters, the user can select the existing value (minimum value) or enter another bigger one. The width of the crest must allow for vehicular traffic (trucks). The height of the dam (H_{DF}) is usually about 10 m, but the tool offers this value or allows the user to enter a different one. The inclination of the upstream (S_U) and downstream (S_D) slopes (in degrees) also define the structure of the toe dam. To do so, the tool requests the user to select the existing value or enter another (lower) one and then calculates the width of the bottom dam (W_{BD}) in meters (Equation 3). The dam stability depends on this. For that reason, the tool indicates any angle data above 45º as wrong. In order to calculate the cross section of the dam (A_{SD}) in m^2 the tool applies equation 4.

$$W_{BD} = W_{CR} + \frac{H_{DF}}{\tan(S_U)} + \frac{H_{DF}}{\tan(S_D)} \quad (3)$$

$$A_{SD} = W_{CR} \cdot H_{DF} + \frac{H_{DF}^2}{2 \cdot \tan(S_U)} + \frac{H_{DF}^2}{2 \cdot \tan(S_D)} \quad (4)$$

Here, the user must indicate the value of the length of the toe dam (L_{TD1}) in meters. Therefore, in order to calculate the amount of graded-aggregates needed for the construction of the toe dam (Z_D) in m^3 and according to the density of the graded aggregate (Z_{G2}) in t m^{-3}, the tool applies Equation 5.

$$Z_D = A_{SD} \cdot L_{TD1} \cdot Z_{G2} \quad (5)$$

The tools apply the same procedure to calculate the material needed to construct the higher dams, the dams of the rainfall pond and the leachate ponds.

2.4. Landfill slope stability

In order to know the stability of the landfill slope (Figure 2) the tool applies the equation of the curves showed in the nomograms developed by Colomer et al. (2013). To design the nomogram represented in Figure 3, soil mechanics methods and formulas were applied (Taylor, 1948; Janbu, 1967; Bishop, 1960). The user has to insert the height and inclination of the slope, and the tool calculates the safety factor (SF) according to the following values: effective cohesion of the material (C'o) equal to 1 t m^{-2} and friction angle (Ø') equal to 14º. These values are very low but they ensure the stability of the slope.

