

INVESTIGATION METHODS OF MSWI BOTTOM ASH PROPERTIES FOR USE IN EMBANKMENTS

REPORT 2019:592



Investigation Methods of MSWI Bottom Ash Properties for Use in Embankments

Undersökningsmetoder för slaggrus i dammvallar

KARINA TOMMIK

ISBN 978-91-7673-592-3 | © Energiforsk August 2019

Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Förord

Denna rapport är slutrapportering av projekt 2017–105 Slaggrus i dammvallar inom Askprogrammet som bedrivs av Energiforsk. Askprogrammet verkar för att kunskap tas fram för att stimulera användningar av askor så att ingen eller ringa risk för hälsa och miljö på kort eller lång sikt föreligger.

Projektet har haft fokus på vilka mätmetoder, genomgång av befintliga tekniker och vilka parametrar man behöver ta hänsyn till om slaggrus ska användas som anläggningsmaterial i t.ex. dammvallar. Syftet har varit att titta på de tekniska aspekterna, de miljömässiga tillståndsfrågorna berörs ej.

Arbetet har genomförts av Karina Tommik och Sven Knutsson på Luleå tekniska universitet. Initiativtagare och delaktig i projektet har Henrik Lindståhl, Tekniska verken i Linköping varit.

Projektet har följts av en referensgrupp bestående av:

Einar Port, Mälarenergi,
Mariana Björklund, Borås Energi och miljö
Raul Grönholm, SYSÄV
Johan Lagerlund, Vattenfall

Helena Sellerholm
Områdesansvarig
Termisk energiomvandling, Energiforsk AB

Här redovisas resultat och slutsatser från ett projekt inom ett forskningsprogram som drivs av Energiforsk. Det är rapportförfattaren/-författarna som ansvarar för innehållet och publiceringen innebär inte att Energiforsk har tagit ställning till innehållet.

Sammanfattning

Syftet med projektet har varit att översiktligt beskriva egenskaperna hos slaggrus från förbränningsanläggningar (MSWI) med målet att preliminärt kunna avgöra dess potential för användning vid uppbyggnad av vallar runt gropvärmelager (PTES).

Gropvärmelager (PTES) består som regel av en grävd grop i lämplig geologisk formation vanligtvis fylld med vatten. Varianter av groplager finns där man utöver vatten fyllt gropen med sprängsten eller annat grovkornigt material. Ur värmelagrings-synpunkt är det effektivast att enbart använda vatten i gropen, men att fylla gropen med kornigt material kan vara bra av andra skäl. Bland dessa kan nämnas att i/gropens stabilitet förbättras om den är fylld med annat än vatten, ii/det blir enklare med en takkonstruktion över gropen, iii/ytan över gropen kan användas till något lämpligt där man eventuellt kan nyttiggöra värmeförlusten från gropen ut mot atmosfären. Men effektiviteten och responstiden för lagret blir bättre om enbart vatten nyttjas och därför är det vanligast att lagren byggs på detta sätt. En utmaning är då som regel takkonstruktionen. Denna ska bland annat vara: i/värmeisolerande för att minimera värmeförlusterna, ii/vara stabil nog för att inte blåsa bort vid stormigt väder, iii/ bära last av nederbörd, iv/tåla temperaturväxlingar och de uppkomna gradienterna etc.

Mediet i gropen värms på sommaren och värmen tas ut på vinterhalvåret. Av effektivitetsskäl bör temperaturen i gropen vara så hög som möjligt och här utgör kokpunkten för vatten en övre begränsning, eftersom anläggningen inte rimligen kan trycksättas. Vattentemperaturer på 80-90 °C är önskvärt. Det innebär att materialet, i vilket värmelagret är byggt, kommer att värmas till dessa temperaturer i de delar som ligger närmast det uppvärmda mediet och därmed uppkommer en stor temperaturgradient i det omgivande materialet. Beroende på geologiskt material som groplagret är byggt i och vilken geohydrologisk situation som finns på platsen, kommer grundvattenytan att ligga mer eller mindre nära markytan. Det är sannolikt att stora delar av det omgivande materialet är vattenmättat. Eftersom vatten och fasta partiklar har olika värmeutvidgningskoefficient kommer volymutvidgningen att ske olika i de olika delkomponenterna. Har det geologiska materialet liten hydraulisk konduktivitet (snarare konsolideringskoefficient) kommer volymutvidgningen av vattnet att till stor del vara förhindrad. Detta medför uppbyggnad av porvattenövertryck, som minskar materialets hållfasthet och ökar dess deformationsbenägenhet med åtföljande sättningar. Förändringar av hållfastheten i det geologiska materialet påverkar stabiliteten hos groplagrets slänter och säkerhetsfaktorn minskar. Hållfasthetsreduktionen kan bli så stor att slänterna blir instabila. Uppkommer stora sättningar till följd av de höga temperaturerna kan överströmning av de omgivande vallarna uppkomma.

Att klarlägga hur det geologiska materialet reagerar på kraftiga temperaturökningar är därför en avgörande faktor för en säker och bra funktion för ett gropvärmelager. Här måste man utgå från vilket material man har på platsen och klarlägga hur detta reagerar på temperaturökningar och på stora

temperaturgradienter. Variationen i beteende är stor. Ett gropvärmelager som byggs i en relativt torr grov friktionsjord torde enbart uppvisa marginella förändringar till följd av uppvärmningen, medan ett lager som byggs i tät fet lera torde kunna få avsevärda förändringar. I ett lager byggt i lera kan man sannolikt få stora hållfasthetsreduktioner tillsammans med stora sättningar. Å andra sidan har lera andra fördelar. Testmetoder för att studera temperaturens inverkan på hållfastheten i olika material finns till del beskrivna i litteraturen, men de utförs vanligen inte i Sverige idag.

Grundläggningen av själva vallarna i ett gropvärmelager är alltså av största vikt för stabiliteten i hela konstruktionen. Släntstabiliteten i gropen under konstruktionsperioden är central, eftersom extra last läggs på släntkrönet, medan gropen ännu inte har fyllts med vatten. Utöver stabiliteten behöver även sättningarna beaktas särskilt där det påförs en extra belastning.

För att reducera behovet av schaktning, men ändå få tillräckligt stor volym på lagret, är en metod att bygga dammvall på släntkrönet runt den grävda gropen. Dammvallens uppströmssida och gropens insida täcks vanligen med ett vattentätt membran för att undvika läckage från lagret. Kan den omgivande dammvallen byggas med slaggrus från förbränningsanläggningen löser man såväl dammvallens materialfråga, som att man får en bra avsättning för det producerade slaggruset.

I rapporten diskuteras och analyseras vilka egenskaper som ska studeras för slaggrus som ska användas för dammvallar i den föreslagna applikationen. Det ges vidare förslag på hur dessa egenskaper kan kvantifieras med olika testmetoder, såväl i laboratorium som i fält.

Dammar och dammvallar byggs regelbundet för att tex skapa vattenmagasin eller för att skydda områden för översvämningar. I Sverige är det vanligt att sådana dammkonstruktioner byggs som fyllningsdammar av jord och sten. De byggs mindre ofta som homogena jordfyllningsdammar och mera ofta som zonerade dammar. I dessa har de ingående materialen olika egenskaper och olika funktion med målet att uppnå en tät stabil dammkonstruktion.

Den centrala delen av dammen är det parti som är vattentätt och detta skyddas av olika lager av filter för att minska risken för materialtransport och uppkomst av inre erosion. För att ge tillräcklig mekanisk stabilitet åt konstruktionen finns ytterst mer eller mindre stora stödbankar av grov sten för att skapa tillräcklig stabilitet.

Det vattentäta materialet ska ha sådan sammansättning att det går att packa på ett effektivt sätt för att porositeten i konstruktionen ska bli så låg som möjligt. Materialet ska vidare innehålla lämpliga mängder av partiklar av olika storlekar. Det ska finnas små partiklar (lera och/eller silt) mellanstora och stora. Syftet är att de mindre partiklarna ska fylla porerna mellan de grövre och därmed ge en mycket tät massa. Materialet ska alltså vara "månggraderat" och finkorniga moräner är bra exempel på sådana material. Andelen finjord är av stor betydelse för att få ett vattentätt material.

Material som saknar kornfraktioner helt eller delvis är svåra att packa tillräckligt väl för att uppnå en tillräckligt låg porositet med åtföljande täthet. Dessa kan ofta

även bli "instabila", vilket innebär att partiklarna i materialet får en möjlighet att förflyttas i strukturen till följd av en vattentrycksgradient. Partiklarna låser inte fast varandra tillräckligt effektivt när fraktioner saknas eller om det är för lite av någon. Sådan instabilitet är grunden för så kallad inre erosion.

I rapporten görs en genomgång av de olika lagrens funktion och nödvändiga egenskaper. Det konkluderas att slaggrus knappast har möjlighet att uppfylla nödvändiga krav på materialegenskaper för att kunna få en användning i de centrala delarna av en zonerad fyllningsdamm. Som stödfyllning kan materialet möjligen ha en användning.

Däremot kan materialet mycket väl användas för en dammvall där vattentätningen på uppströmssidan sker på annat sätt än med ett välpackat kornigt material. En sådan tätzon kan skapas med till exempel ett vattentätt membran (liner), vilket torde vara lämpligt att använda för att kunna nyttja slaggrus för uppbyggnad av vallar runt gropvärmelager.

I rapporten redovisas en litteraturgenomgång rörande egenskaperna hos slaggrus (MSWI) med tänkt användning för sådana vallar. På grund av den stora variationen i egenskaper hos slaggrus måste mera precisa studier genomföras för varje anläggning där gropvärmelager planeras. Den stora variationen har sin grund i sammansättningen av ursprungsmaterialet och de olika förbränningsanläggningarnas egenskaper, vilket sammantaget skapar variationen. Mera specifika och avgränsade egenskaper som är av särskilt intresse vid uppbyggnad av gropvärmelager har identifierats och testmetoder presenteras.

I en applikation av typen dammvall, kommer egenskaper som densitet, skjuvhållfasthet och friktionsvinkel samt permeabilitet (hydraulisk konduktivitet) att vara primärt avgörande för funktionen. För slaggruset måste de relevanta egenskaperna bestämmas för varje planerat projekt, eftersom standardvärden knappast kan identifieras på grund den stora variationen i slaggruset. Samtliga dessa egenskaper blir kopplade till densiteten hos slaggruset och således till hur välpackat materialet kan bli. Packningsegenskaperna blir därmed av betydelse. Hur materialet påverkas av att det fryser och tinar samt hur lätteroderat det är andra viktiga frågor.

Värmeförluster från ett gropvärmelager kommer att vara av största vikt för ekonomin och därför måste slaggrusets termiska egenskaper klarläggas med syftet att därigenom kunna beräkna värmeförlusterna. Dessa egenskaper behöver bestämmas för varje typ av använt slaggrus. De termiska egenskaperna blir beroende av materialets porositet i den färdiga konstruktionen samt hur fuktigt materialet är. Metoder att kvantifiera dessa egenskaper presenteras i rapporten, liksom hur dessa egenskaper kan beräknas baserat på information om slaggrusets densitet och vattenkvot.

Vid användning av slaggrus i dammvallar runt ett gropvärmelager är det inte möjligt att bygga dammvallarna som zonerade dammar. Frågan om att uppnå tillräckligt låg hydraulisk konduktivitet i slaggruset bedöms därför vara av underordnad betydelse. Användningen ligger i att slaggruset utgör ett stöd för en vattentät liner. Grunderna för hur hydraulisk konduktivitet bestäms i ett kornigt

material presenteras ändå i rapporten, liksom hur denna parameter kan uppskattas baserat på kornfördelning och porositet.

Slaggrusets mekaniska egenskaper är av central betydelse. Främst gäller detta dess packningsegenskaper. Metoder att bestämma dessa med laboratorieförsök presenteras, liksom hur det packningsresultat som uppnås i fält kan bestämmas och relateras till de laboratoriebestämda värdena. På detta sätt erhålls packningsgraden i fält. I litteraturgenomgången visas exempel på vilka torrdensiteter som kan uppnås, men även att det finns en risk för krossning av partiklarna om packningsarbetet är alltför intensivt. Slutsatsen blir att en bra kornstorleksfördelning på ursprungsmaterialet blir viktig för att packningsresultatet ska bli bra utan alltför kraftig packning.

Hållfastheten för korniga massor är relaterad till skjuvhållfastheten och möjligheterna för kornen att förskjutas i förhållande till varandra. Skjuvhållfastheten är beroende av spänningsnivån eftersom kornkontakttrycket blir avgörande för friktionen mellan de enstaka kornen. Låg spänningsnivå medför låg skjuvhållfasthet och hög spänning ger hög skjuvhållfasthet. Detta förhållande beskrivs med parametern friktionsvinkel, som är en avgörande storhet i alla stabilitetsanalyser. Detta gäller särskilt släntstabilitetsanalyser. Friktionsvinkeln bestäms i laboratorium med utrustningar av den typ som beskrivs i rapporten. Vanligen genom direkta skjuvförsök eller ännu hellre med triaxialförsök. För mycket grovkornigt material (>100 mm) är det bara direkta skjuvförsök som kan genomföras utan större ombyggnader av testutrustningar.

