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Landfill capping: engineering and restoration

1. Structure and function of landfill capping systems

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INTRODUCTION AND DEFINITION

The capping system is the final component in the construction of a landfill. Usages differ, but we will here consider the capping system as comprising both engineering and restoration layers (Department of the Environment 1995).

This article is the first in a series of three with the overall title 'Landfill Capping Engineering and Restoration'. The series attempts to bring together aspects of European research and experience into an appreciation of the current state-of-the-art in landfill capping design.

This first article gives an overview of the purpose and structure of capping systems. The second article will go into greater detail on engineering aspects, and the third will discuss restoration aspects.

OPERATIONAL PRINCIPLES

According to Stief's multibarrier principle (1986), the landfill capping system is one of the essential barriers in controlling landfills. Its main task is to prevent gaseous pollutants from migrating towards the atmosphere and rainwater from percolating into the landfill in order to keep leachate generation to a minimum.

Possible consequences of high leachate generation are (Franzius 1984):

- flooding of the landfill body and extensive leaching of the wastes;
- a high load on the landfill base;
- reduction of slope stability;
- increased costs of leachate handling;
- acceleration of decomposition processes and increased gas production;
- risk to groundwater and migration of contaminated water.

As regards increased gas production from accelerated decomposition processes, many experts have traditionally regarded rainwater percolation into municipal landfills as being advantageous and have therefore not demanded a high level of watertightness for capping systems. It was expected that the stabilised final state would be achieved more quickly through intensive decomposition of the wastes within the landfill.

In some countries, e.g. Germany, regulations for new landfills for municipal waste (TA[1] Siedlungsabfall 1993) aim to strictly limit the active organic content by pre-treatment, so that the need for moisture in the biomass is minimised. Elsewhere, e.g. Great Britain, landfills are often designed in such a way that gas production is an intrinsic goal. This notwithstanding, watertightness of the landfill capping system is now increasingly a requirement (National Rivers Authority, North West Unit 1989; North West Waste Disposal Officers Landfill Liners Sub-Group 1988).

BASIC PERFORMANCE REQUIREMENTS

Landfill cappings have to fulfil the following requirements over a long period of time (Der Rat von Sachverständigen für Umweltfragen 1990; Franzius 1986; Bilitewski *et al.* 1987; Thomé-Kozmiensky 1988; Melchior *et al.* 1990*b*; Melchior *et al.* 1992; Melchior 1993; Forster 1993):

- minimisation of the amount of water percolating into the landfill by impermeability, drainage and evaporation;
- high resistance to erosion and frost;
- non-susceptibility to desiccation, encrustation and subsidence;
- resistance to penetration by roots and burrowing animals;
- enabling controlled collection and transport of gas to flaring or energy generation;
- reclamation: the capping system should create a biotop where vegetation is required;
- receptiveness to monitoring, repair or renewal.

The most important potential loads on a landfill capping system are (Günther 1988):

- physical loadings: mechanical influences, hydraulic effects, gas pressure, permeation, heat and frost effects and UV-radiation;
- chemical loadings: waste leachates, landfill gas and gas condensate;
- biological loadings: penetration by roots, rodents and microbial processes.

1. TA refers to a German Federal 'Technical Instruction' document – see References.

Additionally, there can be effects due to the consolidation or breakdown (physical, chemical or biological) of the capping medium itself.

In some ways the physical and chemical requirements upon landfill capping systems are not dissimilar to those on basal liners. One of the major differences is, however, that only in the case of capping systems is there such intimate proximity to the restoration requirements and provisions for the site.

SIGNIFICANCE OF RESTORATION

The continuing acceptability of landfilling as a means of waste disposal is greatly influenced by the success of the restoration process. This is not a new concept:

> *'no matter how well and how scientifically the site has been selected, prepared and operated it is by the standard of restoration and the continuing satisfactory performance of the restored land that the acceptability of landfill will be judged'* (Department of the Environment, Landfill Practices Review Group 1984)

The restored site will influence public opinion for many years, long after the operational phase is completed. A well-restored site will assist in sustaining landfill as a waste disposal option.

The choice of after-use is critical to restoration, as it sets the objectives and design parameters. The purpose of restoration may be seen as being to create an appropriate and attractive setting for the chosen after-use. After-use options should thus be explored in the widest possible sense at the initial design stage.