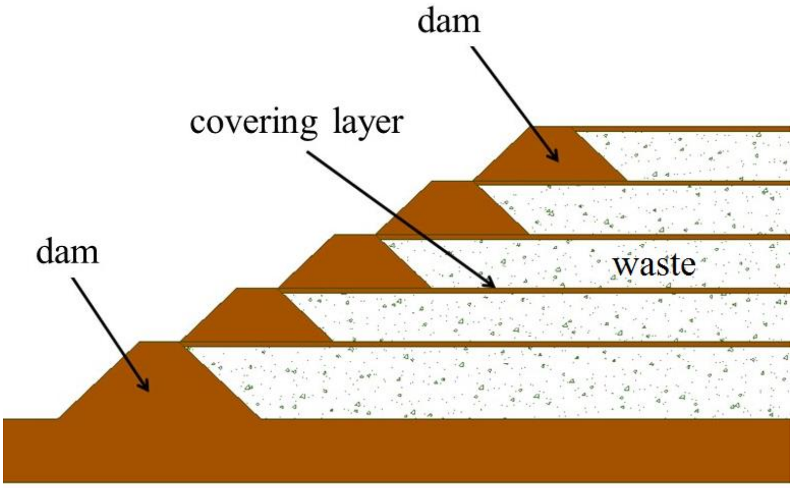

Figure 2. Cross section of a typical landfill slope

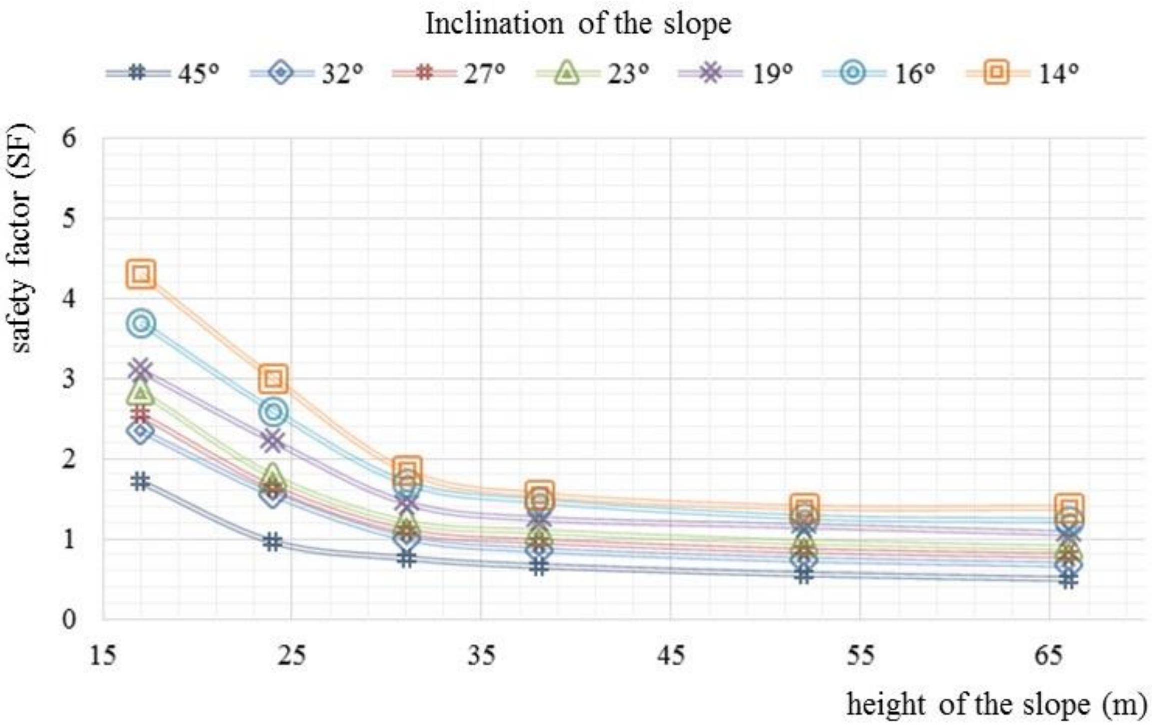

Figure 3. Nomogram from soil mechanics formulas and geotechnical properties of the waste

2.5. Leachate collection system

The leachate collection system is located under the waste cells and it is the element of the landfill responsible for extracting the leachate. Therefore, the following information is compulsory:

1. Number and size of the pipes: From the variables that define the dimensions of the waste cells, this tool calculates the number of pipes required and determines the leachate evacuation system as follows:

$$F_{LE} = \frac{R_{M24} \cdot S_{CW}}{N_{DC} \cdot T_{DS}} \quad (6)$$

where F_{LE} is the maximum flow of leachate to be evacuated (L s^{-1}), R_{M24} is the maximum rainfall in 24 h (L m^{-2} day^{-1})(the pipes have to be oversize because they are not always covered by waste), S_{CW} is the top surface of the waste cells (m^2), T_{DS} is the number of seconds in a day (s day^{-1}) and N_{DC} is the number of drainage collectors (units). On the other hand, according to the studies by Carey et al. (2000) and Guyer (2009), if the user inserts the data on the distance between pipes (D_{DTL}) it is possible to make a relationship between each linear meter of pipe and the surface of the vessel

Using Manning's equation, LABWASTE.14 calculates the number of pipes needed, while also indicating the minimum diameter to ensure leachate evacuation. This method considers the most unfavorable case, in other words, the maximum rainfall in 24 h (L m^{-2}) with a return period of 100 years, on the surface of the waste cells.

2. Ditch size: This tool automatically calculates the trench dimensions according to the diameters obtained for the primary and secondary pipes. The amount of coarse aggregate for use as drainage is also calculated.

3. Geosynthetics and drainage layer: Once the dimensions of the base and side walls of the ditches for the evacuation of leachate are known, this tool then calculates the contact surface to install the geosynthetics and the aggregate necessary for the drainage layer.

2.6. Sizing of the leachate pond

The leachate must be stored in a special pond. This element must be sized according to the foreseeable storage time and the climate of the area. The tool establishes the following requirements:

1. Sizing the leachate pond: The pond capacity is calculated considering a value that is twice that of the daily leachate flow obtained. These calculations make it possible to decrease the risk of overflow, since these kinds of ponds do not have spillways. Furthermore, under normal conditions, by knowing the value of the average monthly rainfall, the tool estimates the average time needed to fill the pond. With these data it becomes possible to establish the time needed to fill the pond and the amount of leachate to be treated.

$$V_{LA} = 2 \cdot R_{M24} \cdot S_{CW} \qquad (7)$$

where V_{LA} is the maximum volume of leachate accumulated (L), R_{M24} is the maximum rainfall in 24 h (L m^{-2} day^{-1}), and S_{CW} is the top surface of the waste cells (m^2). LABWASTE.14 uses Gumbel's method to estimate the maximum volume of leachate that can be generated for a return period of 100 years and determines the maximum volume that could be accumulated. These calculations take into account the rain fall on the pond and on the top surface of the waste disposal zone.

2. Geosynthetics and drainage layer: Once the dimensions of the base and side walls of the leachate pond are known, this tool determines the contact surface for placing the geosynthetics and the aggregates necessary for the drainage layer.