I rapporten redovisas att det i litteraturen beskrivs en variation i uppmätt friktionsvinkel mellan 24 och 59 grader. Detta är en mycket stor variation och detta har sin grund i att slaggrus kan vara av mycket olika typ. Som jämförelse kan anges att löst lagrad makadam har en friktionsvinkel på ca 30-35 grader och motsvarande för fast lagrad makadam är ca 36-40 grader. Sprängsten och andra mycket kantiga material kan ha friktionsvinkel över 45 grader. En viss vägledning av friktionsvinkelns storlek kan erhållas via kornfördelning och packningsgrad. I fallet slaggrus är nedkrossning av partiklar och dess kontaktpunkter av stor betydelse. Ju mera nedkrossningen fortgår, ju mera finkornigt blir materialet med en därmed åtföljande reduktion av friktionsvinkeln. Eftersom kornkontakttrycket avgör friktionen mellan partiklarna och därmed hållfastheten i massan, kommer ett eventuellt vattentryck i porsystemet att reducera kornkontakttrycket och därmed hållfastheten. Följden blir att ju högre vattentrycket är i porerna, ju lägre blir materialets skjuvhållfasthet. Konsekvensen blir att en bedömning av möjligheterna för vatten att dräneras ur dammvallen blir viktig för att rätt kunna bedöma hållfastheten och därmed stabiliteten.

Friktionsvinkeln avgör materialets hållfasthet, men material som belastas för spänningar lägre än denna deformeras också. Denna deformation kan, något förenklat, beskrivas med en elasticitetsmodul (E). Värdet på denna är, liksom skjuvhållfastheten, beroende av medelspänningsnivån. I rapporten presenteras publicerade värden på denna storhet, vilken varierar mellan 10-20 MPa till värden runt 100 MPa för medelspänningen 100 kPa. E-modulen kan alltså variera med minst en faktor 10. Värdet beror på materialets packningsgrad, partikelform, partikelstorlek, krossningsbenägenhet etc. och kan bara avgöras när aktuell

materialsammansättning och belastningssituation är känd. Värdet kan bestämmas i laboratorium eller uppskattas via fälttester.

Den hydrauliska konduktiviteten i ett material av typen slaggrus kommer att vara en funktion av porositeten, dvs packningsgraden eller torrdensiteten. Bra laboratoriemetoder för att kvantifiera parametern finns att tillgå och de beskrivs i rapporten. Svårigheten med laborietester är att få samma porositet på det testade materialet i laboratorium som man har i sin verkliga konstruktion. Men utrustning av olika typ finns att tillgå liksom storlek på utrustningen för att möjliggöra tester på grovkornigt material. Redovisade värden i litteraturen är sådana som motsvaras av värden för ren sand eller mera grusigt material. Det är alltså höga värden som presenteras. Metoder att beräkna hydraulisk konduktivitet utifrån porositet och partikelstorlek finns att tillgå, men variationen blir avsevärd.

En dammvall med en liner som tätande element på uppströmssidan kan vara känslig för inre erosion. En liten skada i linern kan medföra ett koncentrerat flöde av vatten genom dammvallen. Detta kan initiera inre erosion och därför bör materialets inre stabilitet klarläggas. Detta görs företrädesvis via metoder som baseras på kornstorlekssammansättningen. En metod som lyfts fram i rapporten är den av Kenney & Lau, som även vidareutvecklats av Rönnqvist (2010).

Ytererosion på dammens nedströmssida bör studeras med traditionella metoder och torde inte utgöra något stort problem för konstruktionen.

Dammvallar som byggs ovan mark, runt ett gropvärmelager, kommer att utsättas för höga temperaturer vid uppströmssidan och uteluftens temperaturer på nedströmssidan. I konstruktionen uppkommer således en tämligen stor temperaturgradient. Denna kommer att medföra omfördelning av fukt i konstruktionen, men betydelsen av detta för vallens funktion bedöms som marginell. Viktigare är den inverkan uteluften har på materialet på nedströmssidan. Under vinterhalvåret kan vi ha negativa lufttemperaturer och materialet på vallens nedströmssida kommer alltså att utsättas för växlande frysning och tining under samtidig stor temperaturgradient. Detta kan medföra frostsprängning av partiklarna med åtföljande förändringar av de mekaniska egenskaperna. Risken kan bedömas genom att genomföra laborieförsök av rutinartad karaktär.

Slaggrus (MSWI bottenaska) har hög urlakningspotential och därför måste de kemiska egenskaperna med tillhörande urlakningspotential klarläggas. Sannolikt behöver någon form av förbehandling genomföras för slaggruset. Väderpåverkan (luftning) är en förbehandlingsmetod som har låga kostnader och är enligt litteraturstudien effektiv för att minska rörligheten hos tungmetaller i slaggruset. Används liner på uppströmssidan för att uppnå vattentäthet, kommer lakningen av genomströmmande vatten att reduceras avsevärt. Lakningen kommer då att inskränka sig till lakning från nederbörd. Denna vattenmängd kan minskas om linern får täcka större delen av dammvallen och därigenom reducera kontakten mellan slaggrus och vatten samtidigt som en i stort sett vattentät vall erhålls.

En slutsats från den presenterade studien är att slaggrus (MSWI bottenaska) kan vara ett möjligt material att använda för att bygga vallarna runt ett gropvärmelager (PTES). Vallarna kan inte fås vattentäta med detta material, men kombineras det

med en vattentät liner på uppströmssidan uppnås avsedd funktion. Slutsatsen bygger på analys av flera fallstudier samt genomgång av slaggrusets generella egenskaper. Eftersom slaggrus är ett okonventionellt byggnadsmaterial behöver man i varje fall som utförs genomföra mera detaljerade studier av de egenskaper som beskrivits ovan. Tillgängliga utrustningar och metoder för dessa undersökningar presenteras i rapporten.

I rapporten presenteras vidare ett antal fallstudier där man undersökt hur slaggrus fungerar i olika konstruktioner, mestadels vägar.

Summary

The aim of the project has been to describe properties of the municipal solid waste incineration (MSWI) bottom ash and its potential to be used as construction material for pit thermal energy storage (PTES). Literature study of MSWI bottom ash properties has been conducted. Due to large variation in bottom ash properties based on origin material and incineration plants additional research has to be conducted. Specific properties that are of interest for PTES construction are determined and testing methods are suggested.

Properties like densities, shear strength and permeability will have to be determined. In addition it is also important to determine freeze-thaw characteristics of the material and erodibility. Thermal properties are also crucial, since thermal losses are of interest when considering PTES construction.

Foundation of the embankment is immensely important for the stability of the overall structure. Therefore it is important to determine engineering properties of the underlying soil. Slope stability of the pit during the construction process is a concern due to the additional load of the embankment. Also possible settlements under the additional load in the foundation need to be estimated.

MSWI bottom ash has high leaching potential therefore chemical properties and leaching potential of the specific material will have to be determined. In order to comply with legislation some sort of pre-treatment will most likely be necessary. Weathering is the most common pre-treatment practice. It has low costs and is effective in reducing mobility of heavy metals. Liners to cover the whole embankment can also be used to limit the contact of bottom ash with water.

It can be concluded from several case studies as well as general range of MSWI bottom ash properties that it is possible to use bottom ash for PTES embankment construction. Although, it should be taken into account that using an unconventional construction material presents some challenges.

List of content

Introduction	12
1 Description of intended thermal energy storage pit	13
2 Function of the embankment	15
3 Factors that may affect the embankment	16
3.1 Comparison to embankment dams	16
4 Engineering properties	19
4.1 Particle size distribution and classification	19
4.2 Compaction properties	21
4.3 Shear strength	22
4.4 Elastic modulus and settlement	22
4.5 Organic matter content	23
4.6 Hydraulic conductivity (Permeability)	23
4.7 Erosion resistance	24
4.8 Freeze-thaw resistance	25
4.9 Thermal properties	26
4.10 Constitutive model	27
5 Chemical properties and pre-treatment	29
5.1 Weathering	29
5.2 Recovery of metals	30
6 Case studies	32
6.1 MSWI bottom ash applications in Sweden	32
6.2 Umeå test road	32
6.3 Undisturbed samples from road sub-base	33
6.4 Raising of cardinal fly ash retention dam in USA	33
6.5 Experience from the Netherlands	34
7 Possible test methods and methodology	36
7.1 Particle size distribution	36
7.2 Density, particle density, natural water content	37
7.3 Compaction properties	37
7.4 Compressive strength	39
7.5 Permeability	39
7.6 Shear strength	39
7.7 Elastic modulus and settlement	41
7.8 Resistance to freeze-thaw cycling	42
7.9 Erosion resistance	42
7.10 Thermal properties	43
7.11 Leaching	43
7.12 Monitoring of the embankment after construction	45
8 Conclusion	47
9 References	48

Introduction

There are two main concerns regarding utilization of MSWI bottom ash in construction of an embankment. In general the release of heavy metals as well as sulphates and chlorides has been the main concern in management of MSWI bottom ash. Additionally the geotechnical properties of the material must be suitable for an embankment construction. It could be challenging to determine geotechnical properties of the MSWI bottom ash since they depend greatly on the waste used for incineration as well as the incineration facility.

This report focuses on laboratory investigation methods necessary for determining the properties of MSWI bottom ash, for the purposes of PTES embankment construction. The report also briefly touches upon the subjects of embankment foundation as well as monitoring. A literature study is conducted to present general variation of MSWI bottom ash properties. In addition case studies where bottom ash has been used as a part of different embankment constructions are presented.

1 Description of intended thermal energy storage pit

While energy production of most municipal solid waste incineration plants is constant throughout the year the demand for that energy fluctuates depending on the season. Therefore seasonal pit thermal energy storage (PTES) could be a good solution for temporary storage of surplus energy. Moreover the idea has been implemented numerous times in Europe in case of solar collector plants, where underground thermal energy storage is often used to accumulate energy produced in the summer and store it for the winter time. (de Guadalfajara, Lozano, & Serra, 2014)

Pit thermal energy storages are made of an artificial pool filled with storage medium and closed by an insulated lid. The shape of the excavated pit can usually be described as a truncated pyramid or cone. Naturally tilted walls of the pit can be heat insulated and then lined with a watertight welded liner. The storage is filled with water or gravel saturated with water. Since heat storage capacity for pits using water and gravel mixture is lower than for the ones using only water they will not be discussed further in this report. The insulated roof of the pit can be designed as self-supporting or floating on water. (Mangold & Deschaintre, 2012)

Costs of constructing pit thermal energy storage decrease with increasing storage volume. (de Guadalfajara, Lozano, & Serra, 2014). In addition to large PTES are not only more cost efficient but also have better thermal performance. Although all of the cases of pit storages should be looked at separately, due to differences in construction, there are some general problems that have occurred often.

Denmark has successfully implemented pit heat storages on numerous locations, which have been used to store surplus energy from solar collectors. The largest seasonal heat storage pit is located in the Danish town of Dronninglund. Storage is excavated in an old sand pit and the capacity of the pit is 203 000 m³. The lining of the pit was done by a German company GSE Lining technology. Maximum storage temperature of the pit is 95°C but is planned to keep temperatures around 80°C in order to prolong the life of the liner.

Long term pit thermal energy storage with water as a storage medium was constructed in Marstal, Denmark. Storage is shaped like a truncated pyramid with capacity of 75 000 m³. Storage was constructed by reusing the excavated soil from the lower part of the storage to construct an embankment around the pit. Same method could be modified in case soil from the excavation is not suitable for construction of an embankment, since a different material could be used. When considering construction of pit thermal energy storage for a municipal solid waste incineration (MSWI) plant, bottom ash from the same plant should be considered as a feasible material for the embankment construction. Schematic picture of Mastral type energy storage pit is presented in Figure 1 below. It can be seen that part of the storage is excavated and the other part consists of an embankment.

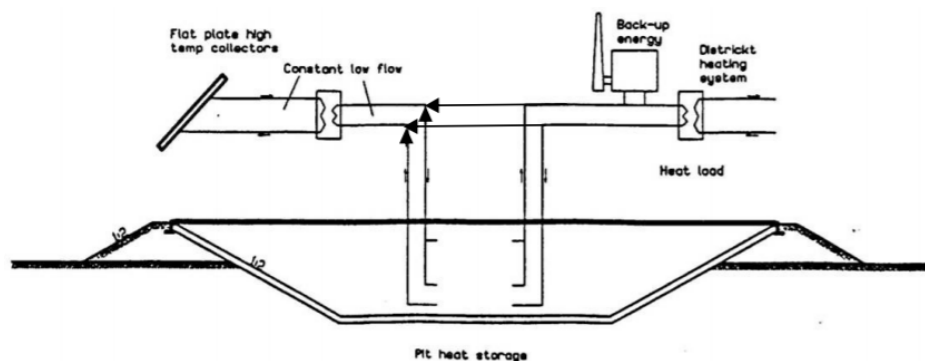


Figure 1. Schematic cross-section of a PTES (Harris, 2011)

Using MSWI bottom ash for part of the construction would have numerous benefits. Firstly, a lot of waste material would be utilized in the construction process, since material from several plants would most likely be needed. Secondly, as bottom ash has lower unit weight, compared to natural alternatives, loading on the foundation would be limited. In addition, using waste material already available at the plant should be more cost efficient compared to using natural material.