Landfill sites are most commonly restored to agricultural grassland, which is not the most appropriate after-use in all circumstances. Restoration must preserve the agricultural potential of good quality land. But where productive agriculture will be technically difficult or costly to achieve, or where there is little demand for this type of land, alternative after-uses should be considered.

Restoration is an integral part of the landfill process and must be taken into account throughout the life of the site, from initial conception to post-closure management. Good restoration and aftercare not only facilitate beneficial after-use; they can also contribute to the environmental protection measures incorporated in the engineering and operational designs.

INTEGRATING ENGINEERING AND RESTORATION

The landfill developer should consider design, development, operations, environmental protection, restoration, aftercare and post-closure management as a continuing process rather than a series of separate steps. This process requires the planning of operations and environmental protection systems to interact with that of afteruse and restoration works, to achieve a satisfactory overall design and implementation.

Operational requirements, environmental control and restoration must be integrated throughout the life of the site. A programme of works to install the capping system and environmental protection systems, and to carry out restoration and aftercare, should be drawn up at the start of the scheme. But this needs to be flexible enough to take account of changing circumstances, such as revisions to the proposed after-use, new technologies and variations in the rate of landfilling.

Restoration plays an important role in supporting and contributing to the environmental protection measures for leachate and landfill gas control. The soil layers which overlie the capping system will assist in controlling rainwater infiltration. If deep enough they can, under some circumstances, prevent rainwater from reaching the surface of the capping layer at all. The vegetation also contributes to the control of rainwater infiltration by intercepting rainfall, and by taking moisture out of the soil for growth.

The choice of after-use and aftercare works will influence the design, installation and management of landfill gas control systems. A wider range of after-use options may be used positively to achieve more cost-effective restoration and to minimise the potential conflicts between aftercare and other requirements. There should be close collaboration between those responsible for the long-term maintenance operations necessary for both the restored land and the engineering systems.

TYPICAL STRUCTURE OF CAPPING

The structure of a 'model' capping system under moderate, humid climatic conditions can be schematically described, from outer layers inwards, as follows (TA Abfall 1991; TA Siedlungsabfall, 1993; Melchior *et al.* 1990*b*; Jessberger 1990*a*; Thomé-Kozmiensky 1992):

Layer		**Indicative thickness**
surface vegetation		
reclamation layer		≥1 m
drainage layer		≥0.3 m
protective layer	thickness depends on overburden pressure	
sealing layer, comprising[a]	geomembrane (HDPE[b])[c]	≥2.5 mm
	mineral liner (2 lifts)	≥2 x 0.25 m
regulating layer		≥0.5 m
gas drainage layer		

a. Usually constructed as a composite liner with intimate contact between geomembrane and mineral layer.
b. High density polyethylene.
c. In Germany certification by the Federal Institute for Materials Research and Testing (BAM) is required.

The capping layers are laid with a suitable inclination for rainwater drainage (minimum 3–5%) (Müller-Kirchenbauer *et al.* 1990).

The sealing layer (sealer) elements can be:

– artificial materials (geomembranes, commonly HDPE);

- compacted cohesive earthen materials (cohesive mineral sealers);
- non-cohesive mineral materials (capillary barriers);
- other materials;
- combinations of the above (composite sealers).

TA Abfall (1991) requires cappings to incorporate a composite sealer (geomembrane in intimate contact with a mineral layer), or systems with a proven equivalent or higher efficiency. However, for landfill class I (highly neutral waste) of German municipal landfills, a 0.5 m mineral sealer (in two 0.25 m lifts for compaction purposes), or an equivalent system, is sufficient for the capping.

A composite sealer is considered by the majority of experts to provide the most effective capping for landfill classes II (processed municipal waste) and III (hazardous waste) (Gross *et al.* 1997). It is, however, not compulsory in all Western European countries, nor in the USA (Forster 1993). Its long-term efficacy is sometimes questioned because of potential impairment by settlement, desiccation and/or vegetation.

The composite system is probably the most extensively and intensively tested type of sealer, taking into account trials in the context of both capping and basal lining. Its barrier efficacy has now been investigated over many years: for instance, by the German Federal Institute for Materials Research and Testing (BAM) since 1984 (August 1995; August and Tatzky-Gerth 1992; August *et al.* 1992; August 1992; August and Tatzky-Gerth 1991; Lüders and Müller 1995; Müller 1993*a,b*; Müller 1995*a,b,c*; Müller *et al.* 1995). The findings of such work tend to be broadly valid for both capping and lining applications, although cappings are generally considered to be more vulnerable, due to greater desiccation risks and settlement related problems.

