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Reducing drying energy and costs by process alterations at aggregate stockpiles

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Abstract In the field of bulk solids, handling knowledge on moisture behaviour in aggregate stockpiles can be useful for process optimisation in terms of energy consumption. In the asphalt industry, an increase in moisture content leads to a significant increase in energy consumption. To determine the characteristics of moisture behaviour, correlations are investigated between theory on soil–water movements and moisture in aggregates. With column drainage experiments with porous bottom, similarities between theory and practice are found. This allows the use of theoretical hydrologic models to determine and predict the moisture behaviour in drained piles. The effect of process alterations within the system of piles on energy consumption was investigated, and a significant reduction of energy consumption was found.

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Keywords Energy savings · Loss prevention · Aggregates · Asphalt production · Stockpiles · Moisture behaviour

List of symbols

α	Curve parameter
φ	Porosity
h	Pressure head
γ_w	Weight density of water
K_h	Hydraulic conductivity
K_s	Saturated hydraulic conductivity
ψ	Pressure head
ψ_{ae}	Air-entry tension
n	Curve parameter
m	Curve parameter
p	Water pressure
q_x	Volumetric flow rate in the x-direction
S_e	Effective water content
θ	Water content
θ_{fc}	Field capacity
θ_{res}	Residual water content
θ_{sat}	Saturated water content
z	Elevation above arbitrary datum

Introduction

This paper investigates the effects of process alterations at the aggregate stockpiles on the drying energy and drying costs. Process alterations have a positive effect on the energy for drying and as a result on drying costs, when the moisture content in the aggregates is lower. Knowledge on the moisture content is desirable in all aggregate processing industries like asphalt production, concrete production and coal fired power plants. For instance, 1% moisture content reduction at asphalt production can save up to €200,000 per year for a single plant, while other researches have shown that a coal fired power plant has to fire €87,000 per year extra coal to evaporate the moisture present in the material (Schott et al. 2008; Thijssen 2009).

Earlier research in this field was done by Eckersley for coal stockpiles (Eckersley 1994a, b, c). His research was initiated because of the hazards of flowslides caused by excessive moisture contents at the base of the stockpile. He gained knowledge on the threshold moisture content below which no significant redistribution of water occurred and has indicated that this threshold moisture content changes with height and residence time. However, the results of Eckersley remain at theoretical level and are not translated to practice or concrete recommendations.

This research is inspired on the method of Eckersley, but is extended to practice. Because the aim of the research is to reduce the drying energy and costs, not only knowledge on the moisture behaviour is necessary, but also on the effect of process alterations on moisture behaviour is important. Furthermore, it is based on aggregate drying at asphalt production plant where lowest attainable moisture content is of interest, while Eckersley aimed at the minimal moisture content below which no hazards of flowslides occur.

Figure 1 indicates the schematic process at the aggregate stockpiles. Aggregates enter the stockpile, and their moisture content is directly influenced by precipitation and evaporation and indirectly by drainage due to vertical redistribution of the water. The effect obviously depends on the process parameters or characteristics of the pile(s). Since the effects of precipitation and evaporation can be directly determined with knowledge of area and residence time, first, the more complex effect of drainage will be determined by theory (the "Theory" section), experiments and simulation of uniaxial vertical drainage conditions (the "Method" and "Results" sections). In the "Application of results to aggregate stockpiles" section, the effect of process alterations on the final moisture content of an aggregate is investigated. The process alterations which are investigated are roofing, capacity and height alterations of the piles and restrictions on the initial moisture content.

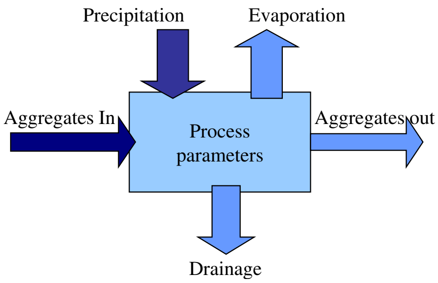


Fig. 1 Process scheme of aggregate flow at stockpiles

Theory

Hydrogeology

To determine the effect of drainage, theory on percolation of water in porous media is consulted which belongs to the field of hydrogeology. Hydrogeology is the study of water movements in soils. Soils are a porous media which means that they consist of granular materials with voids in between. These voids can be filled with water, air or both. Large part of the study is the moisture behaviour in the soil during and after a precipitation event.

Figure 2 shows that a soil can be divided in a saturated and an unsaturated zone. The boundary between the two zones is the water table. In the saturated zone, all voids are filled with water, and in the unsaturated zone, the voids are partly filled with water or dry. During a precipitation event, water infiltrates in the unsaturated zone and is redistributed to the saturated zone.