For each constructed PTES a study of existing conditions is needed with main focus on physical properties of the soil used for construction. Since planned storage will be constructed using MSWI bottom ash in addition to natural soil on location additional parameters must be determined in order to verify the stability of the construction as well as the cost effectiveness. Properties of MSWI bottom ash that are of interest will be further discussed in following chapters.

2 Function of the embankment

The embankment can be considered as an aboveground extension of the storage pit excavation. It must resist pressure exerted on it by the contained water. The embankment must also be light enough to limit the loading on the foundation.

Engineering properties of the MSWI bottom ash have to be determined to be used in further calculations. Therefore, optimal size and shape of the embankment has to be determined as well as the effect of embankment on the existing excavation. An additional weight of the embankment might decrease slope stability of the excavated pit.

While constructing an embankment out of waste material it must be made sure that there is minimal danger of contaminating the adjacent soil and groundwater. Necessary measures should be taken to limit the environmental effect of the embankment and it must be made sure that embankment complies with environmental regulations. There are multiple pre-treatment options as well as cover methods available in order to protect the environment from contamination.

When using bottom ash for construction of the pit thermal energy storage heat losses through the embankment should be taken into account. Therefore, total thermal losses and efficiency can be estimated. Heat losses through the embankment must be reduced to a minimum.

Regardless of the type of liner used, all PTES experience leakage problems. Taking previous experiences into consideration the embankment must be resistant to internal erosion in case of leakages. In case leakages occur the stability of the embankment must not be endangered.

The embankment constructed out of MSWI bottom ash must be resistant to temperature changes and freeze thaw cycling. Stability of the embankment must remain unaffected regardless of temperatures outside or inside the thermal energy storage pit.

3 Factors that may affect the embankment

It is possible to collect data about chemical and physical properties of MSWI bottom ash from previous studies but since properties of bottom ash vary between different countries and plants the values presented should be considered as a mere reference point. Properties of actual bottom ash used in the project should be determined in the next research phase and design of a potential project should be based on those.

As properties of MSWI bottom ash depend greatly on the used waste a lot of variation can be seen in chemical composition and physical properties. This vary from country to country. In addition material properties of MSWI bottom ash are not constant over the full service life time. In short term they will change during production, storage, transport and placement. In long term they will change under the combined effects of loading conditions, ageing, climate and additives (Lindquist & Frogner Kockum, 2016).

3.1 COMPARISON TO EMBANKMENT DAMS

Every embankment dam is designed to suit the topographical and foundation conditions of the site and to use available construction material. Therefore, no standard design for embankment dams exists. An embankment dam with a zoned cross-section can include some or all of these zones: earthfill, fine filter, coarse filter, upstream filter, filter under rip rap, fine cushion layer, coarse cushion layer, rockfill, coarse rockfill, rip rap. Each of these sections has a specific purpose and aids in achieving a stable dam construction based on existing conditions. Functions of each zone can be seen in table 1 as described by Fell. Placement of some of the zones can be seen in Figure 2 (Fell, MacGregor, Stapledon, & Bell, 2005)

Table 1. Zones of an embankment dam (Fell, MacGregor, Stapledon, & Bell, 2005)

Zone	Description	Function
1	Earthfill ("core")	Controls seepage through the dam
2A	Fine filter (or filter drain)	(a) Controls erosion of Zone 1 by seepage water, (b) Controls erosion of the dam foundation (where used as horizontal drain), (c) Controls buildup of pore pressure in downstream face when used as vertical drain
2B	Coarse filter (or filter drain)	(a) Controls erosion of Zone 2A into rockfill, (b) Discharge seepage water collected in vertical or horizontal drain
2C	Upstream filter Filter under rip rap	Controls erosion of Zone 1 into rockfill upstream of dam core Controls erosion of Zone 1 through rip rap
2D	Fine cushion layer	Provides uniform support for concrete face; limit leakage in the event of the concrete face cracking or joints opening
2E	Coarse cushion layer	Provides uniform layer support for concrete face. Prevents erosion of Zone 2D into rockfill in the event of leakage in the face
1-3	Earth-rockfill	Provides stability and has some ability to control erosion

Zone	Description	Function
3A	Rockfill	Provides stability, commonly free draining to allow discharge of seepage through and under the dam. Prevents erosion of Zone 2B into coarse rockfill
3B	Coarse rockfill	Provides stability, commonly free draining to allow discharge of seepage through and under the dam
4	Rip rap	Controls erosion of the upstream face by wave action, and may be used to control erosion of the downstream toe from backwater flows from spillways

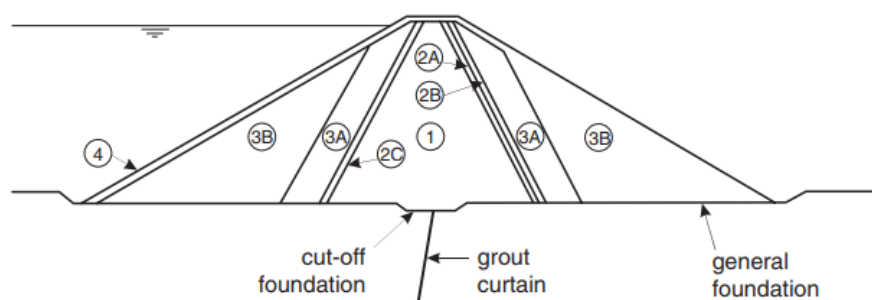


Figure 2. Schematic cross-section of an earth and rockfill dam (Fell, MacGregor, Stapledon, & Bell, 2005)

For construction of a core of a dam, very fine material with low hydraulic conductivity is used in order to control the seepage through the embankment. Common materials are: Clay, sandy clay, clayey sand, silty sand. Material is often described in terms of particle size distribution. It is desirable that at least 15% of the material would pass 0,075 mm sieve. Material and geometry of the core is dependent on tolerable seepage losses as well as other materials chosen for the construction of the dam. For example core material has usually less shear strength than the rest of the embankment and therefore a narrower core would provide better stability. On the other hand a thicker core would provide better resistance to differential cracking. This phenomena may lead to piping. (Fell, MacGregor, Stapledon, & Bell, 2005)

Filters in embankment dams and their foundations perform two basic functions. Firstly, they must prevent erosion of soil particles from the soil they are protecting. Secondly, they must allow drainage of seepage water. Filters are usually described in terms of particle size distribution. They must be sufficiently fine compared to the particle size of the soil they are protecting to prevent erosion. Simultaneously they must also be sufficiently coarse to allow drainage of seepage water. (Fell, MacGregor, Stapledon, & Bell, 2005)

It can be concluded that embankment in the context of the PTES is not a dam construction. While it retains water it does not have a sectioned cross-section, neither does it have controlled seepage trough the embankment. PTES embankment is protected by a liner on the inside. Therefore, flow of water inside

the construction is avoided. Absence of different zones in the construction simplifies the design and construction process. Embankment that uses only one material for construction is more similar to a road embankment than a dam in its application.

The main research focus concerning MSWI bottom ash has been on use of the material in road embankment construction. Most studies regarding MSWI bottom ash engineering properties were conducted between 2000 and 2010. Basic material properties like compaction, density and strength have been widely researched and there is a lot of data available. Properties that are not always relevant to road construction such as thermal properties and erodibility are only briefly mentioned in a few studies.

4 Engineering properties

This chapter will further discuss properties of MSWI bottom ash and factors that might affect them, based on previous studies and experiences. In regard to the embankment construction there are two main aspects that might raise concern. Engineering properties of MSWI bottom ash as well as soil that will serve as foundation for the embankment; this will help to determine the feasibility of the design.

4.1 PARTICLE SIZE DISTRIBUTION AND CLASSIFICATION

MSWI bottom ash looks like grey-black sandy gravel, it can also be noticed that particles have a porous texture. Gradation and shape of the bottom ash particles affect the compaction properties, shear strength and hydraulic conductivity of the material. Well graded aggregate includes particles of wide range of sizes and therefore it forms less voids during compaction. Compaction also causes angular particles of well graded material to interlock and thus increase the stability and shear strength of the matrix. Therefore it is important to monitor the shape of the particles as well as the size. More flat elongated particles may break under stress while more round particles are difficult to interlock and therefore give a lower degree of compaction. Well graded material would also make the embankment more resistant to erosion as it would be more difficult for water to transport smaller particles through the voids in the construction.

Particle size distribution of bottom ash varies from country to country but generally the particles are up to 60 mm in size. As an example particle size distribution of MSWI bottom ash from Son Reus incinerator in Mallorca can be seen in Figure 3 as it covers a range between sand and gravel. (Forteza, Far, Seguí, & Cerdá, 2004)

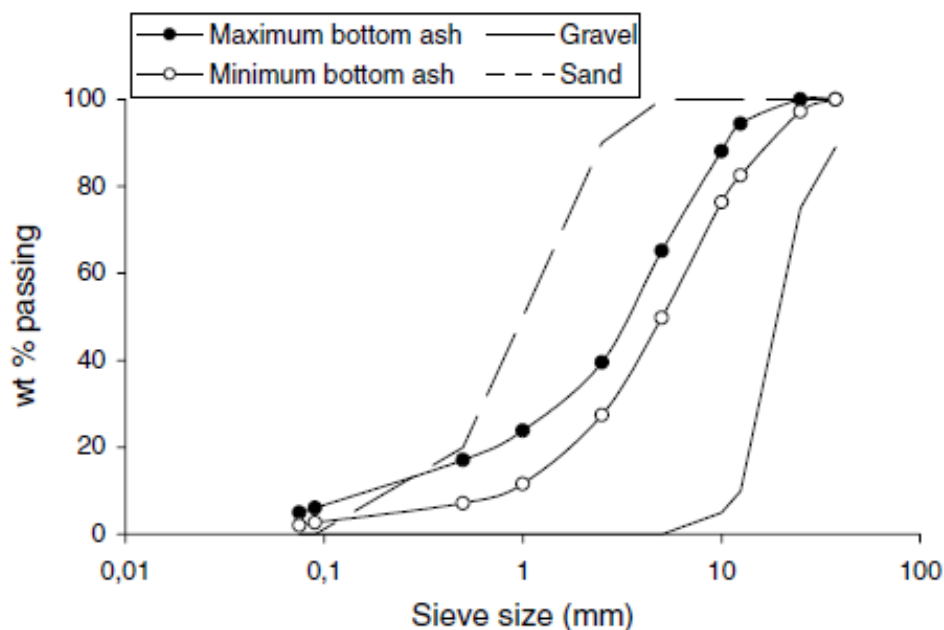


Figure 3. Highest and lowest size distribution curves obtained for bottom ash compared with typical curves for sand and gravel (Forteza, Far, Seguí, & Cerdá, 2004)

In general, bottom ash (MSWI) has previously been classified in the Unified Soil Classification System (USCS) as SW (well graded sands), SM (silty sand) and SP-SM (poorly graded sand with silt). With AASHTO system bottom ash has been classified as A-1 category, which is associated with “excellent to good” subgrade rating. Non-plastic behaviour has been reported for bottom ash which might benefit its shear strength properties. (Lynn, Ghataora, & Dhir, 2017)

Grain size distribution of the bottom ash can also be altered by crushing, sieving or washing of the bottom ash. This might help to improve compaction properties of the material, although any kind of pre-treatment of the bottom ash will result in additional costs. Initial as well as treated material will have to be tested in order to determine the effect of treatment on the final stability of the construction.

A previous study has compared MSWI bottom ash to limestone aggregate of similar fraction. There were two types of bottom ash used: crushed as well as sieved and washed. Looking at particle size distribution curves in Figure 4, comparison between bottom ash and limestone can be seen. It is clear that crushed limestone 2/6 and bottom ash 0/6 are within the same range. Only the fraction smaller than 1 mm is more present in the bottom ash 0/6. The crushed fraction of bottom ash has in general more fines than sieved and washed fraction. This is most likely due to dust generation during crushing. (Van den Heede, o.a., 2015)

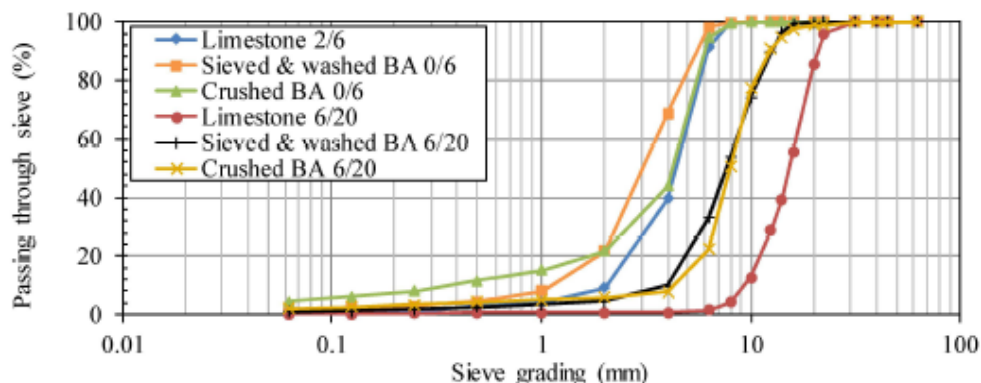


Figure 4. Comparison between aggregate type (limestone vs. bottom ash) and MSWI bottom ash pre-treatment (sieving and washing vs. crushing) on particle size distribution (Van den Heede, o.a., 2015)

It has been also noted that particles tend to deteriorate under stress (Lynn, Ghataora, & Dhir, 2017). Therefore effect of shear and compressive stress on the material particle distribution should be investigated. The chapter on compatibility discusses the problem of deterioration in more detail.