In the selection of the materials to be used for the capping sealer, economic factors must also be considered. The additional costs of a more expensive structure may be compensated for by savings in other cost components (e.g. leachate management). In many cases only the construction costs are considered. But as voidspace values increase, so can the benefits of either a capping solution which generates waste void by use of material excavated on site, or a relatively hi-tech solution which conserves waste void due to its relative slimness. The need for capping systems to last for 50, 100 or more years, free of major maintenance, must also be taken into account.

COMPONENTS AND MATERIALS

Surface vegetation

Vegetation both provides shelter and reinforcement for the capping system and contributes to its basic functioning, especially in the area of water balance. It is however a risk factor, due to potential damage by root penetration of some species into some types of sealer.

Reclamation layer

The reclamation layer supports vegetation and acts as protection for the lower layers. Its minimal thickness (typically 1 m in Western Europe) is determined by the maximal depth of frost and root penetration (Rettenberger 1988; Jessberger 1990*a*). But caution is suggested by recent observations and test results on the Hamburg-Georgswerder landfill, which indicate that 1 m thickness may be insufficient, if no root barrier is incorporated. Permeability in the reclamation layer should not be below 10^{-7} or 10^{-6} m/s; therefore it must not be overcompacted. However, a satisfactory shear strength needs to be achieved on steep slopes (Bahnsen 1990).

Drainage layer

The drainage layer has to divert the water which percolates through the reclamation layer. A long-term permeability of k□□□ $\geq 10^{-3}$ m/s should be maintained. Not only mineral but also artificial materials with proven long-term performance may be used for drainage layers. Gravel, sand and by-products (e.g. glass ash, incineration slag and mining spoil) can be found utilised as mineral drainage materials, although the acceptability of slag or ash may be limited by the presence of toxic metals, while colliery spoil can become too acidic. Polyethylene (PE), polypropylene (PP), polyamide (PA), polyester (PES) and polyacrylnitril (PAC) are the most commonly applied materials for geonets or so-called drain mats (though the suitability of PES and PAC has not yet been proved as thoroughly as for PE). Water collection is usually achieved using HDPE or PVC pipes (Jessberger 1990*b*).

Protective layer

In capping systems, as in basal liners, mineral layers or geotextiles (PE and PP non-woven geotextiles, sand mats, bentonite mats, etc.) are applied to protect the geomembranes (Lüders *et al.* 1995; Müller and Müller 1993; Seeger *et al.* 1995; Seeger 1995).

Sealing layer

The sealing layer has to prevent rain-water from percolating into the landfill and landfill gas from escaping into the atmosphere. It is in that sense the most critical component of the capping system. The main solutions in common use are polymer sheeting (known as geomembranes or flexible liners) or clayey materials (known as cohesive mineral sealers). Composites of both are increasingly found, as are certain hybrids (asphaltic liners, bentonite mats). A more distinct alternative relies on layered gravels (capilliary barrier system). Alone this is not gas-tight nor resistant to root penetration; but in combination with other layers (e.g. geomembranes), and constructed on sufficient drainage slopes, it can form an effective sealer.

Regulating layer

The regulating layer separates the capping from the waste and provides a firm and levelled grounding for the compaction of the mineral sealing layer.

Gas drainage layer

Landfill capping systems have to prevent uncontrolled gas emission into the atmosphere, and gas migration towards the surroundings, and to retain sufficiently high methane concentration for gas utilisation where appropriate (Rettenberger 1986). The gas drainage layer has the task of intercepting, and where desired collecting, such landfill gas. Gas extraction in itself affords vital protection against emission and migration (Rettenberger 1990; Martens and Weber 1990; TA Siedlungsabfall 1993).

ADDITIONAL PROTECTION MEASURES

Mobile shelters

Landfill 'top' shelters can be regarded as a special (surface) protection measure. This is usually achieved by means of a mobile or transportable structure, with the aim of preventing rain falling on the active area of the landfill during operations (Franzius 1986). The total prevention of rainwater infiltration by this means, in the Rondeshagen hazardous waste landfill, is reported (Ernst 1989). Savings in leachate treatment were calculated to compensate for the costs of the covering structure within two years. A covering structure (roof supported by steel piles) is also used over the Wirmsthal landfill near Bad Kissingen in Bavaria, which accepts municipal waste and incineration residues.