2.7. Leachate generation potential

The amount of leachate generated during the lifetime of the landfill could be said to be variable as it depends on the climate zone and the amount is reduced after the closure of the landfill (Guyer, 2009; Tchobanoglous et al., 1994; Vaquero, 2004; Colomer and Szantó, 2012). LABWASTE.14 estimates the foreseeable amount of leachate with a mathematical formula that makes it possible to link the variables with the most influence of flow variations. Estimation of the leachate generation: the tool takes into account the waste properties, the number of inhabitants related to the landfill, the estimated rate of waste generation, the estimated dimensions of the unit cells, the climate zone, as well as the landfill surface, its maximum height and its waste capacity field, to determine, using mathematical relationships, the estimated leachate generation flow and the volume of leachate to be stored. All the calculations are performed as a function of time and always keeping in mind the factor of safety against overflow risks.

$$V_{LM} = D_{WD} \cdot P_{AB} \cdot D_{NM} \cdot \left(\frac{R_{MA} - E_{MA}}{D_M \cdot H_{CU}} - \left(1 - \frac{M_i}{100}\right) \cdot C_F + \frac{M_i}{100} \right) \quad (8)$$

where V_{LM} is the monthly volume of leachate generated (L month^{-1}), D_{WD} is the waste generation rate (kg inhab^{-1} day^{-1}), P_{AB} is the population (inhabitants), D_{NM} is the number of days in the selected month (days), R_{MA} is the monthly average rainfall (L m^{-2}), D_M is the average waste density (kg m^{-3}), H_{CU} is the thickness of the unit cell (m), M_i is the average initial moisture of the waste, C_F is the estimated field capacity of the waste (kg_{H2O} $kg_{dry\ mat}^{-1}$) and E_{MA} is the monthly average evapotranspiration (L m^{-2}).

2.8. Cover material for the unit cells

Cover material for the unit cells is necessary to prevent bad smells, presence of rodents, birds and insects and dispersion of light wastes (Lutton et al., 1979; Koerner and Daniel, 1997; Vieira and Horvath, 2008), By means of this item, the user has to insert information to define the structure of the unit cells, and therefore the amount of cover material. In order to estimate the number of cells in the vessel (designed in section 2.2) it is necessary to define the height of the cells (H_{CU} in m), the thickness of the layer of daily cover (T_{DC} in m) and the density of the cover material (sand, clay or graded-aggregate) (D_{AS} in kg m^{-3}). Therefore, the user must indicate either the value supplied or a different one.

The information shown in the previous sections allows the tool to automatically calculate the material required for daily coverage in m^3 day^{-1} (Equation 6). This data is used to calculate the number of cells that the vessel can contain and to estimate the amount of aggregates required to construct the cover layer of the cells (C_{CND} in t day^{-1}).

$$C_{CND} = \frac{A_{GR} \cdot 1000}{365 \cdot D_M \cdot H_{CU}} \cdot T_{DC} \cdot D_{AS} \qquad (9)$$

2.9. Stormwater evacuation channels

According to the type of landfill depending on the physiography, evacuation channels could be necessary or not (Carey et al., 2000; Vieira and Horvath, 2008). If the landfill is located in a ravine then a header could be compulsory to divert the runoff water by means of a channel. Thus, upstream rainwater does not come into contact with the waste in the landfill. The tool requires the user decides if the construction of evacuation channels is necessary or not.

To dimension the channel, the tool requires data about average annual maximum rainfall in 24 h and standard deviation in that period of time. The user also has to enter the desired return period. With these data the tool supplies, by means of Gumbel method, the maximum flow rate (Q) in the return period under consideration.

The following step is to dimension the channel (Figure 4). The tool supposes an initial condition B=I. Hence, the user must indicate the inclination of the sidewalls and the material used. If this material is concrete, a proportion of recycled aggregates bigger than 15% is not recommended (Cardoso et al., 2016; Vieira and Horvath, 2008). So, in accordance with Baghi (2004) the tool applies the Manning equation (Equation 10) in which (n) is the Manning's friction coefficient (values between 0.013 and 0.017), S is the longitudinal slope (m/m) (values between 0.5 and 2%), (R) is the hydraulic radius in meters, (A) is the section of the channel (m^2) and (Pm) is the wet perimeter of the channel (R = A/Pm). The user has to choose the thickness of the wall.

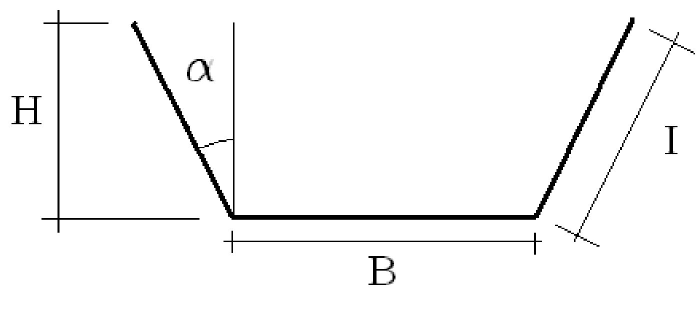

Figure 4: Diagram of the channel section

$$Q = \frac{1}{n} \cdot S^{\frac{1}{2}} \cdot R^{\frac{2}{3}} \cdot A \qquad (10)$$

$$A = B^2 \cdot (\text{Cos}\alpha + \text{Sin}\alpha \cdot \text{Cos}\alpha) \qquad (11)$$

This procedure can also be used to calculate the aggregates needed for the channel around the vessel.