4.2 COMPACTION PROPERTIES

Compaction is the process of increasing the density of soil (bottom ash) by packing the particles closer together with a reduction in volume. In construction of embankments soil is generally placed in layers ranging 75-450 mm in thickness. Each layer is compacted by means of rollers, vibrators or rammers. In general the higher the degree of compaction the higher the shear strength and lower the compressibility of the soil will be (Knappett & Craig, 2012).

Degree of compaction of soil is measured in terms of dry density- mass of solids per unit volume of soil. MSWI bottom ash samples have achieved a good degree of compaction. Optimum moisture content for the material varies from 12%-19% with maximum dry densities 1200-1800 kg/m³. Dry density of the material is similar to values given for silty sands, heavy clays and coal fly ash. Although, it is lower than natural sand and gravel. (Lynn, Ghataora, & Dhir, 2017) (Crillesen & Skaarup, 2006)

Dynamic compaction tests revealed degradation of the larger particles under compaction, with 18% reduction in fraction > 4,75 mm. This trend decreases with the decrease of particle size with only 2,5% reduction of fraction < 0,075 mm (Lynn, Ghataora, & Dhir, 2017). This should be taken into account when assessing the grading of the material as the material will have to be compacted using dynamic compaction during construction of the embankment.

Since all of the mechanical properties of the bottom ash are dependent on the degree of compaction, it is especially important to monitor these changing relationships in order to facilitate the most optimal design considering material properties and cost. Degree of compaction should be investigated in relation to the

gradation and water content of the material. Other properties such as density, void ratio, shear strength etc. should be investigated in relation to degree of compaction.

4.3 SHEAR STRENGTH

Shear resistance of the soil is a result of friction and interlocking of the particles. Before shear failure can take place, the interlocking of particles must be overcome in addition to frictional forces at contact points of particles. In general greatest degree of interlocking is achieved using very dense, well-graded soils consisting of angular particles (Knappett & Craig, 2012). Shear strength of the MSWI bottom ash is a particularly important characteristic in design to avoid slope failures of the embankment.

When the PTES is operational shear failure on the upstream faces of the embankment is unlikely, as water contained in reservoir exerts additional pressure onto the pit walls. However, special attention should be paid to downstream faces of the embankments, as well as the storage pit itself during the construction period. When the reservoir is empty shear failure is more likely to occur on the upstream side, especially when the load exerted by the embankment onto the foundation is taken into account.

Shear strength properties of MSWI bottom ash have been assessed with direct shear and triaxial testing. Variation of friction angles of the material have been reported from 24° up to 59° , with average being around 45° . Generally high reported values in friction angles are likely due to the angular shape of the particles (Lynn, Ghataora, & Dhir, 2017). Dilatancy and critical void ratio of the material should also be estimated as these properties could indicate potential decrease in shear strength during construction and application.

In addition an equation has been developed for estimating the friction angle of the bottom ash based on its chemical composition. Mainly the Al_2O_3 and Fe_2O_3 contents can serve as a useful tool in design process. Using average values of Al_2O_3 and Fe_2O_3 from literature an average friction angle of 46° has been determined. This corresponds quite well with friction angles found through testing. Therefore it might prove to be a useful tool for initial approximate estimation of friction angle (Lynn, Ghataora, & Dhir, 2017).

4.4 ELASTIC MODULUS AND SETTLEMENT

Elastic modulus is a measure of soil stiffness; it is defined as ratio of stress along an axis over strain along the same axis. Elastic modulus is useful when estimating soil settlement (Knappett & Craig, 2012). In further research the elastic modulus of the foundation of the embankment should be determined. With construction of the embankment, load on the foundation will increase and settlements are to be expected. Possible extent of the deformations should be estimated as it will affect the stability of the PTES. MSWI bottom ash is lighter than sand or gravel materials, which may reduce the settlement in use due to the lower normal stresses caused by self-weight. (Lynn, Ghataora, & Dhir, 2017)

There are some substantial differences between reported values of elastic modulus. This can be partly due to use of drained and undrained conditions as well as load application with confining pressures ranging from 35 to 500 kPa. Elastic modulus increase with increasing confining pressure. At confining pressure of 100 kPa results of 60 MPa, 90 MPa and 35 MPa have been reported in two studies (Becquart, Bernard, Abriak, & Zentar, 2009) (Cosentino, Kajlajian, Heck, & Shieh, 1995). At lower confining pressures MSWI bottom ash reached a stiffness similar to loose or silty sand (10-20 MPa). At upper end of the tested pressure it reached a stiffness that can be compared to very dense sand (100-200 MPa) (Lynn, Ghataora, & Dhir, 2017). While not explicitly reported in the studies, differences in elastic modulus could also occur due to different degrees of compaction of the material. During the compaction process the amount of voids between the particles decreases. Therefore, possible settlements, as a result of loading, will decrease as the elastic modulus is increased. Stress strain relationship of the material should be investigated in relation to the degree of compaction.

There are several variations of E-modulus that can be used depending on the application, chosen constitutive model and testing methods used to determine the modulus. The elastic modulus is one of the more popular moduli to describe stress-strain relationship of soil. There are also several other parameters that could be used to describe occurring settlements, separately or in combination with E-modulus. For example Poisson ratio describes change in volume of soil during loading and shear modulus describes the materials response to shear stress.

4.5 ORGANIC MATTER CONTENT

Amount of organic matter content of the material affects numerous mechanical properties. Residual organic matter remaining in MSWI bottom ash after the combustion process can potentially lead to negative impacts on density, stiffness, shear strength and increased risk of degradation of the material over time (Knappett & Craig, 2012). Loss of ignition tests are used to provide an estimate of organic fraction by comparing the difference in mass of samples before and after ignition. Based on previous studies organic matter content, from loss of ignition, for bottom ash ranges from 1% to 15%, with mean value of 5% (Lynn, Ghataora, & Dhir, 2017). The European Union has set a threshold of 5% for all of MSWI bottom ash (Directive 2010/75/EU of The European Parliament and of the Council, 2010).

4.6 HYDRAULIC CONDUCTIVITY (PERMEABILITY)

Hydraulic conductivity primarily depends on the average size of pores, which in turn is related to particle size distribution, particle shape, degree of compaction and soil structure. Generally, the smaller the particle, the smaller is the average pore size and the lower is the Hydraulic conductivity (Head, 2006). Low permeability of the compacted MSWI bottom ash would be desirable as in case of a leak from the reservoir the possibility of erosion would be reduced.

There is a large variation in reported values of hydraulic conductivity as the results are very sensitive to the moisture changes, material grading and related degree of compaction. Recorded hydraulic conductivity of the material ranges from 2×10^{-9} to

$6,8 \times 10^{-4}$ m/s. In general, hydraulic conductivity of bottom ash falls into the same category as similarly graded natural soils (Lynn, Ghataora, & Dhir, 2017). Recorded range of hydraulic conductivity of bottom ash corresponds to “clean sands and gravel mixtures” on higher end and “un-fissured clays and clay-silts” on the lower end (Knappett & Craig, 2012).

Hydraulic conductivity of the material should be investigated further in relation to degree of compaction and water saturation. Generally, the higher the degree of compaction, the lower is the hydraulic conductivity. The higher the degree of saturation the higher the hydraulic conductivity (Lambe & Withman, 1969).

The effect of temperature on hydraulic conductivity should also be investigated as water inside the embankment can be transported due to temperature gradients. Under a large temperature gradient the movement of water from warmer regions to the colder, may lead to significant differences in the material moisture content and therefore correspondingly other mechanical properties. In addition temperature changes in material with low hydraulic conductivity can induce excess pore pressure and increase in effective stress. This can then affect stability of the embankment (Lambe & Withman, 1969). As this can lead to stability problems it is important that this effect is investigated for both the embankment as well as for the foundation material.

4.7 EROSION RESISTANCE

In most constructed PTES, leaks in liners were detected in the initial stages of operation. In most cases initial leakage could be solved (de Guadalfajara, Lozano, & Serra, 2014). Therefore, it is essential to investigate how a breach in the liner would affect the function of the PTES. No studies concerning the erosion of MSWI bottom ash have been found.

Leakages might present problems for a PTES which is partly constructed out of MSWI bottom ash. There are several aspects that raise concern in case a leak develops in the embankment constructed out of bottom ash. An additional source of leachate is created, as water is seeping through the embankment. Secondly, a leak might lead to internal erosion of the embankment and even failure, especially if the soil is poorly graded and compacted.

When looking at construction methods of other PTES it can be seen that in most cases a layer of sand and geotextile is installed under the watertight liner. These two layers serve two different purposes. Firstly, sand protects the liner from punctures in case there are sharp particles in the material. Secondly, in case of a leak the sand layer can act as a filter, providing possibilities for the material to self-healing.

In addition the surface of the embankment must also be resistant to erosion if left uncovered. Even if the embankment will be covered when finished, it is important to account for possible surface erosion of the embankment during the construction process.

Many criteria for assessment of internal stability of dams have been developed. Most of these criteria rely on investigation of the gradation curve to detect

deficiency in particles of certain ranges. One of the more common criteria is Kenney and Lau method. It is based on studying the lower parts of the gradation curves. If the curve is gently inclined migration of small particles is more likely to occur. The method evaluates mass increment F between particle size D and $4D$, relative to mass of fraction smaller than D , called F . The boundary between stable and unstable material has been identified as $H = 1.0F$ by Kenney and Lau. For widely graded material evaluation range of the curve is from 0-20%. Methodology for establishing $H:F$ curve is shown in Figure 5. (Rönnqvist, 2010)

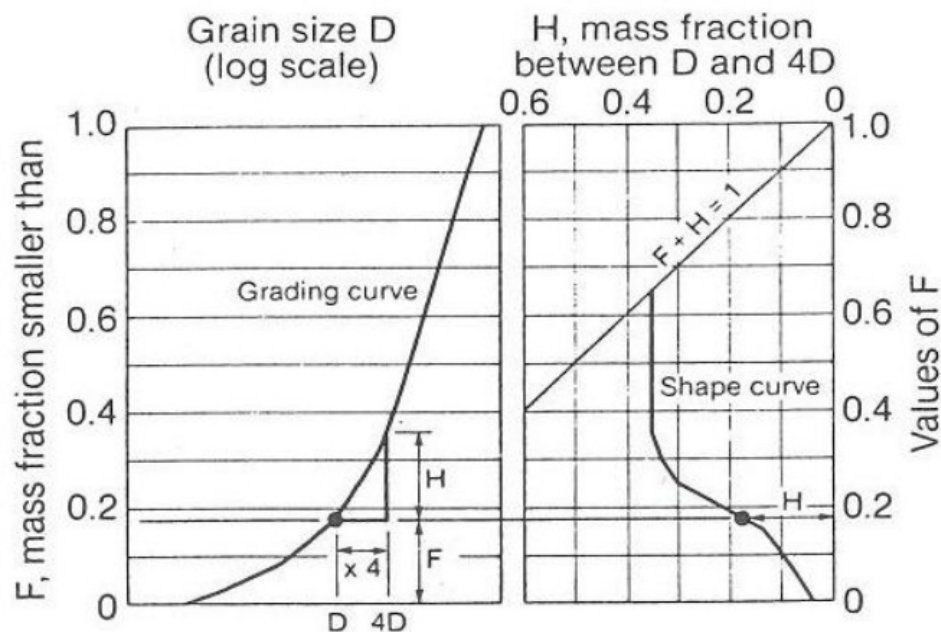


Figure 5. Establishing of $H:F$ curve (Rönnqvist, 2010)

4.8 FREEZE-THAW RESISTANCE

Resistance to freeze-thaw cycling is an important characteristic for any granular material that will be subjected to weathering in a climate where temperatures regularly fall below 0°C . As temperatures decrease, the water present in the pores and cracks of the material, freezes and expands. This breaks the structure, with each following cycle the degradation of the material will continue. Freeze thaw resistance is affected by the structure of the material, more open pores generally means less resistant material. Higher moisture content would also result in lower freeze-thaw resistance.

A study published in Baltic Journal of Road and bridge engineering studied MSWI bottom ash from Lithuania for the purposes of road construction. Among other parameters bottom ash was tested for freeze-thaw resistance according to EU standard EN 1367-1. MSWI bottom ash fractions of 2/4, 4/8, 5/11, 11/22 were tested. The smaller the fraction, the larger the loss of mass of the specimen. Loss of mass varied between 12,7-10,4% which would mean that bottom ash is moderately susceptible to freeze-thaw cycling. Larger decrease in weight means worse freeze thaw resistance (Vaitkus, Grazulyte, Vorobjovas, Sernas, & Kleiziene, 2017).