Covering structures are also applied to facilitate the placement of landfill liners and/or sealers under otherwise unfavourable weather conditions. Those most commonly used employ a metal framework and reusable roofs, and in some instances the piles are designed as lost piles. Krath and Schwarz (1993) report on tents with a plan area of 2500 square metres which can be used for the interim storage of mineral liner material and as protection against the weather. The structure can accommodate heated construction methods and enables landfill lining with composite liners in winter, in accordance with the Technical Recommendations 'GLC' (German Geotechnical Society 1993) and the Guidelines of the Federal Institute for Materials Research and Testing (1994).

Interim covers

Sometimes part of a landfill requires interim cover. This may be either for a period of hours or days, primarily with the aims of odour, dust, vermin and windblown nuisance abatement. Or it may be for a period of months or years, due to the phasing, operational or market requirements of a site.

Such interim covers may be temporary, and stripped (as far as practicable) upon the resumption of tipping. In other cases they are left in the landfill permanently, and their performance in the longer term has to be considered, as well as their temporary capping function. Geomembranes save room and can be re-used, but earthen materials are especially advantageous if the cover layer is expected to remain in position.

The most commonly used daily cover materials are geomembranes, construction debris, industrial wastes and earthen materials. Easy-to-produce on-site foams and sprayed layers of waste paper mulch have the advantages of being strongly compacted under the overburden, yet degenerating readily, so that in the long term they hardly impede gas and leachate transport at all (Meyer *et al.* 1991; Ashton 1993; Hull 1993).

Interim restoration

With the practice of interim restoration, a shallow subsoil depth is spread and restored as a temporary measure, for the first few years after the cessation of landfilling. Full soil replacement, and the establishment of final restoration and landscape features, are delayed until it can be demonstrated that the landfill gas system is operating reliably and efficiently.

The purpose is to minimise the effects upon the restoration of settlement, and of remedial works to the gas control system (Environment Agency, forthcoming 1997). Interim restoration allows much of the subsoil and all topsoils to remain untouched throughout the period of most frequent remedial works. It also provides a clearer division of responsibility, separating continuing engineering and operational phases from restoration and aftercare.

CONCLUSIONS AND ONGOING ISSUES

Value of capping research

While much technical emphasis in landfill design has been upon basal liners, the landfill capping might be said to be equally important in engineering terms, and perhaps more so from a restoration viewpoint. The two companion articles attempt to summarise recent developments in engineering and restoration thinking, on capping systems in Germany and the UK. Some of the main overall conclusions, and the key issues considered to be outstanding, are now previewed.

Although much of our knowledge of landfill cappings has been obtained under real operational conditions, it is not yet sufficient in every aspect to ensure reliable predictions of long-term performance. High priority has to be given to systematic investigations into the technology of landfill cappings, especially through planned programmes using trial sites. Greater sharing, comparison and replication of results, including internationally, is vital if confidence is to be re-established and maintained in landfill as a responsible means of waste disposal.

Engineering and restoration strands

The strongest research relating to cappings in Germany has focused upon materials specification and performance for the sealing layer. Perhaps most crucial – if only because it is the one type of sealer which tends to be commonly used both alone and in combination with other materials – is the work on cracking in cohesive mineral sealers. In clayey cappings, given carefully selected materials, this tends to be induced either by settlement and/or defects in placement (mechanical cracks), or by drying out and shrinkage (desiccation cracks). Both types of cracks can be shown to be self-healing under surcharge; however, mechanical cracks will not heal themselves under the depth of surcharge commonly found in landfill cappings, unless the mineral sealer has retained its plasticity (Savidis and Mallwitz 1995).

Much of the experience in UK restoration design and practice is highly relevant to such findings. The practical arts of soil handling and vegetation establishment are now approached with a degree of caution and refinement reminiscent of the veteran farmer, forester and gardener: but with added complications, such as the need to use imported soil making or drainage materials, and the need to avoid disturbing gas control installations or root penetration of the cap. But more to the point, the protective, drainage, reclamation and vegetation layers over the sealer are now more clearly seen not only in relation to the site afteruse, but also as having a vital function in preventing cohesive mineral sealers and bentonite matting drying out and losing their plasticity.