There are other water movements possible in soils, but for this research all precipitation is assumed to infiltrate and vertically redistributed.

Flow in unsaturated zone

Studies of Eckersley show that the largest part of a coal stockpile behaves like an unsaturated zone. This behaviour has also proven to be true for mineral

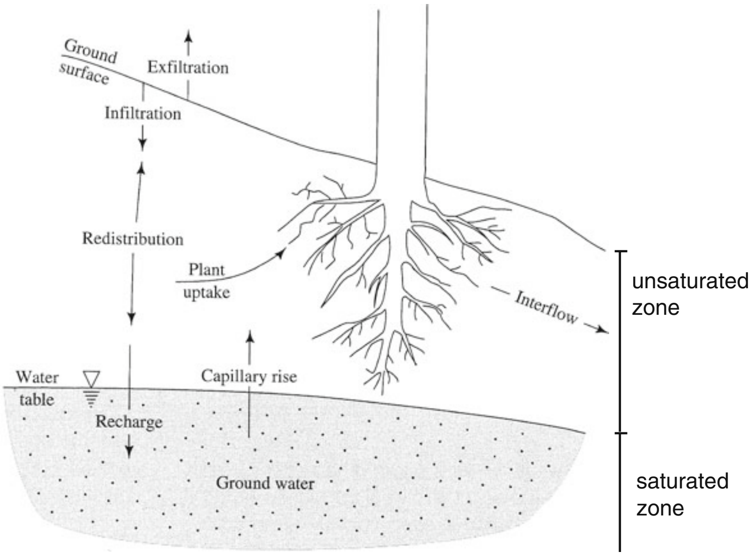


Fig. 2 Water movements in soils (Dingman 2002)

aggregate stockpiles at, e.g. asphalt production plants (Brooks and Corey 1964).

Flows in an unsaturated porous medium are described by Darcy's law (Dingman 2002) as

$$q_x = -K_{\mathrm{h}} \cdot \left[\frac{dz}{dx} + \frac{d(p/\gamma_{\mathrm{w}})}{dx}\right]. \tag{1}$$

Here, q_x is the volumetric flow rate in the x-direction per unit cross-sectional area of medium [ms^{-1}], z is the elevation above an arbitrary datum [m], p is the water pressure [Nm^{-2}], γ_{w} is the weight density of the water [Nm^{-3}] and K_{h} is the hydraulic conductivity of the medium [ms^{-1}].

Darcy's law describes the flow at a representative elemental volume of the soil which includes pore spaces and soil particles. Flow occurs in response to the spatial gradients of mechanical potential energy, which has two components: the gradient of gravitational potential energy dz/dx and the gradient of pressure potential energy $d(p/\gamma_{\mathrm{w}})/dx$ per unit weight of flowing water. This means that water always flows to a point where the combination of gravity and pressure is higher than at the current point. The rate of flow is amplified by the hydraulic conductivity K_{h} which is a measure of the resistance of a material to flow. A high hydraulic conductivity means less resistance to flow and therefore higher flow rates. The hydraulic conductivity is a material property which depends on the pore-size distribution and the water content in a material.

Because in the scope of this research only flow in the vertical direction is considered (uniaxial vertical drainage), Darcy's law can be rewritten as

$$q_z = -K_{\mathrm{h}}(\theta) \cdot \left[1 + \frac{d\psi(\theta)}{dz}\right]. \tag{2}$$

Here, ψ is the pressure head [L] which is defined as p/γ_{w}, θ is the volumetric water content of the porous medium which is the ratio of water volume to soil volume and γ_{w} is the weight density of the water. The latter is effectively constant for hydrologic problems which do not involve temperature or salinity gradients. The hydraulic conductivity and the pressure head depend on the volumetric water content. Both are crucial determinants of unsaturated flow in soils.

Pressure in the unsaturated zone is negative and often referred to as suction or tension head. The negative pressure is caused by the surface tension forces of water trapped in the menisci of the voids. If the water content decreases then the surface tension in these menisci will increase causing the tension head also to increase. The relation between tension head and water content is often plotted on a logarithmic scale creating the moisture characteristic curve or soil–water retention curve (Fig. 3). When the volumetric water content is equal to the porosity φ, all the voids are filled with water and the soil is considered saturated. This occurs at zero tension head. Figure 3 shows when the tension head increases from the point of saturation, the water content changes little for a