Even if the bottom ash is not highly resistant to the effects of freeze thaw cycling this does not automatically mean that the material is unsuitable for the construction or that the embankment structure might develop weaknesses during its lifetime. There are multiple factors that will affect the freeze-thaw resistance of the dam as a whole. Since the bottom ash will be compacted, the hydraulic conductivity of the material will be quite low. Therefore, top layers of the embankment will mostly be affected by freeze-thaw cycling as the moisture content will be higher. The upper layers of the embankment will act as insulation, protecting the centre from low temperatures and moisture. It should also be taken into account that the PTES will exert heat that will raise the temperature of the bottom ash embankment to some extent, therefore protecting part of it from freezing.

Installing a liner or a blanket on the downstream face of the dam to protect the structure from precipitation would also improve the freeze-thaw resistance of the material. Some leaks and accumulation of moisture in the liner can be expected but general moisture content of the material should be decreased over time.

It is important to investigate to which depth the frost front would penetrate the embankment in relation to the outside temperature. The high temperature inside the PTES should be taken into account. Degradation of bottom ash particles should also be studied as a function of water content rather than studying the frost susceptibility of only saturated material. Thawing processes in the material should also be investigated. The speed of thawing and release of free water from the process should be looked into. Since the embankment will have relatively low hydraulic conductivity, accumulation of free water in the construction could lead to decreased stability.

4.9 THERMAL PROPERTIES

Thermal losses have always been a concern regarding pit storages. Based on operational pits thermal losses they are around 30% which is over 100% higher than what has been designed for or simulation values. This has generally been due to the fact that very low value of thermal conductivity was used for the insulation material and it was not taken into account that thermal conductivity of the insulation material increases with increased moisture (de Guadalfajara, Lozano, & Serra, 2014)

When using bottom ash as the main construction material thermal properties of the bottom ash should also be investigated. Having this information, the thermal losses through the embankment can be calculated.

Within the first few years of operation the soil around the storage pit excavation would warm up and act as insulation for the thermal energy storage as it is not as affected by outside temperatures (Mangold & Deschaintre, 2012). On the other hand the embankment portion of the pit is greatly affected by outside temperatures as it has a larger surface area exposed to the elements: air, temperature and precipitation. Also as a rule thermal conductivity of soil increases with increasing moisture content, therefore it is necessary to keep the material as dry as possible.

As MSWI bottom ash has a porous texture the heat loss is smaller compared to conventional embankment construction materials. When thermal properties of the bottom ash are determined a thermal analysis should be performed. Variation of temperatures outside as well as inside the pit can be accounted for and potential heat losses through the embankment can be estimated.

Due to its porous nature bottom ash has better insulating properties than gravel or sand. Heat conductivity of Swedish bottom ash has been assumed to be 0,2-0,5 W/m, K, at natural water content. Heat conductivity increases with increased water content (Andersland & Ladanyi, 2004). Lower thermal conductivity of MSWI bottom ash would mean less heat losses through the embankment.

Many exothermic reactions such as depolymerisation and oxidation occur during landfilling of the bottom ash. This may cause for temperatures to rise up to 90°C. Therefore it can be assumed that if bottom ash is not affected by the temperature increase caused by chemical reactions it will also not be affected by high temperatures inside the PTES. As the bottom ash itself is not affected by elevated temperatures liners covering the construction may be. (Klein, Nestle, Niessner, & Baumann, 2003).

Thermal conductivity of the surrounding soil should also be taken into account. It takes time to heat up a large volume of soil around the pit and correspondingly decrease its moisture content. If there is dry soil around the excavation this will be a part of the insulation and help to reduce the heat losses (de Guadalfajara, Lozano, & Serra, 2014).

In the future investigations thermal conductivity of MSWI bottom ash should be investigated further as only one study concerning the matter was found. Thermal conductivity and volumetric heat capacity of the material should be determined in relation to moisture content. It is reasonable to assume that cross section of the embankment will have a variation in moisture content. Therefore, it should also be assumed that different sections of the embankment will have different thermal properties. (Andersland & Ladanyi, 2004)

4.10 CONSTITUTIVE MODEL

Mechanical behaviour of MSWI bottom ash could be modelled to various degrees of accuracy. Numerous constitutive models exist to model stress-strain behaviour of soils. Precision of such analyses depend on the accurate representation of stress and strain relationship of the material as well as accuracy of the parameters chosen for modelling (PLAXIS 2D Material Models Manual, 2018).

A suitable constitutive model to describe the material behaviour should be chosen based on the measured properties of the material, after which it is possible to conduct numerical analysis of the structure and therefore predict the possible behaviour of the embankment. Two most commonly used constitutive models are Mohr-Coulomb (MC) and Hardening soil (HS) model, with HS being the most advanced and also require most input parameters. It can be seen in Figure 6 that HS model represents the stress-strain behaviour of the soil more accurately.

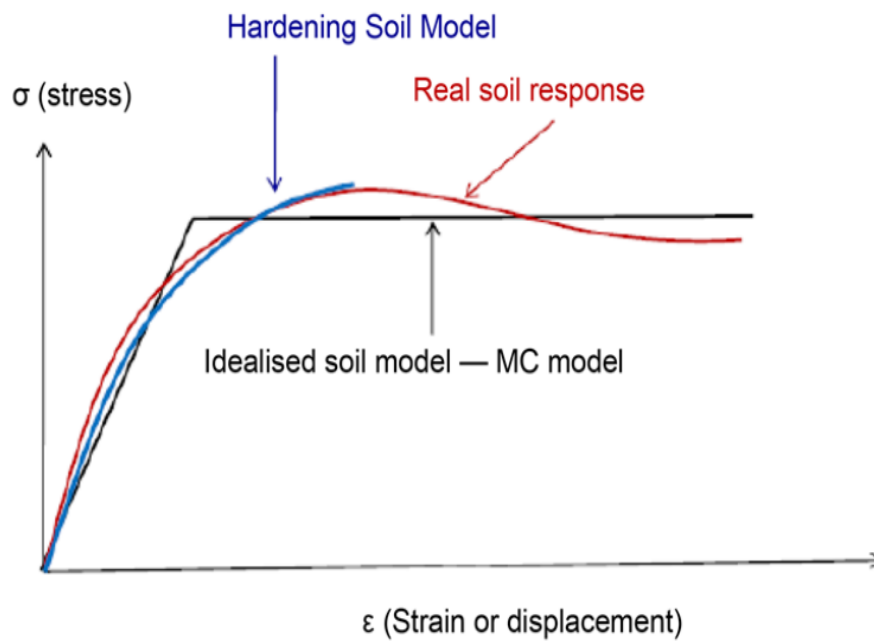


Figure 6. Hardening Soil and Mohr-Coulomb model compared to real soil behaviour

5 Chemical properties and pre-treatment

One of the main environmental concerns using MSWI bottom ash is the long-term leaching and transport of heavy metals into the environment. Concentrations of potential contaminants such as Cu, Pb and Zn in the bottom ash are in the range of g/kg.

Components that might be environmentally critical during utilization of bottom ash as construction material must be identified based on previous recorded experiences. Components can be considered critical if they fulfil at least one of the following criteria: they exceed regulatory leaching limits or they are released from bottom ash in higher concentrations than from conventional construction material during application.

It is possible to decrease the leaching potential of MSWI bottom ash by using pre-treatment methods. Depending on the plant that produces the bottom ash many of these technologies may already be applied beforehand. For example Sysav incineration plant uses sifting for separation of particles larger than 45 mm, magnetic and non-magnetic metals are also separated as well as plastic after which the bottom ash is weathered (Sysav, 2011). Following two chapters will discuss weathering and metal recovery in greater detail as these two methods can be considered more impactful regarding the chemical properties.

5.1 WEATHERING

Main problem with most bottom ash treatment methods are the high investment and operating cost. In many EU countries weathering of bottom ash for 1-3 months before the utilization is commonly used due to low costs of the operation. While storing the bottom ash outside many chemical reactions can occur making the metals and metalloids less reactive. Oxidation, carbonation and neutralization of pH are some of the reactions that can occur while weathering (Chimenos, Fernández, Nadal, & Espiell, 2000). In table 2 data obtained from the bottom ash leachate with different ripening times is seen. It can be seen that concentration of some metals (and metalloids) in the leachate drops after 30 days of weathering and continues to decrease with time. Also pH drops from 12,6 to 10,7 within 165 days. It has been assumed that pH of the leachate is controlled by solubility of $\text{Ca}(\text{OH})_2$. Most significant changes can be observed for Ca and Pb concentrations. The decrease in calcium concentration is mainly due to formation of calcite (CaCO_3) and ettringite ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12}\cdot 26\text{H}_2\text{O}$) (Forteza, Far, Seguí, & Cerdá, 2004). Leachability of many metals is not affected by weathering, therefore necessary measures should be made to decrease the risk of soil and groundwater contamination, for example in the form of liners.

Table 2. Evolution of content of metals in bottom ash leachate. Bottom ash particles smaller than 50 mm, from Son Reus incinerator in Mallorca (Forteza, Far, Seguí, & Cerdá, 2004)

Leachates	Starting	30 Days	90 Days	165 Days
pH	12,6	11,3	11	10,7
Conductivity (mS/cm)	4,49	1,78	1,83	1,47
Chlorides (mg/l)	181	190	247	200
Sulphates (mg/l)	66	102	192	198
Al (mg/l)	0,3	70	123	134
As (µg/l)	<8	<8	<8	<8
Ca (mg/l)	404	51	170	185
Cd (µg/l)	<3	<3	<3	<3
Cr (µg/l)	<75	78	140	84
Cu (µg/l)	898	822	728	564
Fe (mg/l)	<0,5	<0,5	<0,5	<0,5
Hg (µg/l)	<7	<7	<7	<7
K (mg/l)	65	70	76	53
Mg (mg/l)	<0,5	<0,5	<0,5	<0,5
Mn (µg/l)	<60	<60	<60	<60
Na (mg/l)	158	177	168	144
Ni (µg/l)	<40	<40	<40	<40
Pb µg/l)	1698	<100	<100	<100
Sn (µg/l)	<250	<250	<250	<250
Zn (µg/l)	<200	<200	<200	<200

5.2 RECOVERY OF METALS

Metallic fraction of the bottom ash can be recovered. Since metals are a valuable resource European countries have been making an effort to separate metals from bottom ash. Based on electrical and magnetic properties of different metals, it is possible to recover ferrous and non-ferrous metal through magnetic and eddy current separators respectively (Xia, He, Shao, & Zhang, 2016).

In studies advanced methods for metal recovery have reached recovery rates of 83% and 73% for ferrous and non-ferrous materials respectively. However, generally recovery rates for ferrous metals have been significantly higher compared to non-ferrous metals (Muchová & Rem, 2006). Around 57%-83% of ferrous metals can be recovered while only 30% of aluminium and 35% of other non-ferrous metals (mainly Cu and Zn) can separated using commonly available technology (Xia, He, Shao, & Zhang, 2016).

The chemical analysis of bottom ash from many countries around the world has shown that the finest fraction (<2mm) contributes a significant proportion of heavy metals and soluble inorganic salts (Chimenos, Fernández, Nadal, & Espiell, 2000). Therefore by removing the fines from the material the amount of heavy metals is also reduced.

By increasing the rate of non-ferrous metal recovery, risk of leaching of heavy metals into adjacent ground and contamination of ground water is reduced. In addition recovery of larger pieces of metal would reduce the possibility of the PTES liner to be punctured. If metal recovery is not already being performed at the incineration plant the costs of the procedure may outweigh the benefits. The liner of the pit can also be protected by installing a thin layer of sand in between the liner and bottom ash. While washing of the MSWI bottom ash would reduce the content of fines and therefore heavy metals, it would also increase the hydraulic conductivity of the material which might make it more susceptible to erosion.

6 Case studies

Previous experiences with MSWI bottom ash help to understand the changes in properties over the years as well as in different applications and levels of exposure. Most common application of bottom ash is as a sub-base in road embankment. In Sweden bottom ash has been only used in test road stretches for research purposes.

6.1 MSWI BOTTOM ASH APPLICATIONS IN SWEDEN

As mentioned before there have been few applications of bottom ash in Sweden in the form of test roads. Since roads are constructed in Sweden it is possible to see the effect of the climate on the bottom ash as well as assess the leaching potential throughout the years of use. It should be accounted for that the embankment for PTES does not experience dynamic loading (only during compaction process) and in case of the embankment a static load is applied to the upstream slope of the embankment by the water. Also since the height of PTES embankment is greater than that of a road the load on the foundation and lower layers of the embankment will be higher. In addition as the road has an almost impermeable asphalt cover only the sides of the road are affected by precipitation, in case of the PTES embankment it is unknown at this point how much of the construction will be left uncovered.