Timing of and measures pending capping

The stage at which a capping system is applied, relative to the state of degradation and consolidation of the waste, is critical. To provide a stable sub-grade, biological activity should have subsided to a point where the waste body exhibits a predictable and limited settlement behaviour. In Germany, this is assisted by the limits (under TA Siedlungsabfall 1993) upon the organic content of municipal wastes for disposal to landfill: but that presupposes acceptable methods of pre-treatment. *In situ* treatment of the waste body by dynamic intensive compaction could also be beneficial.

For long-term stability, residual settlement after installation of the capping must not be such as to exceed allowable strains in its sealer materials. Asphaltic concrete is most susceptible in this regard. The tolerance of mineral sealers largely depends upon their composition and specification. Geomembranes perform well. Bentonite matting is least susceptible to settlement.

Although not as thoroughly researched as the mainstream capping systems, we have felt the emphasis upon additional protection – mobile shelters, interim cover, interim restoration – worth reporting here. The interest in such matters reflects a practitioner's concern that the very best end-state design is of limited benefit unless one can better cope with all the various stages of construction and partial completion.

With a landfill operation, construction and completion can be very extended in space and time: the more so where final capping is to be delayed as suggested above. One of the skills to be nurtured, in managing a landfill site, is that of phasing. Facilities should be developed and used so as to meet demand at acceptable economic cost and risk, while supporting more advanced techniques of operational and environmental control, such as those offered by mobile shelters and interim restoration.

More fundamental design questions

Despite interest in accelerated stabilisation of landfills, and awareness of the role of moisture in achieving that, it is not yet possible to design a capping which will attain and maintain an optimal water balance in the waste mass, due primarily to seasonal fluctuations in rainfall and temperature. The common recourse is to seek to exclude all water ingress; but the downside of that could be undesirable prolonging of waste degradation processes (Young 1993).

One solution is the injection of sewage sludge or recycled leachates (via pipe systems) under the capping. An alternative approach might be to try to specify a capping which allowed only optimum percolation into the waste under wet conditions, but presented the possibility of above-capping irrigation to maintain the water balance in drier periods. The latter design philosophy would have to take into account the changing moisture requirement of the waste mass as it degraded over the years. Its achievement may be dependent upon the implications for containment and extraction of landfill gas.

It is difficult to conceive of a gilled or valved membrane sufficiently robust for landfill capping purposes which would allow measured water ingress without permitting significant gas escape; but there may be 'low tech' solutions by providing for controlled irrigation at the joints in standard impermeable geomembranes. Research has shown that it is the moisture content at placement, rather than in operation, which is critical in determining the gas permeability of clayey mineral sealers; so there is also perhaps hope there. Active gas extraction (negative pressure) does of course assist in minimising losses, but gives rise to air ingress and aerobic conditions if taken too far.

Towards 'discerning' capping systems

The basic mechanism of greatest relevance, then, is the flow of water purely under gravity (and hydraulic head), and the resistance to such flows (including due to capillary forces), in the pores of the capping materials. This interest applies just as much to water movement in the drainage, soils and vegetation above the seal, as to percolation through the sealing layer itself. It is perhaps in this area that our review has revealed most promise. One cannot fail to be impressed by the parallels between the understanding among soil scientists as to how a wetting front moves seasonally within the reclamation zone, and the emerging knowledge from engineering trials of capillary barriers as a component of capping sealers.

This symbiosis suggests to us that it should indeed be theoretically possible to design an integrated cap of soils, drainage layer and cohesive materials, for any given climate, which allows annual infiltration to be kept down to a predictable maximum, yet permits topping up by irrigation, before, during or after drier periods, to maintain a desired long-term rate of stabilisation of the waste. Moreover, in principle there should be a range of possible design solutions, in sympathy with the types and availability of soils and other materials, and the nature of the landfill and its afteruses.

It could take many years before such 'discerning' cappings can be reliably designed and constructed; by which time they may be outpaced by even more sophisticated geomembranes and geotextiles. But there does now seem to be a prospect on the horizon of more enlightened approaches to capping than the absolutist aim of trying to keep all water out of a landfill, regardless of the consequences for longevity of engineering aftercare, and delay in restoration and beneficial use.

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