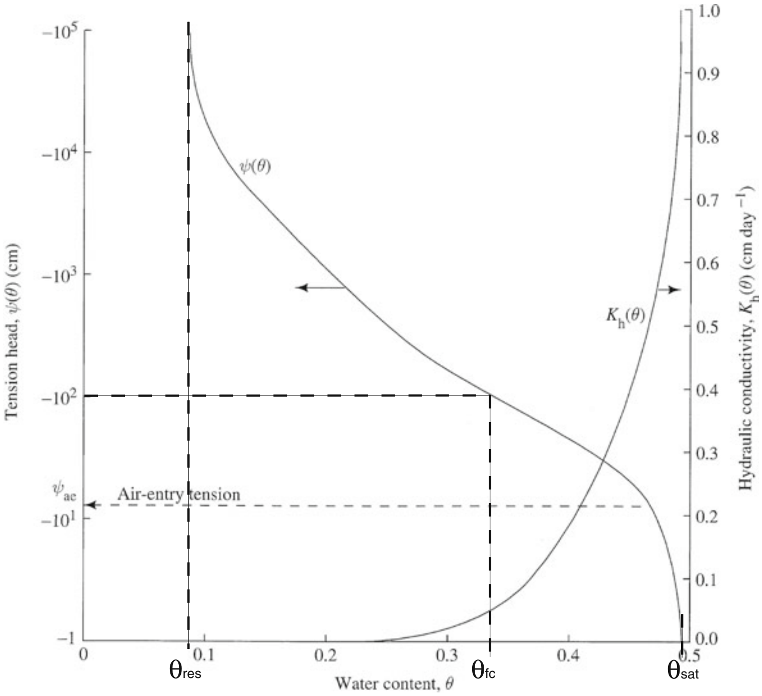


Fig. 3 Typical forms of hydraulic relations $\psi(\theta) - \theta$ and $K_h(\theta) - \theta$ for unsaturated soils. For this soil porosity φ=0.5 (Dingman 2002)

while and then decreases rapidly and later on more gradually. Two significant points are recognised: the air-entry tension ψ_{ae} and the field capacity θ_{fc}. The air-entry tension is the point of deflection from saturated to rapidly decreasing water content. At this point, volumes of air begin to appear in the soil pores. The field capacity is the moisture content to which a soil will drain under normal circumstances and measurable time intervals. The lowest moisture content is the residual water content θ_{res} which can only be reached with extreme suction.

The hydraulic conductivity K_h also depends on the moisture content. Figure 3 shows that initially the hydraulic conductivity drops rapidly and then decreases more gradually with decreasing moisture content.

The Mualem–Van Genuchten model

Both the pressure head–water content and hydraulic conductivity–water content relations need to be known to apply Darcy's law for flow calculations. The pressure head–water content relation can be determined by field measurements or laboratory experiments, but determination of the hydraulic conductivity–water content relation is more difficult (Dingman 2002). For this reason, often analytical approximations of these relations are used. Various models use analytic approximations ranging from relatively simple equations to extended models. In this paper, the model of Mualem–Van Genuchten will be used because it is best suited for practical applications where the results do not depend on minimal differences in the water flow at small time increments or at the boundaries of full saturation or residual water content (Van Genuchten 1980). Other models, among which the Brooks and Corey model is well known (Brooks and Corey 1964), show the same range of results.

The Mualem–Van Genuchten model is based on the equations from Mualem's model (Mualem 1976). Mualem has derived an equation for predicting the relative hydraulic conductivity from knowledge on the soil–water retention curve. Van Genuchten has added formula to analytically approximate the soil–water retention curve from observed soil–water retention data. The Mualem–Van Genuchten Model is described as

$$\theta(h) = \begin{cases} \theta_{\mathrm{res}} + \frac{\theta_{\mathrm{sat}} - \theta_{\mathrm{res}}}{\left(1+|\alpha h|^{n}\right)^{m}} & h < 0 \\ \theta_{\mathrm{sat}} & h \geq 0 \end{cases} \tag{3}$$

$$K(h) = K_{\mathrm{s}} S_{\mathrm{e}}^{1} \left(1 - \left(1 - S_{\mathrm{e}}^{\frac{1}{m}}\right)^{m}\right)^{2}. \tag{4}$$

Here, $\theta(h)$ is the relation between water content and pressure head and $K(h)$ is the relation between hydraulic conductivity and pressure head. Furthermore, α, n and m are dimensionless curve parameters obtained from observing soil–water retention curves. These parameters determine the shape of the curve while θ_{sat} and θ_{res} are the left and right boundaries between which the curve propagates. K_{s} is the saturated hydraulic conductivity [LT^{-1}], and S_{e} is the effective water content defined as

$$S_{\mathrm{e}} = \left[\frac{1}{1+(\alpha h)^{n}}\right]^{m}. \tag{5}$$

By finding the correct values for the parameters in (3) to (5) the water content–pressure head and hydraulic conductivity–pressure head can be inserted into Darcy's law to calculate the water flow properties.