6.2 UMEÅ TEST ROAD

Bottom ash originating from Däva power plant near Umeå was used to build a test road near Umeå. Leachate sampling lysimeters were installed under two road stretches. One of the stretches was constructed using bottom ash as sub base layer and the other using conventional gravel for comparison, thickness of the layers 420 mm. MSWI bottom ash was weathered outdoors for the duration of 6 months before the construction (De Windt, Dabo, Lidelöw, Badreddine, & Lagerkvist, 2011). Sampling was carried out 21 times between October 2001 and 2004 (Todorovic', 2006).

During the first two months of the experiment leachates from the road constructed using bottom ash had 2-3 orders of magnitude higher release of easily soluble salts Cl, K, Na and 2 orders of magnitude higher release of Cu compared to the road constructed with gravel. During the 3 years of utilization the composition of leachate from the bottom ash became more similar that of the conventional road. Nevertheless concentrations of Al and Cr stayed relatively unchanged in the bottom ash leachate, 2 orders of magnitude higher than gravel. After 3 years pH from bottom ash leachate was still high, 11.69 (Todorovic', 2006).

The study shows that after three years in application the leachate concentration of the material start to decrease and become more similar to those of a natural material. Another study, from Spain, has also concluded that after two years of test road operation most of the constituents in bottom ash are depleted (Izquierdo, Querol, Vazquez, Josa, & Lopez-Soler, 2005). This further confirms that most of the leaching occurs in the first few years of application. Concentrations and rate at

which the potential contaminants are being released can be predicted. Therefore, range of possible contaminated area can be calculated and the environmental effect assessed.

6.3 UNDISTURBED SAMPLES FROM ROAD SUB-BASE

MSWI bottom ash in this study was part of a 60 m long road stretch, which was sampled eight years after construction. The objective was to obtain a sample with very low disturbance to study the in situ properties. (Lindquist & Frogner Kockum, 2016)

Bottom ash used in the investigation originally came from Sysavs municipal waste plant in Malmö. It was not possible to determine how long the ash was piled outdoors before being used in the test road construction. Based on the properties of the ash it must have been stored outside for at least six months but it could have been up to 4 years. After storage, the ash was used as a sub-base in a 60-meter stretch of Törringe road in Malmö area. The pH of bottom ash used was in the range of 7,5-8. Sub-base thickness was 465 mm and total road pavement 745 mm. Sampling of the bottom ash sub-base was carried out in September 2006, 8 years after construction. (Lindquist & Frogner Kockum, 2016)

Undisturbed samples were collected and the structure of samples was studied. Study of the microstructure of the material showed no cracks that imply movements in the material or rotation of particles, all reaction products surrounding the decomposed particles were undisturbed. The SEM/EDS analysis showed that most particles had reacted to some extent in the road construction. The observed reactions involve an increase in volume. However, microstructural analysis detected no disturbances such as cracks or physical redistribution of the material. The interpretation was that the expansion had been taken up as plastic deformation and a decrease in pore volume without changes in volume or shape of the road construction. (Lindquist & Frogner Kockum, 2016)

The study shows that compacted MSWI bottom ash maintains its integrity throughout its lifetime, as the material did not show significant signs of degradation over the span of 8 years. However, some increase in volume of the particles was noted due to chemical reactions. As the loading situation of the PTES embankment is different from the road they may affect the volume or shape of the embankment.

6.4 RAISING OF CARDINAL FLY ASH RETENTION DAM IN USA

The Cardinal fly ash retention dam is located in eastern Ohio, USA and it is used to retain fly ash from coal combustion. The original dam consisted of a 54 m high arched earth embankment with a zoned cross section. To increase disposal capacity the dam was raised 15 m in 1998. A composite structure made of Roller Compacted Concrete (RCC) upstream shell, clay core, granular drainage blanket and earthen downstream shell was used. Bottom ash from the coal plant was used as an aggregate in RCC which lowered cost of construction considerably as well as provided a long-term disposal at considerable savings to the plant. In addition use

of the lightweight aggregate minimized the loading and deformation experienced by the old and new structure (Buhac & Amaya, 2002).

The RCC zone consisted of a mixture of coal bottom ash, cement and water. In order to produce a mixture with optimal moisture content, the natural water content of the coal bottom ash was tested twice a day. Optimum compaction of 30 cm loose lift of mix was achieved by CAT 563 single drum vibratory roller in 8 passes. Compression strength of the compacted mix after 7 days of curing was around 3,5 MPa. The upstream face of the RCC zone was designed with a slope angle of 40°. The zone was constructed in 30 cm high steps using temporary forms which were left in place for at least 4 hours after compaction. Thermal and settlement cracks developed during construction in the RCC zone. Four years after beginning of operation of the dam no further movement of the cracks developed during construction was noticed (Buhac & Amaya, 2002).

It is inconvenient that properties of bottom ash used are not presented in the paper, only properties of RCC are given. Properties of coal bottom ash from another plant can be used for a rough comparison with MSWI bottom ash. Chemical and engineering properties of coal and MSWI bottom ash are relatively similar, although leaching potential of coal bottom ash is lower. Mobility of chemicals would also be reduced by using concrete as the particles will be bound together, the embankment would also be less pervious to precipitation and water in general. Overall improved stability of the embankment would be achieved, but loading on the foundation would be increased.

6.5 EXPERIENCE FROM THE NETHERLANDS

In total 1,0 Mt of MSWI bottom ash is produced each year in the Netherlands. All of the bottom ash is treated: sieving, crushing and sorting out ferrous, non-ferrous metals. Bottom ash has been in use in large scale projects since 1985. Bottom ash has been used in construction of wind barriers, highway embankments, sound barriers and industrial building sites (Leenders, 2002).

One of the largest projects constructed was a highway embankment in Flevoland in the central part of the Netherlands. Total length of the new highway was 19 km and highest point of construction was 16 m above the sea level. The construction started in 1994 and was completed in 1997. Height of the embankment varied between 1 and 10 m (Leenders, 2002).

Main differences using MSWI bottom ash in embankments compared to sand are:

A drainage layer of sand is installed under the bottom ash. In this case even with the settlements expected during the lifetime of the embankment there is always a distance of at least 0,5 m between bottom ash and ground water.

According to environmental regulations a sand-bentonite capping with minimum thickness of 0,2 m must be installed on top and on the slopes of MSWI bottom ash embankment.

Near concrete constructions the embankment was stopped at a distance of at least 15 m to prevent possible negative effects of chlorides and sulphates on the concrete construction.

The bottom ash was laid in 0.4 m layers before compaction. The compaction rate of bottom ash was monitored using the sand-replacement method. The average compaction measured was 102%. In the summer of 1994 there was a local erosion of the compacted bottom ash due to heavy rainfall over a short period of time. This happened when the protective sand-bentonite capping was not in place yet. To prevent further erosion and contamination of the adjacent soil surface it was decided to cover the compacted bottom ash weekly with a thin layer of bitumen-emulsion. Sand-bentonite for the project was compacted using a dynamic roller on the horizontal and a dynamic plate on sloped surfaces. Hydraulic conductivity of $1 \cdot 10^{-10}$ m/s was measured (Leenders, 2002).

Groundwater level and quality was measured monthly along the road at 9 places. After 1997 the measurements were carried out yearly. The quality was measured with the inorganic parameters of copper, zinc, arsenic and molybdenum. No significant changes were found (Leenders, 2002).

This project provides a good indication for how an embankment of this size could be constructed and what are the possible problems. No major problems concerning the embankment have been discovered. Although, it should be taken into account that the embankment of a road experiences different loading conditions compared to the embankment of a PTES.

7 Possible test methods and methodology

Physical and chemical properties of MSWI bottom ash should be determined in order further determine the suitability of the material for embankment construction. Properties of the bottom ash from the specific plant have to be determined since they depend on the waste as well as incineration technology. Bottom ash properties vary from incinerator to incinerator. If bottom ash from several incinerators were to be used their properties should be tested separately.

If any pre-treatment is considered the bottom ash properties should be tested prior to the treatment as well as after. If this is done the full effect of the pre-treatment is known and it is possible to estimate whether or not it is worth an investment.

In addition, properties of the foundation material of the embankment also have to be determined in order to determine whether the foundation can withstand the load from the embankment or not.

7.1 PARTICLE SIZE DISTRIBUTION

Gradation affects numerous material properties and the final overall stability of the embankment. Particle size distribution affects compaction, hydraulic conductivity and shear strength of the material. Particle size distribution of the material can be determined by sieving tests. If material has a large amount (>2% of mass) of particles smaller than 63µm the distribution of fines has to be determined. This can be done by the means of sedimentation test or laser diffractometry (Šinkovičová, Igaz, & Kondrlova). Setup of a sieving apparatus can be seen in Figure 7. Apparatus includes a number of sieves that are mounted on a vibrating table.

In addition to determining particle distribution of the original material without any additional pre-treatment, gradation of washed, sieved and crush material should also be determined. The effect of changes in particle size distribution on other material properties should also be determined. Therefore it would be possible to decide whether additional pre-treatment of the material yields desired result considering the increased investment costs.



Figure 7. Sieving apparatus (Equipment, 2018)

7.2 DENSITY, PARTICLE DENSITY, NATURAL WATER CONTENT

It is important to determine initial characteristics of the material as this provides a general description of the material as well as comparison point with other materials and treated bottom ash. Natural density and maximum density of the material should be determined. Also particle density of the material should be determined.

7.3 COMPACTION PROPERTIES

Compactability of the soil affects the overall stability of the structure. Hydraulic conductivity, shear strength, hydraulic conductivity and loading on the foundation are all affected. Compaction properties of the material are also dependent on the moisture content. Therefore it is important to determine water content at which maximum compaction is reached, as well as the density of the compacted material.

Compaction characteristics can be assessed using standard laboratory tests for example a proctor test, where soil is compacted in a cylindrical mould using a standard compactive effort. Size of the mould and weight of the compactor depend on the used procedure. Figure 8 shows a proctor test apparatus.



Figure 8. Proctor test apparatus available at LTU

Dry density of the compacted sample is plotted against water content and a curve shown in Figure 9 is obtained. It can be seen that there is a particular value of water content, known as optimal water content, at which maximum value of dry density is obtained. Testing is carried at numerous times at different water contents. (Knappett & Craig, 2012)

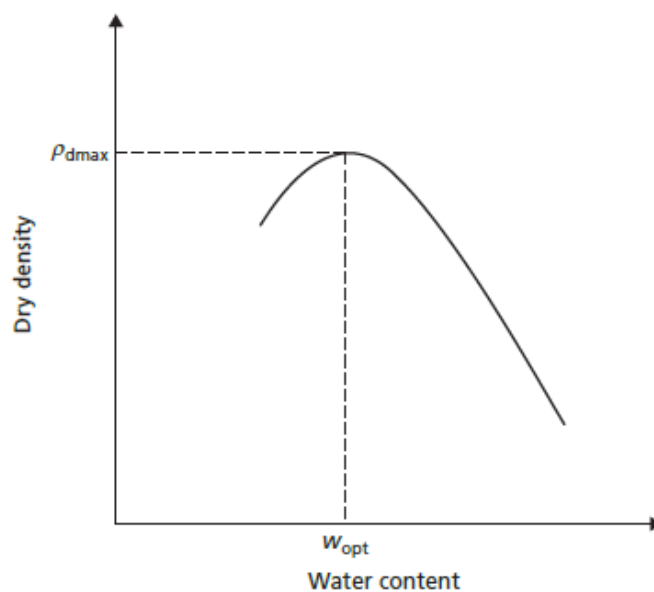


Figure 9. Dry density water content relationship (Knappett & Craig, 2012)

7.4 COMPRESSIVE STRENGTH

It is impossible to determine the compressive strength of the MSWI bottom ash as a whole, as it is a granular material, but it is possible to determine the compressive strength of a particle. Compressive strength of the particles could be used for estimation of compressive strength for the material as a whole.

7.5 PERMEABILITY

Constant and falling head tests can be conducted in order to determine hydraulic conductivity of the material. Falling head tests are commonly used to measure the hydraulic conductivity of fine grained soils. Constant head tests are commonly used to measure hydraulic conductivity of coarse grained soils (Knappett & Craig, 2012). As mentioned before, hydraulic conductivity of the material should be determined at different degrees of compaction as well as different water contents. Schematic diagram showing a constant head permeability test is presented in Figure 10.