2.10. Biogas collection System

MSW landfills are required to have a biogas collection system because of the anaerobic fermentation of biowaste (Christensen et al., 2012). This group of data has been specifically designed to allow the user to enter the information needed to determine the characteristics of the aggregates required for the construction of biogas collection wells. To do so, the first step consists in indicating whether a gas evacuation system is necessary or not (depending on the type of waste deposited). A biogas collection system is usually compulsory in landfills for municipal solid wastes (non-hazardous waste) and hazardous waste but not for inert waste. In any case, biogas collection wells are needed in landfills with biodegradable wastes (Figure 5) (Council Directive 1999/31/EC).

The tool needs to know the diameter of the ducts (inner duct and outer duct): outer diameter (D_{CE}), inner diameter (D_{CI}), action radius (R_{AC}) and depth (L_C). Then, the tool applies Equation 12 in order to calculate the amount of gravel needed (drainage material) for each of the wells (A_{PPC}) in m^3. Figure 6 describes the distance between wells. By means of Equation 13 and the estimated available area of the landfill (E_{AV}), the number of wells in the vessel

(N_T) is calculated. Thus, it is possible to know the amount of gravel needed for all the biogas collection wells.

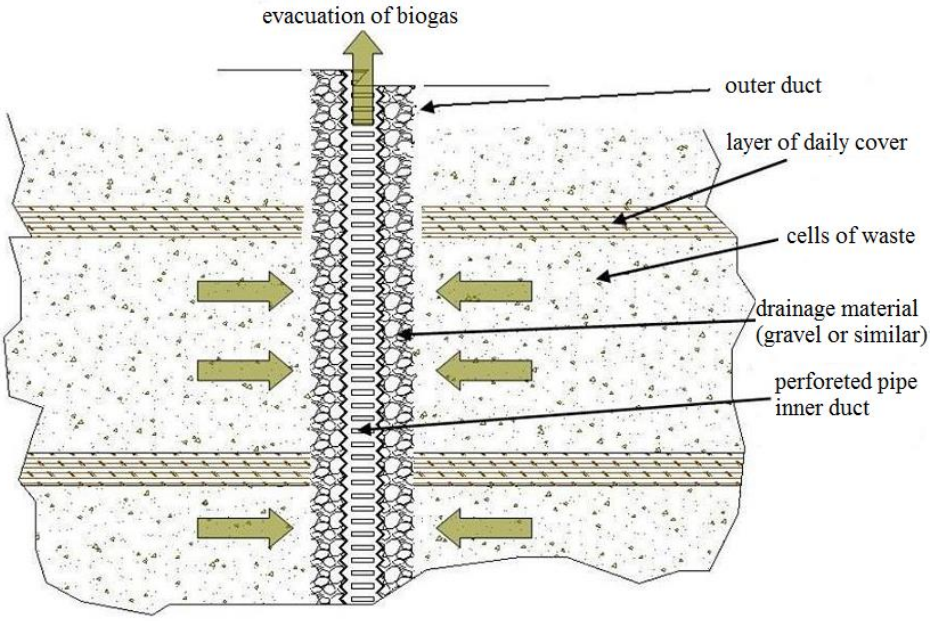

Figure 5. Example of A biogas collection well

$$A_{PPC} = \pi \cdot (D_{CE}^2 - D_{CI}^2) \cdot L_C \quad (12)$$

$$N_T = \frac{E_{AV}}{2.60 \cdot R_{AC}^2} \quad (13)$$

Therefore, in order to find the total volume of gravel in the landfill, the tool multiplies NT • APPC. Using the average density, the weight of the gravel is also provided.