Method

The final goal of the method is to determine the influence of residence time on the threshold moisture content. The threshold moisture content is the average moisture content in a stockpile below which no drainage occurs in the associated residence time. This relationship will be depicted as drainage curves in the next section. Since drainage is caused by percolation, the Mualem–Van Genuchten model will be used to determine the percolation effect in the selected materials. The selected materials originate from the asphalt industry and are mineral sand and recycled asphalt. The experiments and simulations deal with a porous bottom or a uniaxial drainage condition.

Column drainage experiments

With these experiments, the drainage behaviour in the aggregates could be observed under more controlled circumstances. Two series of column drainage experiments were conducted. The first series consisted of one column of 159 cm high and was primarily designed for the comparison with literature. The second series consisted of two columns of 268 cm high. These columns were constructed for more resemblance with the situation in practice.

The columns were constructed of PVC cylinders of 12.5 cm outside diameter. At height intervals of 36 cm, holes were made in the column as sampling points for determination of the aggregate moisture content. The column of the first series was equipped with five sampling points and in the second series with eight. The bottoms of the columns were provided with a coarse filter and a glass container for the drained water to simulate the drainage behaviour in practice.

During an experiment, a column is filled with the concerned aggregate. The aggregate is prepared to the desired initial moisture content and remains in the column during a certain drainage period. Aggregate samples are taken from sample points when the drainage period is expired.

Software simulation

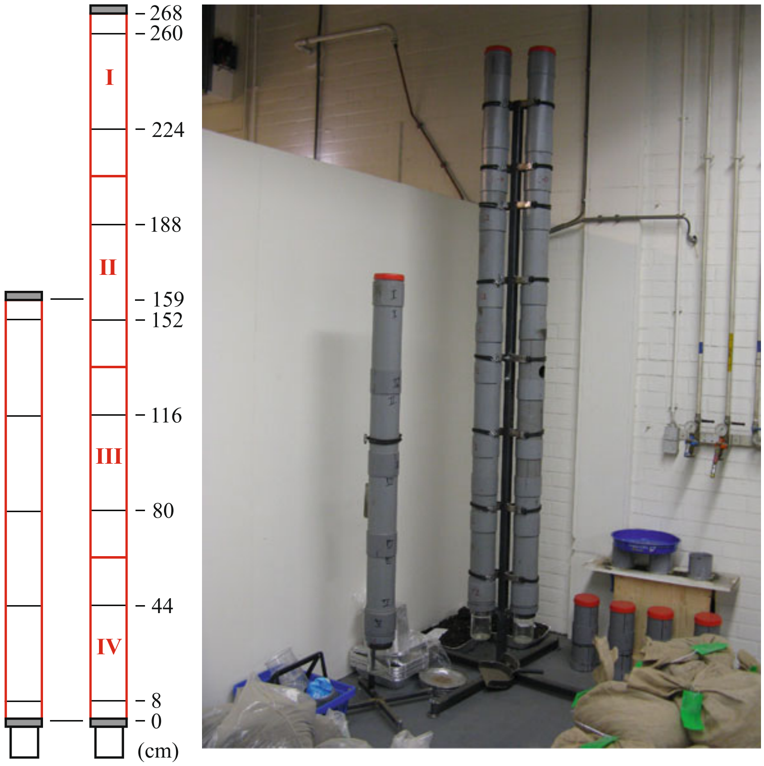
The parameters needed for the Mualem–Van Genuchten model will be derived from column drainage experiments. Figure 4 shows that three columns with two different heights were constructed. The columns were filled with material having homogeneous moisture content throughout the height. The material was left to drain during a specified residence time. Once this residence time had passed, firstly, the density of the total column was determined and, secondly, samples for moisture content determination were taken from the column at different height levels.

The sample data on moisture content is set out against height to construct the moisture characteristics. With aid of these moisture characteristics combined with software simulation program Hydrus 1D (version 4.12, 2005–2008; Šimůnek et al. 2008), the needed parameters for the Mualem–Van Genuchten model are derived in the following steps (Hydrus 1D, version 4.12, 2005–2008):

- The curve parameters α and n are assumed equal to those of typical sand
- With bulk density known, the average porosity in the columns is equal to the saturated moisture content
- The field capacity can be derived from the smaller column and is converted to the residual moisture content with Hydrus 1D
- The saturated hydraulic conductivity K_{s} is obtained by iteration to the retrieved moisture characteristics with Hydrus 1D

Previous research has indicated that the data from the column drainage experiments complies with the

Fig. 4 Construction of column drainage experiments



field measurements as well as with the theory on water movement in the unsaturated zone. This means that the data from the experiments can be used as a basis for modelling the moisture behaviour in the aggregates stockpiles (Thijssen 2009).