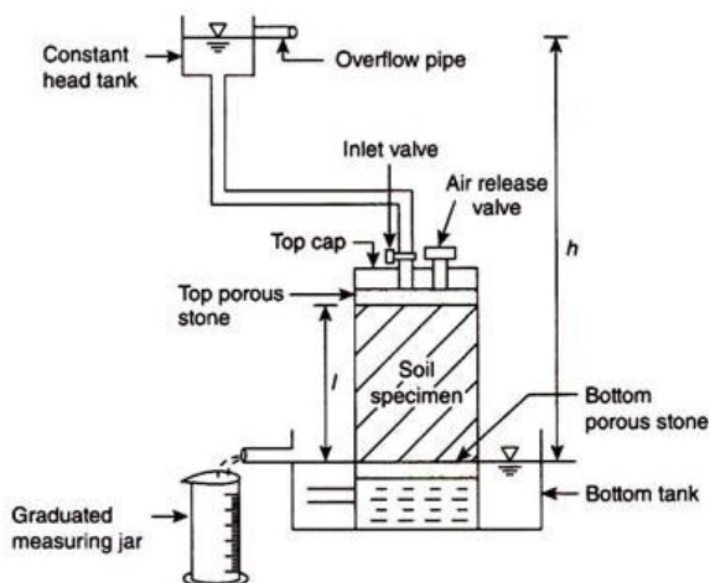


Figure 10. Constant head permeability test (Soil Management, 2018)

7.6 SHEAR STRENGTH

Shear strength parameters of the material can be determined using direct or simple shear test and by the means of triaxial testing. Advantages of the direct and simple shear tests are their simplicity and ease of specimen preparation (Head, 2006). Direct shear apparatus can be seen in Figure 11.

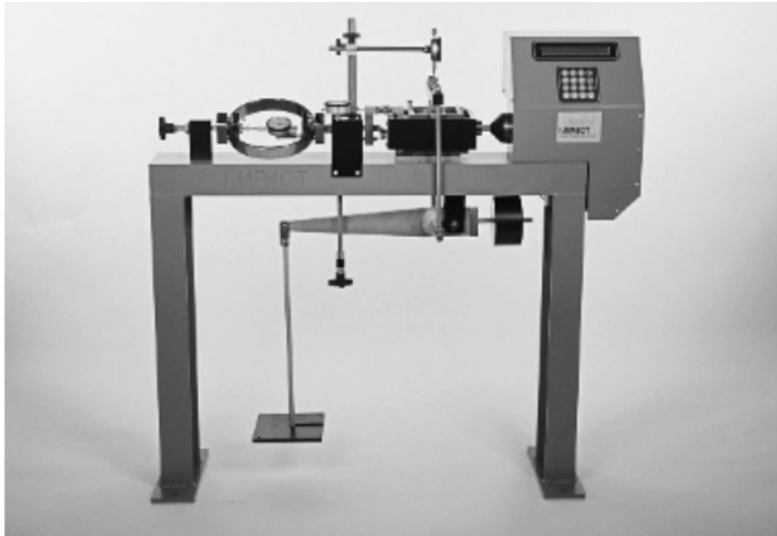


Figure 11. Direct shear apparatus (Knappett & Craig, 2012)

Triaxial apparatus is the most widely used laboratory device for measuring soil behaviour in shear and is suitable for all kinds of soil. Only drained strength of coarse grained soils is normally relevant in practice (Knappett & Craig, 2012). While triaxial test is generally considered more expensive and time consuming it allows determining settlement properties of the material in addition to the shear strength. Triaxial testing also gives more reliable values of shear strength compared to alternatives.

A cylindrical specimen with length/diameter ratio of 2 is generally used for the triaxial test. The test specimen sits in a chamber of pressurized water. The specimen is stressed radially by the pressurized water and axially by a loading ram. The most common test conducted in the triaxial apparatus is triaxial compression. Axial load is applied to the specimen while the confining radial pressure is constant. This leads to shear failure of the specimen. Triaxial testing apparatus schematic can be seen in Figure 12.

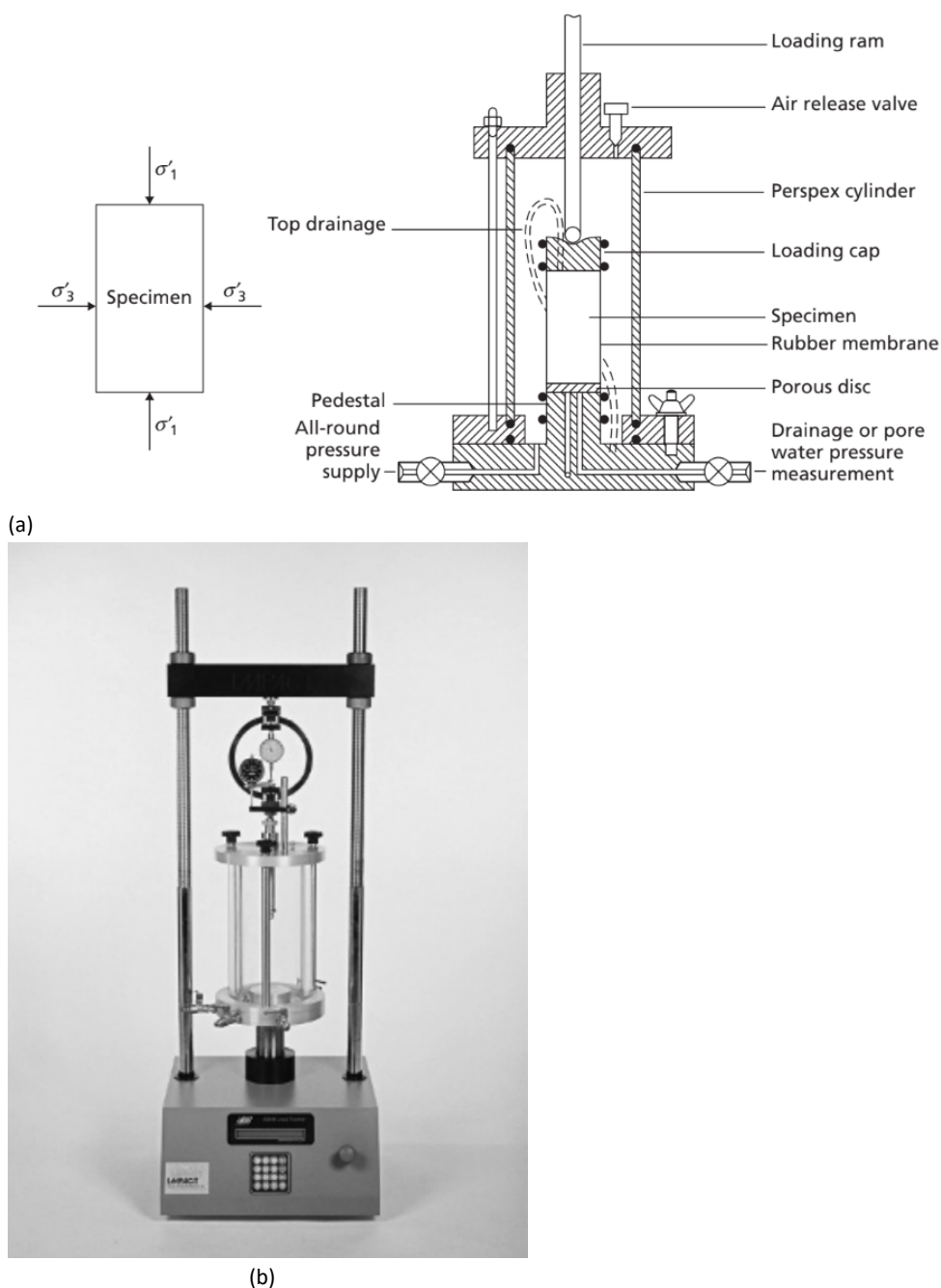


Figure 12. Triaxial apparatus schematic (a) and standard triaxial apparatus (b) (Knappett & Craig, 2012)

7.7 ELASTIC MODULUS AND SETTLEMENT

Elastic modulus can be used to predict future settlements. Elastic modulus can be determined by triaxial testing, discussed in the previous paragraph. Additional stress-strain relationships can be determined using oedometer testing which describes the material during one-dimensional compression. During the oedometer test the test-specimen is held inside a metal ring in between two porous stones.

Upper stone is free to move and is attached to the metal loading cap through which the pressure is applied to the specimen. The whole assembly is placed in water to which the water in the specimen has free access. The load is applied to the loading cap and the deformation of the specimen is measured by the means of a dial gauge or electronic displacement transducer. The oedometer setup is shown in Figure 13.

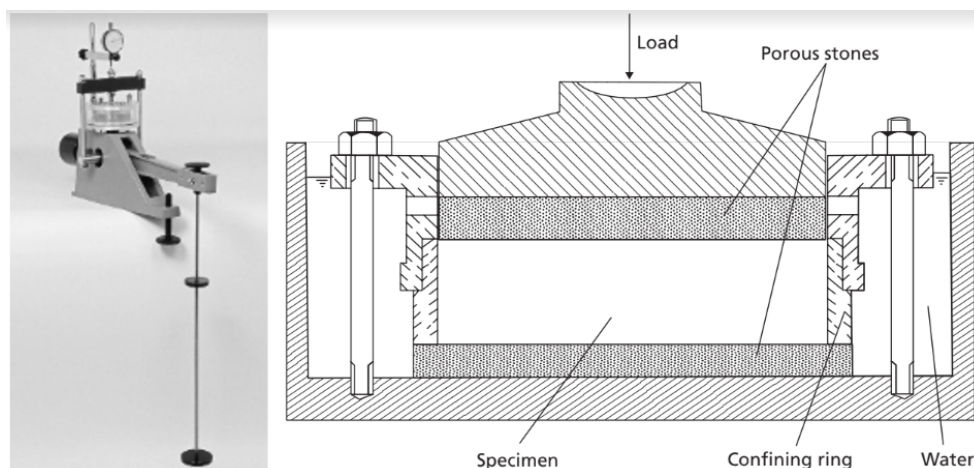


Figure 13. Oedometer setup and schematic (Knappett & Craig, 2012)

7.8 RESISTANCE TO FREEZE-THAW CYCLING

EU standard EN 1367-1 provides information on how an aggregate behaves when it is subjected to the cyclic action of freezing and thawing. The stresses on aggregates due to frost depend, amongst other factors, on the degree of water saturation as well as the rate of cooling. The results provide a means for assessing an aggregate's resistance to this form of weathering. The test is applicable to aggregates having a particle size between 4 mm and 63 mm. Specimen is subjected to 10 freeze-thaw cycles during the test (European Committee for Standardization, 2007).

The whole embankment would not be affected by freezing and thawing processes. Therefore, it is necessary to determine the possible extent of freeze-front penetration. This can be done based on calculation of frost penetration depth. High temperatures inside the PTES should be taken into account.

7.9 EROSION RESISTANCE

When designing a typical embankment dam the choice of soils are aimed at reducing or eliminating the detrimental effects of seeping water. In case of PTES a leak in the liner could cause internal erosion of the embankment. In addition to internal erosion surface erosion can occur due to heavy rainfalls leading to slope failure. Therefore it is important to investigate surface erosion if the embankment is left uncovered. Erosion potential of the material can be determined by examining the gradation curve. Nevertheless, laboratory testing may prove to be necessary to validate the results.

It is possible to investigate internal stability using empirical methods. For the purpose of preliminary investigation it should be sufficient to study the gradation curve of the material to determine internal stability. If in further investigations laboratory testing proves necessary it is possible to construct a small scale model to simulate seepage of water through the embankment in case a leak in the lining develops.

It is relatively easy to test surface erosion based on simple laboratory methods. For example one study used a Plexiglas cube (7x7x7 cm) filled with fully saturated soil. Water layer of 5 cm was established on top of the soil after which rain was simulated over the soil. The overflow spout maintained a constant 5 cm of water on top of the soil. Samples from overflow were collected and analysed for particles. (Heilig, o.a., 2001)

7.10 THERMAL PROPERTIES

It is important to investigate thermal properties of the bottom ash as it will be used for a construction of thermal energy pit storage, as heat losses through the embankment might be higher than through the underground portion of the storage pit. There are several methods available in order to determine thermal conductivity of MSWI bottom ash. Tests to determine thermal conductivity are based on either measuring the power needed to create a constant temperature difference or constant power is applied and the temperature difference is measured (Hamdhan & Clarke, 2010).

A cylindrical specimen is used to perform the test. The specimen is insulated by jacket and its ends are kept at different temperatures therefore allowing the heat to flow axially through the sample. The specimen is sealed preventing any changes in water content. Constant heat is applied to the bottom of the specimen. Temperatures at the bottom and at the top of the sample are recorded with an interval of 5 min until temperature gradient across the sample is constant, after which the heating plate is switched off and the cooling rate of the sample is recorded with interval of 5 min (Hamdhan & Clarke, 2010).

There are also portable testing methods available, to determine thermal properties of the material, that can be used in situ as well as in laboratory conditions. For example portable thermal resistivity meters can be used to measure thermal conductivity quickly (within 2 min) and accurately (accuracy of 5%). (Thermtest: Thermophysical Instruments, 2018).

7.11 LEACHING

Leaching is a method to remove soluble components from a solid matrix. Potential leaching and release of heavy metals from the residues must be evaluated before a final decision about the application of bottom ash is made. Lead, copper, cadmium and zinc are of main concern. Many leaching tests have been designed to assess trace element mobility and simulate field-leaching scenario. Therefore the amounts of toxic trace elements can be estimated (Chimenos, Fernández, Nadal, & Espiell, 2000).

There is great variety of leaching test procedures available. Leaching methods are often categorized by the number of steps in which leaching fluid is added- single addition tests are called static extraction tests and multiple addition test are called dynamic tests. Another way to classify tests is batch leaching tests, such as column or flow through systems and bulk or flow around systems for monolithic samples. In many methods liquid to solid ratio (L/S) is used to quantify the volume of leachant in respect to the amount of solid sample.