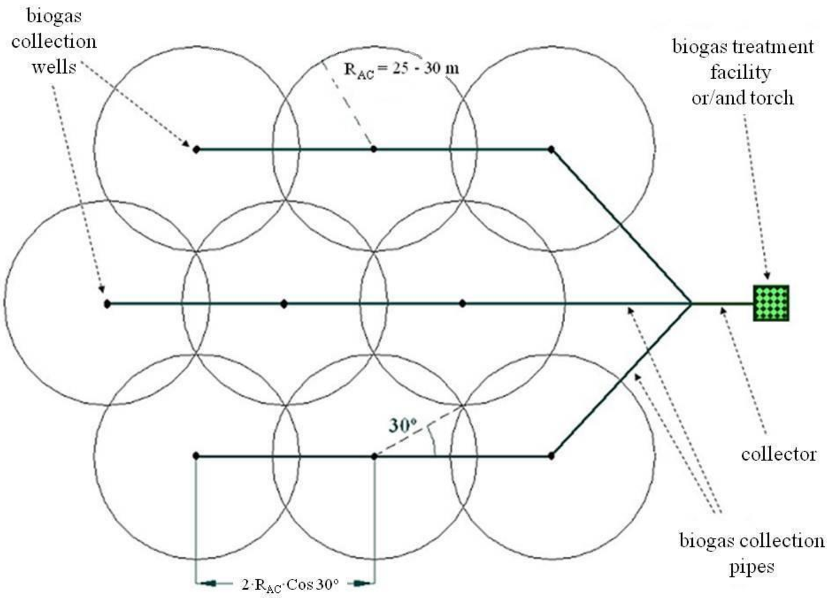

Figure 6. Ideal arrangement of biogas collection wells in a landfill

On the other hand, this chapter provides an estimation of the generation and possible collection of biogas. To perform this estimation, the tool applies the SWANA Zero-order model (Solid Waste Association of North America) (SWANA, 1997), as it provides similar biogas capture results to those measured in known landfills and because it is easy to apply (Esteban et al., 2015). In this chapter, the tool automatically shows the value provided by this method to calculate the methane generation power. The user must select the year in which the operations will start and, by means of a mathematical equation that contains previous variables, the tool plots the biogas generation graph and the feasibility of its valorization (Figure 7).

2.11. Sealing and closure

This group of data has been designed to allow the user to enter information about the general characteristics of the closure phase of the landfill. The main purpose of closure is to build a physical separation between the waste and the atmosphere, so that the environmental impacts are controlled. This includes the final coverage with or without waterproofing and connecting all the biogas wells with a final collector. This also prevents fuzzy emissions of biogas (Tchobanoglous et al., 1994; Colomer and Szantó, 2012; Council Directive 1999/31/EC; Hontoria and Zamorano, 2000).

As shown in Figure 8, the closure of a landfill must have a gas drainage layer, an impermeable layer (which is usually a geomembrane, clay layer, bentonite or geosynthetic layer) and rainwater drainage (Tchobanoglous et al., 1994; Council Directive 1999/31/EC). In order to integrate the landfill both visually and environmentally, a layer of topsoil is applied (final earth cover). Thus, by means of Equation 14, the amount of gravel needed (m^3) for the drainage layer (A_{DGC}) is calculated. E_{DG} represents the thickness of the gas drainage layer. Similarly, for the rainwater drainage layer (A_{DPC}), Equation 15 is applied. Knowing the density, the tool provides the total weight of gravel. E_{DP} represents the thickness of the rainwater drainage layer.

$$A_{DGC} = E_{AV} \cdot E_{DG} \quad (14)$$

$$A_{DPC} = E_{AV} \cdot E_{DP} \quad (15)$$

3. Results and discussion

Economically speaking, recycling CDW can be attractive when the recycled product is competitive with natural resources in terms of cost and quality. Recycled material will generally be competitive where there is a shortage of both raw material and suitable deposit sites. Coarse recycled aggregates have been studied quite thoroughly, because they are simpler to reintroduce in the market as a by-product, and so has the performance of concrete made with them (Rodrigues et al., 2013).

Some research indicates a positive and encouraging trend towards the utilization of recycled aggregates for construction purposes, especially for pavements of all types (Singh and Sharma, 1998). However, some reservations have been expressed with regard to certain properties of recycled aggregate and recycled aggregate concrete when it is used for structures (Kishore, 1996). Moreover, the recycled aggregates must not contain hazardous materials.

The performance of building waste as fine aggregate in concrete has also been studied (Babu, 1996). The water absorption of coarse recycled aggregates increases as the size of the aggregate decreases regardless of the concrete (Hansen and Narud, 1983).

For inert wastes, recovery aggregates for road engineering is a better solution than the use of these aggregates to produce concrete blocks (Roussat et al., 2009). For all countries with a high percentage of recycling of construction and demolition waste, recycling of dredging soil, soil and track ballast accounts for a large part of the recycling carried out (Fisher and Werge, 2009). The use of coarse recycled aggregates in concrete production is already a valid option, since research has proven that their incorporation is viable. Rahal (2007) concluded that concrete made with coarse recycled aggregates has similar mechanical properties to those of concrete made with coarse natural aggregate. However, the use of fine recycled aggregates, i.e. with size of less than 4 mm, in concrete products is not yet widely accepted. There are some countries whose regulations forbid the use of fine recycled aggregates in concrete, namely China, Germany, Hong Kong, Portugal, Spain and UK (Gonçalves and De Brito, 2010). This limitation of the use of fine recycled aggregates is explained by the unpromising results of early research work, in particular because of high water absorption and contaminant content (Angulo et al., 2009), properties that may create problems in concretre in both fresh and hardened states (Zega and Maio, 2011). Therefore, these aggregates have been used mostly in the bases and sub-bases of transport infrastructures and the recovery of former quarries by landscaping (Rodrigues et al., 2013), or as a daily covering for waste in landfills, in accordance with the purpose of this work.