As described earlier, the model of Mualem–Van Genuchten will be used. The simulation is done with the software program Hydrus 1D which uses a finite element method for calculating the water flow characteristics (Hydrus 1D, version 4.12, 2005–2008). In this program, a vertical column of desired height is specified and constructed with one or more materials of choice. The vertical column is divided in a specified number of nodes. For each node, the spatial flow characteristics are calculated according to Darcy's law. The vertical column can be accommodated with observation point for which the flow data is logged. This data can be studied after simulation.

With the parameters known, Hydrus 1D is used to extrapolate the moisture behaviour to other heights and residence times, based on a practical situation. With this extrapolation, the drainage curves are constructed to gain insight in the threshold moisture content at different heights.

Results

Column drainage experiments were conducted for the same materials as in the field measurements. With these experiments, the drainage behaviour in the aggregates could be observed under more controlled circumstances. The gained data from the experiments is compared with the results from field experiments and with the literature for reliability of the simulation. With the results of the column drainage experiments, the moisture behaviour is simulated by Hydrus 1D which finally led to the construction of drainage curves. Drainage curves show how the average moisture content in stockpiles at different heights respond to the residence time.

Column drainage experiments

The experimental plan consists of experiments with relatively high or average moisture contents set out to different drainage periods ranging from relatively short to long periods.

For the results, the moisture contents from the sample points are set out to the corresponding heights of the sample points to construct the moisture characteristics in Figs. 5, 6 and 7. Four experiments from the first series and two of the second series are selected to be presented in this paper.

For comparison with literature, the following can be observed:

- Both materials in the first series drain within a measurable time interval to a minimum moisture content. Since the aggregate is not subjected to extreme suctions, this moisture content is the above discussed field capacity θ_{fc}
- The drainage curve for river sand resembles a typical retention curve for sand
- The drainage curve for recycled asphalt does not resemble a typical drainage curve for sand as close as river sand, but has a field capacity which is comparable to sand. As discussed in the results of the field observations, recycled asphalt tends to behave like sand but with an extreme high hydraulic conductivity caused by the smooth bitumen present around the particles

Drainage curves

The first step in simulating the moisture behaviour for the aggregate stockpiles is to define the soil hydraulic parameters from (3) and (4). The curve parameters α, n and m are set equal to the values for typical sand which are provided by Hydrus 1D (Table 1). The saturated water content θ_{sat} is equal to the porosity of the material which is determined from the column drainage tests by measuring the bulk density. The residual water content θ_{res} differs by 0.005 from the field capacity θ_{fc} with the chosen curve parameters α, n and m. The field capacities for river sand and recycled asphalt are obtained from the column drainage experiments and found to be respectively 0.060 and 0.074 volumetric or 4.2% and 4.6% gravimetric which results in residual water contents of 0.055 and 0.069.

The second step is taken by fitting the drainage curves obtained from the column drainage experiments to the moisture data generated by the simulation. This way, the only parameter left for iteration, the saturated hydraulic conductivity K_s, is determined.

The results of these two steps are displayed in Fig. 8, where the drainage curves for the two materials at two different heights are constructed. It becomes clear that for both materials within a few days the largest part of the water is drained. The material was given enough time to drain towards constant moisture content. The difference between the materials is that mineral sand is able to absorb more water than recycled asphalt and drains slower. Noticeable is the final moisture content which is about equal for both materials given enough time. Figure 8 also shows an increase in height resulting in slower drainage for both materials. According to the "Introduction" section of this paper, height alterations are considered one of the process alterations in order to reduce energy costs which will be further discussed in the next section.

Application of results to aggregate stockpiles

In this section, the application of the results to the aggregate stockpiles in order to reduce the drying energy costs is investigated. First, the current moisture behaviour at an aggregate stockpile is analysed followed by the impact of process alterations on this