In the case of pavements and embankments, the number of trial tests when using recycled materials is expected to be higher than those necessary for natural aggregates, because the properties of recycled aggregates are not well known. In addition to this, the compaction procedure must be updated according to the variability of the recycled aggregates as well as their changes during construction and exploitation. For some countries and applications (for example, earth and rockfill dams), the design rules are very restrictive and the use of recycled materials is still not allowed (Cardoso et al., 2016). On the other hand, recycled aggregates for concrete have demonstrated satisfactory performance as an embankment or as fill material. Nevertheless, its use is covered by special provisions to specifications in a number of jurisdictions. Desirable attributes of recycled aggregates for concrete for use in embankments or fill include high friction angle, good bearing strength, negligible plasticity, and good drainage characteristics (González, 2002; US Department of Transportation, 2009; PCA, 2015). Studies related to the use of recycled CDW as filling material in geosynthetic-reinforced embankments have also been carried out. The reported studies allow concluding that recycled CDW materials, when properly selected and compacted, can exhibit similar shear strength to the backfill materials commonly used in the construction of geosynthetic-reinforced structures. Notwithstanding the encouraging results, more studies are still needed to promote this application in a general use (Vieira and Pereira, 2015). However, for mechanically stabilized earth walls and reinforced soil slopes the US Federal Highway

Administration recommends a backfill material free from organic or other deleterious materials (US Department of Transportation, 2009).

On the other hand, the use in drainage (biogas wells, drainage in the bottom of the vessel and in the closure layer) has been widely studied. According to PCA (2015), recycled aggregates can be used as applications with any processing, including the base of the fill for drainage structures. According to Molineux et al. (2015), CDW could be viable constituents even of growing substrate.

Regarding the stability of the slopes of dams, the tool, in accordance with Figure 3, automatically calculates the SF, which has to be higher than 1.4 to ensure a safe slope from the geotechnical point of view (Lambe and Hansen, 1990; Terzaghi et al., 1996; Colomer-Mendoza and Gallardo-Izquierdo, 2007).

In order to establish the design of biogas collection wells, the tool supplies widely accepted values for these elements, (DCE=0.8 m; DCI=0.25 m; RAC=20, 25 or 30 m) (Tchobanoglous et al., 1994; Colomer and Szantó, 2012; Hontoria and Zamorano, 2000; Colomer-Mendoza and Gallardo-Izquierdo, 2007; USBR, 2001). Recycled coarse aggregates can be used as a drainage material between DCE and DCI (Molineux et al., 2015; Tam and Tam, 2008). To determine the production of biogas of the landfill, some previous factors allowing the calculation of biogas valorization cost-effectiveness must be analyzed. Therefore, the tool is based on the EPA handbook (LMOP, 2015) “Handbook Landfill Gas to Energy Project”, which fixes the minimum values that must be reached to consider the valorization of landfill biogas cost-effective. Other works were based on the first-order model (Oonk et al., 1994; Faour et al., 2007; US-EPA, 2005), the Afvalzorg multi-phase model, the French EPER model (Scharff and Jacobs, 2006), the SWANA Zero-order model, SWANA simple first model (Lagerkvist, 1995), the LandGEM US EPA model, the Biogas Mexican model, and the Scholl Canyon model (Scharff and Jacobs, 2006).

Definitely, according to information from several works, application of recycled aggregates in construction must be controlled in some cases. In landfills, some cautions must be taken into account. The use of recycled aggregates should be limited in some construction such as storm water evacuation channels with walls of concrete. In some countries there are no rules about the use of recycled aggregates in dams (toe dams and leachate dams) although their application has been studied and tested by many researches. Nevertheless, recycled aggregates couldbe used as covering layer material (fine aggregates: sand), drainage material in the leachate evacuation system (coarse aggregates: gravel), biogas evacuation wells as a drainage material (coarse aggregates: gravel) or tracks in the landfill (graded aggregates), as well as in the closure phase in the final covering layer (fine aggregates or gradded aggregates), and drainage layers (coarse aggregates: gravel).

4. Implementation case

To test the validity of this methodology, a real landfill in a Spanish region with a Mediterranean climate has been analyzed. The initial data are: the landfill has been receiving refuses from a composting plant since may 2012, which serves about 160,000 inhabitants with a generation rate of 1.022 kg inhabitant^{-1} day^{-1}.The vessel of the landfill occupies an area of 50,000 m^2 with a depth of 25 m, which means there is capacity for an annual dumping of about 60,000 tonnes. The nearest CDW recycling plant is 15 km away, and the natural aggregates plant is located at a distance of 8 km. The transportation cost is 0.96 € km^{-1} and the track load volume is 14 m^3. The average price of the different types of aggregates is shown in Table 1.

Table 1. Price of aggregates depending on their origin and their grain size

Type of aggregate	Sand (€/t) 0 – 12 mm	Graded-aggregate (€/t) 0 – 40 mm	Gravel (€/t) 20 – 40 mm
CDW recycling plant	3.68	4.24	3.48
Natural aggregates from quarry	7.50	3.80	6.60

4.1. Construction phase

The activities of the construction phase are: installation of drainage and waterproofing of the vessel and leachate evacuation system (Table 2), construction of the leachate dam, construction of landfill dams (Table 3), and construction of stormwater evacuation channels (Table 4).

Table 2. Input and output data concerning drainage and waterproofing of the vessel and leachate evacuation system

Input data	
Area occupied by the vessel	50,000 m^2
Average depth of the vessel	25 m
Average density of compacted waste (bales of waste)	750 kg m^{-3}
Is it an artificial waterproofing layer necessary?	yes
Thickness of the drainage layer	0.50 m
Length of trenches for leachate evacuation system (0.04 $m/m^{2)}$	2,000 m
Average width of trenches	1.00 m
Average depth of trenches	0.50 m
Output data	
Aggregates for drainage layer (gravel)	60,375 t
Aggregates for trenches (gravel)	2,100 t
HDPE Geomembrane layer (1.5 mm thickness)	57,500 m^2

Geotextile layer (3 layers)	172,000 m^2

Table 3. input and output data concerning construction of the dam at the bottom of landfill slope (DBLS) and leachate dam (LD)

Input data		
In order to dimension the leachate dam		
Thickness of the drainage layer	0.15 m	
Average flow of leachate (Equation 8)	32,083 L day^{-1}	
Maximum rainfall in 24 h (100 year period return)	210.50 L m^{-2}	
Shape of the dam	round	
Radius of the bottom	9 m	
Radius of the crest	13 m	
	DBLS	LD
Width of dam crest	5 m	5 m
Height of the dam	7 m	4 m
Inclination of the upstream slope	45º	45º
Inclination of the downstream slope	26.6º	26.6º
Length of dam	155 m	102 m
Output data		
Capacity of leachate dam	--	1,270 m^3
Aggregates for drainage layer 0.30 m (gravel)	0	439 t
HDPE Geomembrane layer (1.5 mm thickness)	0	697 m^2
Geotextile layer	0	697 m^2
Aggregates for dams (graded aggregates)	26,889 t	7,177 t

Table 4. Input and output data concerning construction of stormwater evacuation channels

Input data	
Data collection period	40 years
Maximum rainfall in 24 h (100 year period return)	210.50 L m^{-2}
Standard deviation	12.10 L m^{-2}
Rainfall water catchment areas	10,000 m^2
Safety coefficient	1.10
Inclination of the channel walls	90º
Roughness coefficient	0.017
Slope downstream	0.5%
Hydraulic radius	0.23 m
Width of the channel	0.70 m
Height of the channel	0.70 m
Wall thickness of the channel	0.30 m
Proportion of recycled aggregate	15%
Output data	

Amount of aggregate	292 t

4.2. Operating phase

The activities of the operating phase include leachate generation, biogas generation, installation of biogas evacuation wells, intermediate dams and daily covering layer (Table 5) and monthly biogas generation according to the SWANA Zero order model (Figure 7). These data are obtained from the 8.54 years of useful operating life. This model has been chosen because of its simplicity and accuracy (SWANA, 1997).

On the other hand, in accordance with Figure 2, it is necessary to build intermediate dams to retain wastes.

Table 5. Activities of the operating phase

Input data	
Average height of unit cell	2.70 m
Thickness of daily covering layer	0.30 m
Diameter of outer duct	0.60 m
Diameter of inner duct	0.11 m
Operating range for each well	25 m
Predicted year of biogas generation	2012
Potential generation of biogas	34.51 $m^3\ t^{-1}$
Time for generation	25 years
Number of intermediate dams	4 units
Intermediate dam height	5 m
Intermediate dam crest	3 m
Inclination of the slopes	45º upstream 26.6º downstream
Output data	
Amount of aggregate for daily covering layer (sand)	1,788 t/month
Number of biogas evacuation wells	31 units
Amount of aggregate for biogas evacuation wells (gravel)	23.86 t/month
Amount of aggregate for each well (gravel)	14.35 t
Amount of aggregate for each intermediate dam (graded)	13,010 t
Annual amount of aggregate for intermediate dams (graded)	6,505 t

Figure 7. Biogas generation in the analyzed landfill

Equation 8 has been applied in order to estimate the leachate generation potential of a landfill in the east of Spain with a Mediterranean climate for 160,000 inhabitants. The resulting volume of leachates was 3,168 m^3 $year^{-1}$. The average data measured in the landfill has been 2,745 m^3 $year^{-1}$, which represents a variation of 13%. Similar data have been obtained from other landfills (between 9% and 14% of variation) (Esteban et al., 2015). These values are similar to those obtained from other tools like the Water Balance Method (WBM) developed by the la U.S. EPA (Fenn et al., 1975), Serial Water Balance (SWB) (Orta de Velasquez et al., 2003), or the work by Al-Thani et al. (2004), Cossu and Raga (2008) or Agostini et al. (2012).

4.3. Closure phase

According to Directive 31/1999 when a landfill is full of waste it shall be closed, following current rules. The closure of the analyzed landfill was designed by means of the scheme in Figure 8 and the required data shown in Table 6.