Fig. 5 Results column drainage experiments river sand, first series

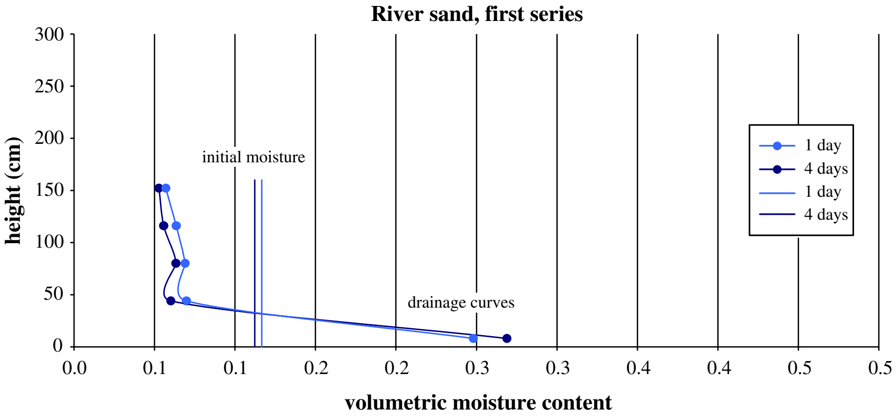
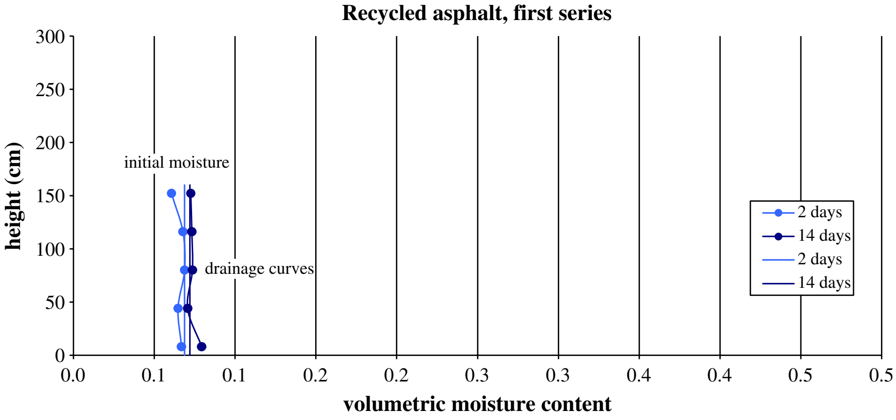


Fig. 6 Results column drainage experiments recycled asphalt, first series



behaviour. As a case study, two stockpiles of mineral sand and recycled asphalt are selected for analysis.

Current moisture behaviour

As an example, the knowledge on drainage is applied to the stockpile situation at an asphalt production plant. Figure 9 denotes the moisture behaviour at the stockpiles of river sand and granulated recycled asphalt. River sand enters the stockpile with a yearly average of 5.8% and increases to 6.5% due to precipitation, while the drainage curves show that the material drains towards a yearly average of 4.9%. This means that river sand loses water because the initial moisture content is higher than the threshold moisture content and will therefore benefit from measures which lower the threshold moisture content.

Granulated recycled asphalt behaves opposite to river sand. This material enters the stockpiles with an initial moisture content of 3.1% which is lower than the threshold moisture content of 4.7%. Due to precipitation, the moisture content increases to 4.9% and drains towards 4.2%. This means that granulated recycled asphalt will benefit from measures which limit or prevent the effect of precipitation.

Process alterations

The previous section has shown that a granular material can either benefit from measures which limit the effect of precipitation or increase the effect of drainage. As stated in the "Introduction" section of this paper, by applying process alterations, the effect on the drying costs will be determined. According to Fig. 1, the following effects are analysed:

– Altering process parameters: pile capacity and height
– Precipitation prevention by roofing
– Restrictions on initial moisture content

Increasing capacity and decreasing height are measures which result in lower threshold moisture contents

Fig. 7 Results column drainage experiments river sand, second series

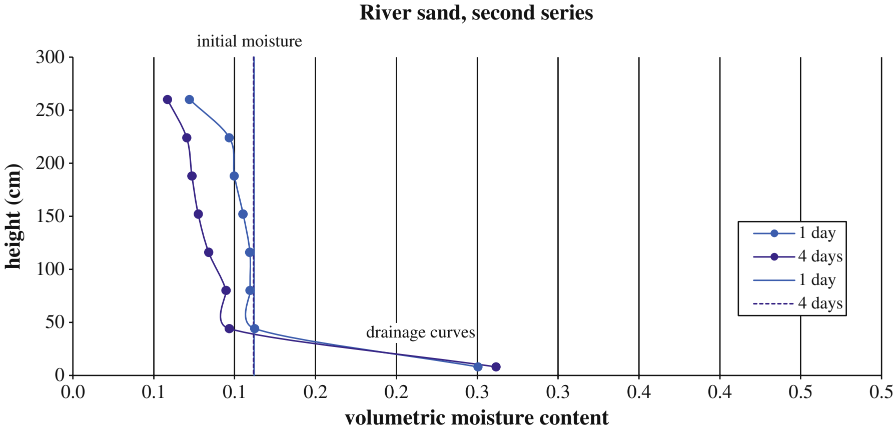


Table 1 Soil hydraulic properties

	River sand	Granulated recycled asphalt
α (cm^{-1})	0.145	0.145
n	2.68	2.68
m	0.63	0.63
θ_{sat}	0.49	0.40
θ_{res}	0.055	0.069
K_s (cm/h)	400	1,000

because increasing capacity leads to longer residence times and thus more time for drainage and decreasing height results in a lower drainage curve. In analogy with the previous section, these measures would have a positive effect on materials entering the process with higher initial moisture content than the threshold moisture content. This is applicable to river sand.