Table 6. Activities of the closure phase

Input data	
Estimated area to be closed	50,000 m^2
Thickness of gas drainage layer	0.50 m
Thickness of rainwater drainage layer	0.30 m
Thickness of topsoil	0.70 m
Safety coefficient	1.15
Output data	
Amount of aggregate for gas drainage layer (gravel)	60,375 t
Amount of aggregate for rainwater drainage layer (gravel)	36,225 t
Area of geomembrane (HDPE 1.5 mm thickness)	57,000 m^2
Area of geotextile	115,000 m^2
Amount of topsoil	54,338 t

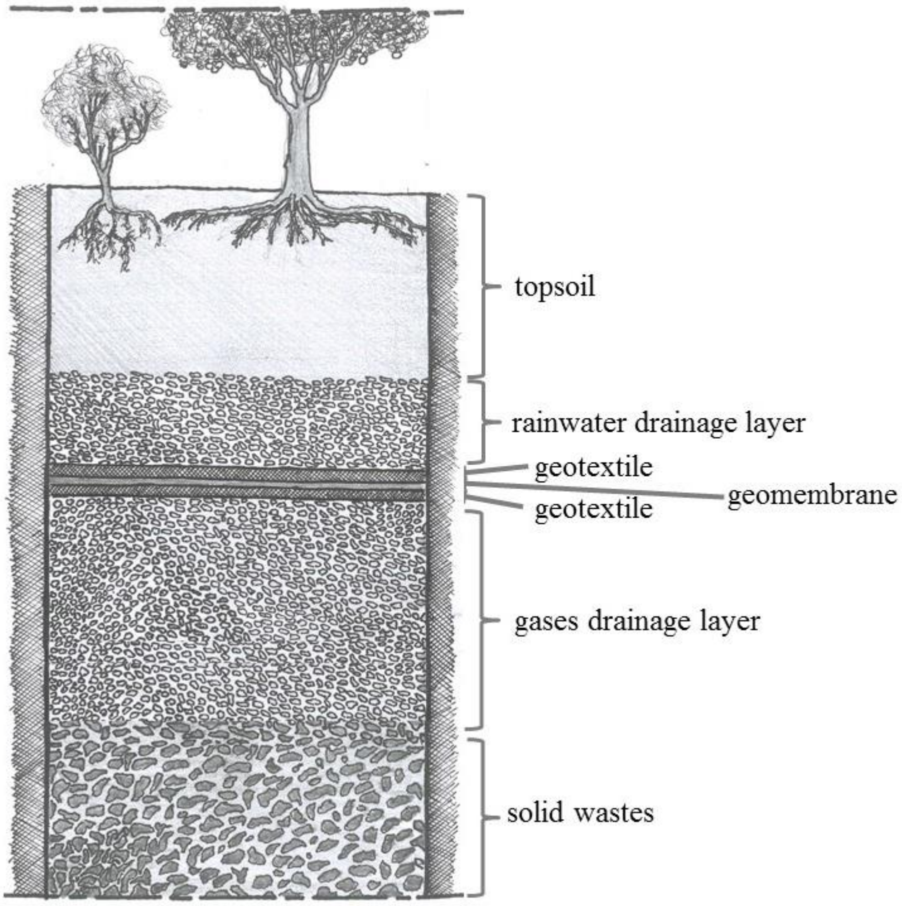

Figure 8: Layers in the landfill closure

4.4. Economic analysis

From the above data and the mentioned cost it was possible to calculate the quotation for the different phases of the landfill (Table 7). In this table the cost of recycled aggregates is compared with the cost of natural aggregates. The tool compares both options. It considers the price of both types of aggregates (Table 1) and the cost of transport (0.96 €/km). The application of recycled aggregates seems to be the most cost-effective solution, since the cost of recycled aggregates is usually subsidized in Spain in order to foster their consumption. Nevertheless, in order to apply the tool in other regions or/and conditions, the user can change these values. Therefore, the most cost-effective solution is not allways the same. In fact, if the price of recyclable aggregates would not be subsidized, the best solution would be probably different.

In any case, the promoter company can decide which the best option for each type of aggregate is.

Nevertheless, in the column of recycled aggregate the limitations about the use of recycled aggregates has been taken into account. It was used 100% of recycled aggregates in all the mentioned elements of the landfill, except in stormwater evacuation channels where the proportion of recycled aggregates is recommended by 15%.

The tool has an option to decide the amount of each type of aggregates used in each phase of the construction and management/closure of the landfill, since it is possible that the recycling plant could not to reach the needed amount of aggregate for the landfill.

Table 7. Quotation of the quantities and costs

Application of aggregates in each phase	**m^3**	**t $year^{-1}$**	**recycled aggregate**	**natural aggregate**
Total quotation of the construction phase	**51,947**		**421,901**	**586,870**

graded aggregate	21,292		166,341	165,404
gravel	30,655		255,559	421,466
Total quotation of the operating phase	**117,999**	**13,817**	**877,993**	**1,408,472**
graded aggregate	34,720	4,066	271,114	269,724
sand	83,069	9,727	605,125	1,135,856
gravel	210	25	1,754	2,892
Total quotation of the exploitation phase	**86,250**		**775,782**	**1,005,414**
gravel	46,000		383,482	632,434
topsoil	40,250		392,300	372,980
TOTAL QUOTATION	**256,196**		**2,075,676**	**3,000,756**

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