Decreasing capacity and increasing height have opposite effects on the threshold moisture content, but have a positive effect on precipitation limiting, because both measures result in an area decrease. For this reason, materials which gain in moisture content due to precipitation would benefit from these measures. This is applicable to granulated recycled asphalt. Furthermore, limiting precipitation by roofing would also benefit the materials with higher threshold moisture contents than initial moisture contents, the most.

Effect on energy costs

Figure 10 shows the percentage cost reduction that comes along with the measures. This figure is a distillate of the two materials: river sand and granulated recycled asphalt. The left figure shows the effects of altering capacity, height and roofing for mineral sand. The right figure also shows the effect of initial moisture content restrictions for recycled asphalt. As expected, reducing height and increasing capacity results in a cost reduction for mineral sands and in a cost increase for granulated recycled asphalt. In these pile configurations, when height is halved and capacity doubled, it saves 240 t of water per year due to longer and faster drainage in these piles. However, the cost reduction is higher when height is increased and capacity lowered for recycled asphalt. For instance, when height is tripled and capacity halved, it saves up to 900 t of water per year because of the area reduction and thus limited effect of precipitation. Compared to the maximum amount of precipitation to be prevented by roofing (1,200 t per year), this means that already more than 70% can be saved by altering process parameters alone.

Figure 10 also shows that setting a restriction on initial moisture content not only influences the final moisture content directly, but also indirectly. For instance, practice has shown that when a restriction of 3% moisture content is set on the supplied granulated recycled asphalt, the effect of increasing height and reducing capacity becomes amplified as indicated by the grey areas.

Conclusions

By conducting column drainage experiments similarities have been found between hydrologic models and the moisture behaviour in aggregate stockpiles. The moisture in the aggregate stockpiles behaves similar to the unsaturated zone in soils. The drainage curves

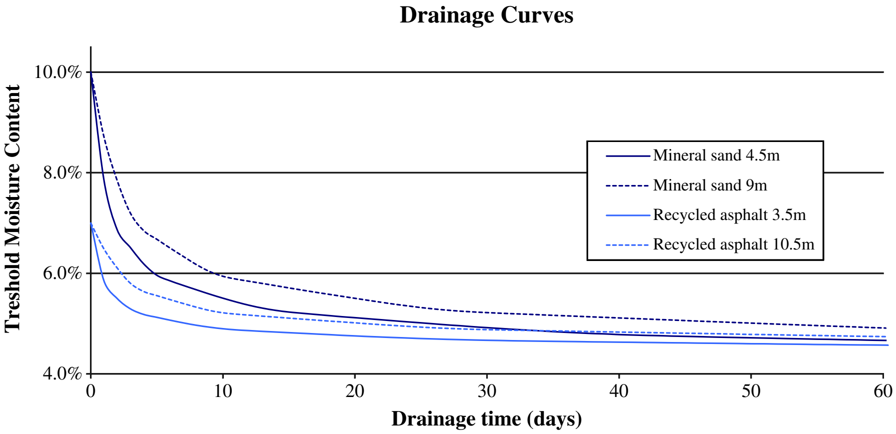
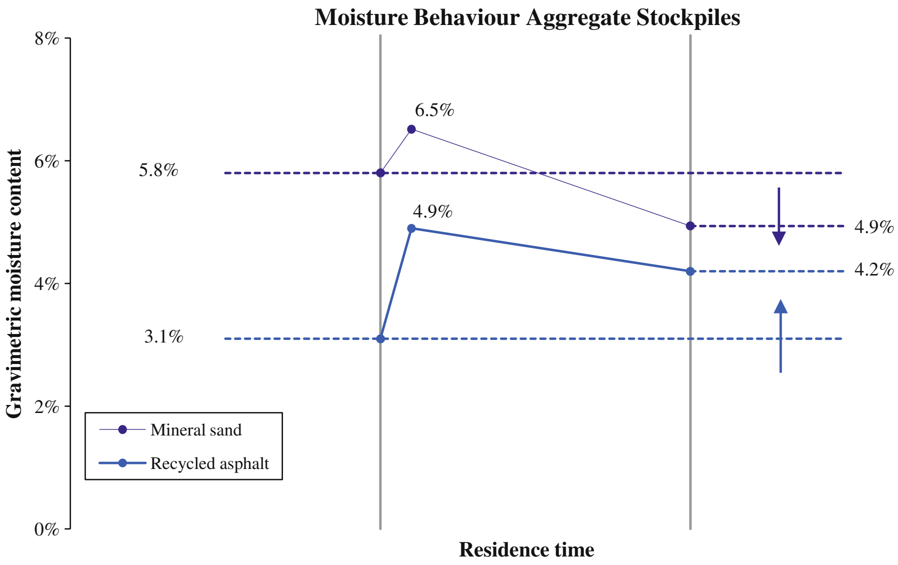


Fig. 8 Resulting drainage curves from simulation

Fig. 9 Moisture behaviour stockpiles



of river sand are in accordance with part of the retention curve of typical sand and have a field capacity of 4.2%. The recycled asphalt behaves like sand at the field capacity of 4.6% and at high hydraulic conductivities.

The hydrologic model of Mualem–Van Genuchten can be used to determine and predict the behaviour. Usually, the soil parameters to use in the model are determined by extensive laboratory research. This is done by determining the moisture retention curves or creating and counselling soil property databases. However, for most aggregates, no soil property databases exist. For aggregate stockpiles, the data from column drainage experiments can be used to

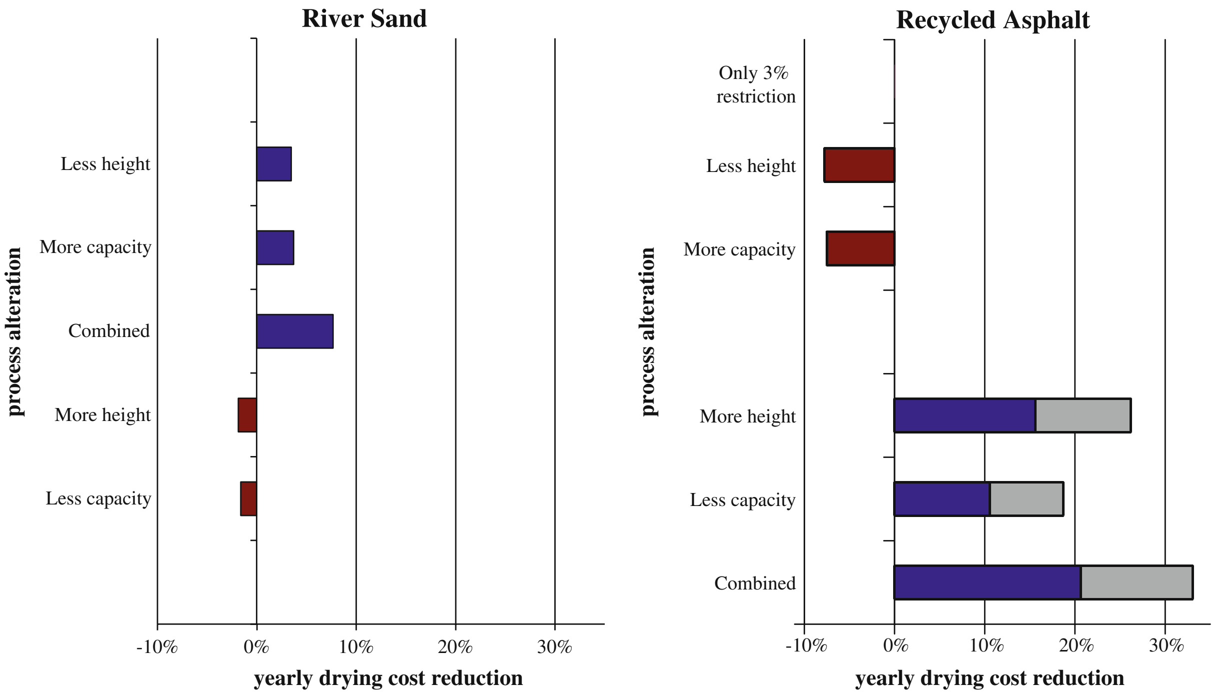


Fig. 10 Effect process alterations

estimate these parameters. This method can be used because the required knowledge of aggregate stockpiles is less than the desired knowledge for standard hydrologic research.

With knowledge on this percolation behaviour, the effect of process alterations can be determined. It becomes clear that stockpiles must be divided into two categories: initial moisture content above the threshold value and initial moisture content below the threshold value.

When the initial moisture content is above the threshold value, the drying energy and costs can be reduced by reducing the stockpile height and increasing the capacity. When the initial moisture content is above the threshold value, a reduction can be realised by increasing the stockpile height and reducing the capacity depending on the practical situation and taking logistics into account.

Recommendations

Knowledge on the drainage curve of a selected material can be used to intelligently operate the stockyard. With knowledge of initial moisture contents and precipitation effects, the minimum required residence time can be determined for different materials. Furthermore, the moisture characteristics have indicated that materials can be significantly wetter at the bottom of the pile, thus for plant operation from reducing energy consumption, it would never be advisable to obtain material from the bottom part of the pile.

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