In case of the embankment for PTES the leaching test should be somewhat modified, as water temperatures are high inside the storage pit. Therefore, in case of a leak, the temperature of leachant would be higher than room temperature. Whether this has effect on the leaching properties of bottom ash is unknown since all previous test have been conducted with room temperature water.

Batch leaching tests are most commonly used tests for leaching of granular waste. Batch leaching tests methods are those in which sample is placed in a given volume of leachant solution for a set period of time. Most of these methods require some type of agitation to ensure constant contact between the sample and the leachant. At the end of the leaching period the liquid is removed and analysed. When choosing the leachant liquid for the test, it should be taken into consideration what type of liquid the material would come into contact with in-situ. In case of bottom ash that would be precipitation, therefore distilled water can be used as leachant.

In serial batch leaching tests a sample is leached consecutively with new portions of the same leaching fluid. Each step uses the same amount of fluid. This method aims to eliminate the effect of concentration on solubility while simulating long term exposure to the leachant solution (Kim). It has also been shown in a study that 2- stage leaching test that includes successive leaching stages at low L/S ratios rather than a single stage at high L/S ratio, is better at representing field conditions (Izquierdo, Querol, Vazquez, Josa, & Lopez-Soler, 2005).

European Committee of Standardization has compiled most commonly used batch leaching standards in Europe. Standards are available for one stage batch leaching test with S/L ratio of 10 kg/l (European committee for standardization) as well as two stage leaching test with S/L ratio of 2kg/l and 8 kg/l (European Committee for Standardization).

Column leaching tests are designed to simulate flow through porous bed of granular material. Flow of the leaching solution may be either down-flow or up-flow direction. The flow rate is usually accelerated compared to natural conditions but should be slow enough for leaching reactions to take place. The test can be performed on saturated or unsaturated material (Kim). The solution passes through the solids and is collected at the bottom of the column, usually filtered and then analysed. Leachate collection time can vary from days till months. Unlike batch leaching tests the sample is not agitated and therefore resembles more in-situ conditions. The procedure is more time and labour consuming than batch leaching but it allows observers to study long term chemical interactions between solid samples and leachates.

Both types of leaching tests could prove very useful when describing the leaching potential of MSWI bottom ash in different situations. While batch leaching test can help analyse overall leaching behaviour of the material column leaching test can simulate flow of water through the embankment over time and leaching potential in case of a leak in the liner. It should be noted that these tests are performed on material in its uncompact state while in application bottom ash will be compacted, therefore making it less permeable to water.

It is also important to know how results obtained in a laboratory conform to in situ conditions. A study analysed leaching potential of MSWI bottom ash in laboratory conditions as well as collected leachate on a test-road stretch constructed from unbound bottom ash. Leaching tests NEN 7341 (Normalisatie-instituut, 1994), CEN 12457-2 (European committee for standardization) and CEN 12457-3 (European Committee for Standardization) were used to assess the environmental performance of the bottom ash in laboratory conditions. Leachate collected in the field had a pH range of 7,3-9,2 which is slightly lower than pH determined in the lab conditions pH 8,5-8,9. However in general good agreement between laboratory and field emissions was observed. For most of the elements field releases were lower than predicted values and for some elements very close to leachable fraction based on CEN test. Only in case of As and Zn poor agreement was found between field and laboratory test. The study also concluded that while test according to CEN predicted leachability of the elements quite accurately NEN method had very limited application showing generally much higher values than found on the test stretch of the road (Izquierdo, Querol, Vazquez, Josa, & Lopez-Soler, 2005).

It should also be considered that testing of leachate after the construction will be required. Therefore a drainage system and leachate collection facility should be a part of the future design.

7.12 MONITORING OF THE EMBANKMENT AFTER CONSTRUCTION

The embankment should be monitored during the construction, filling of the PTES as well as its entire service time. Therefore it is possible to notice any unexpected changes in the embankment and if necessary take action to avoid stability problems. A procedure similar to dam safety monitoring can be used for the PTES embankment. General principle is that level of surveillance of the embankment should be corresponding to the consequences of failure, which may change during the lifetime of the structure. (Fell, MacGregor, Stapledon, & Bell, 2005)

Inspection and monitoring program of the embankment should be planned by qualified engineers. Potential failure modes of the embankment should be investigated in the program. Monitoring data should also be reviewed by qualified engineers in order to identify unusual behaviour. (Fell, MacGregor, Stapledon, & Bell, 2005)

It is possible to monitor deformations in the embankment by taking geodetic measurements from the crest regularly. In addition inclinometers should be installed on the downstream side of the embankment to monitor movement in the slope. Piezometers should be installed on the downstream slope as well as the foundation of the structure in order to measure pore water pressure (Dunncliff,

198). It is also necessary to conduct regular visual inspections of the embankment in order to detect signs of surface erosion, sinkholes, leakages etc. Data collected through monitoring should be compiled into reports in order to have a good overview of the changing state of the embankment. (Fell, MacGregor, Stapledon, & Bell, 2005)

Material properties of the MSWI bottom ash cannot be monitored directly through these inspections. Nevertheless, if the external factors affecting the construction have remained unchanged but changes are seen in the embankment it can be concluded this is due to the altered material properties. After it has been determined that the properties of the construction material have changed, suitable in situ testing and sampling can be carried out.

8 Conclusion

Several challenges concerning MSWI bottom ash applications have been found through conducting a thorough literature study. These issues have to be addressed in the preliminary design process of the PTES embankment. Deficiencies in soil properties should be accounted for.

Main engineering concerns stem from the unknown and varying mechanical properties of the material. For that purpose general material properties of the material have to be determined: densities, shear strength, hydraulic conductivity etc. In addition relationships between these properties have to be established, since small change in one property can lead to a large change in the other. One factor of importance is changes in particle size distribution due to applied stresses.

Additionally freeze-thaw and erodibility properties of the material have to be thoroughly investigated. There are very few studies conducted researching these properties. Both properties are crucial to the stability assessment of the structure.

There is also a lack of information concerning the thermal properties of MSWI bottom ash. Where the purpose of the construction is to retain heat it is extremely important to determine these properties, in order to predict heat losses through the embankment.

Even though only briefly mentioned in this report, stability of the foundation of the embankment is immensely important. Engineering properties of the underlying soil should be investigated. Slope stability of the excavated pit under the additional load of the embankment is one of the main concerns. Therefore shear strength properties have to be investigated. It is also necessary to estimate possible settlement in the foundation and their effect on the overall construction. Necessary properties could be determined by the means of laboratory or in situ testing.

Since the material has high leaching potential, the chemical properties and leaching potential should be determined for the specific material. In order to comply with legislation some form of pre-treatment will most likely be necessary. Weathering is the most common pre-treatment practice; it has low costs and is effective in reducing mobility of heavy metals. Liners to cover the whole embankment can also be used to limit the contact of bottom ash with water. This would also affect other properties of the material that are dependent on moisture content. In this case additional laboratory investigation would be required to determine friction between the liner and material.

It can be said that it is probably possible to use MSWI bottom ash for construction of an embankment. This has also been proven by several case studies presented in this report. But it should be considered that dealing with an unconventional material calls for a thorough investigation.

9 References

- Andersland, O. B., & Ladanyi, B. (2004). *Frozen Ground Engineering*. Hoboken: Wiley.
- Avfall Sverige. (2009). *Rapport U2009:10 Uppföljning av slaggrusprovvägar*. Avfall Sverige.
- Becquart, F., Bernard, F., Abriak, N. E., & Zentar, R. (2009). Monotonic aspects of the mechanical behaviour of bottom ash from municipal solid waste incineration and its potential use for road construction. *Waste Manage*, 1320-1329.
- Buhac, H. J., & Amaya, P. J. (2002). Rasing of Cardinal Fly Ash Retention Dam. *Dam Maintenance and Rehabilitation*. Madrid.
- Chimenos, J. M., Fernández, A. I., Nadal, R., & Espiell, F. (2000). Short-term natural weathering of MSWI bottom ash. *Journal of Hazardous Materials*, 287-299.
- Cosentino, P., Kajlajian, E., Heck, H., & Shieh, S. (1995). *Developing Specifications for Waste Glass and Waste-to-energy Bottom Ash as Highway Fill Materials Volumes 1 of 2 (Bottom Ash)*. Florida Departament of Transportation.
- Crillesen, K., & Skaarup, J. (2006). *Management of Bottom ash from WTE Plants*.
- de Guadalfajara, M., Lozano, M., & Serra, L. (2014). Analysis of large thermal energy storage for solar district heating.
- De Windt, L., Dabo, D., Lidelöw, S., Badreddine, R., & Lagerkvist, A. (2011). MSWI bottom ash used as basement at two pilot-scale roads: Comparison of leachate chemistry and reactive transport modeling. *Waste Management*.
- Directive 2010/75/EU of The European Parliament and of the Council. (2010). *Officila Journal of the European Union*, Article 50.1.
- Dunnicliff, J. (198). *Geotechnical Instrumentation for Monitoring Field Performance*. John Wiley & Sons.
- Equipment, 9. M. (2018, October 10). *Equipment, 911 Metallurgist Process*. Retrieved from Equipment, 911 Metallurgist Process: <https://www.911metallurgist.com/equipment/vibrating-sieve-machines/>
- European Committee for Standardization. (2007). *CEN 1367-1:2007: Tests for thermal and weathering properties of aggregates. Part 1: Determination of resistance to freezing and thawing*.
- European Committee for Standarization. (n.d.). *CEN 12457-3:2002. Characterisation of waste- Leaching- Compliance test for leaching of granular waste materials and sludges- Part 3: Two stage batch test at a liquid to solid ratio of 2 l/kg and 8 l/kg for materials with high solid content and particle size below 4 mm*.

- European committee for standardization. (n.d.). CEN 12457-2:2002. *Characterisation of waste- Leaching- Compliance test for granular waste materials and sludges- Part 2: One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 4 mm (without or with size reduction).*
- Fell, R., MacGregor, P., Stapledon, D., & Bell, G. (2005). *Geotechnical Engineering of Dams*. London: CRC Press.
- Forteza, R., Far, M., Seguí, C., & Cerdá, V. (2004). Characterization of bottom ash in municipal solid waste incinerators for its use in road base. *Waste Management*, 899-909.
- Hamdhan, I., & Clarke, B. G. (2010). Determination of thermal conductivity in coarse and fine sand soils. *World Geothermal Congress*. Bali.
- Harris, M. (2011). *Thermal Energy Storage in Sweden and Denmark: Potentials for Technology Transfer*. Lund.
- Head, K. H. (2006). *Manual of Soil Laboratory Testing*. London: Pentech Press.
- Heilig, A., DeBruyn, D., Walter, M. T., Rose, C. W., Parlange, J. Y., Steenhuis, T. S., . . . Walker, L. P. (2001). Testing a Mechanistic Soil Erosion Model with a Simple Experiment. *Journal of Hydrology*, 9-16.
- Izquierdo, M., Querol, X., Vazquez, E., Josa, A., & Lopez-Soler, A. (2005). Comparison between laboratory leaching properties and field experiments of MSWI bottom ash as an unbound granular material for road pavements. *World of Coal Ash*. Lexington.
- Kim, A. G. (n.d.). *Leaching methods applied to the characterization of coal utilisation by-products*. Pittsburgh: US Department of Energy.
- Klein, R., Nestle, N., Niessner, R., & Baumann, T. (2003). Numerical modelling of the generation and transport of heat in a bottom ash monofill. *Journal of Hazardous Materials*, 147-162.
- Knappett, J. A., & Craig, R. F. (2012). *Craig's Soil Mechanics. Eighth Edition*. Spoon Press.
- Lambe, T. W., & Withman, R. W. (1969). *Soil Mechanics*. New York: John Wiley and Son.
- Leenders, P. (2002). MSWI Bottom Ash- Experiences in the Netherlands. *Sustainable Construction: Use of Incinerator Ash*. Dundee: Thomas Telford.
- Lindquist, J. E., & Frogner Kockum, P. (2016). Long-term performance of MSWI bottom ash in a test road-construction. *International Journal of Sustainable Construction Engineering and Technology*, 38-49.

- Lynn, C. J., Ghataora, G. S., & Dhir, R. K. (2017). Municipal incinerated bottom ash characteristics and potential use for road pavements. *International Journal of Pavement Research and Technology*, 185-201.
- Mangold, D., & Deschaintre, L. (2012). *Report on state of the art and necessary further R+D*.
- Modified Proctor Test: Its Procedure, Apparatus, Result*. (2018, October 10). Retrieved from Civilpie: Civil Engineering Home: <https://civilpie.com/modified-proctor-test/>
- Muchová, L., & Rem, P. C. (2006). Metal content and recovery of MSWI bottom ash in Amsterdam. *WIT Trans. Ecol. Environ.* 92, (pp. 211-216).
- Naturvårdsverket. (2010). *Återvinning av avfall i anläggningsarbeten Handbook*. Naturvårdsverket.
- Normalisatie-instituut, N. (1994). NEN 7341. *Determination of leaching characteristics of soil, construction materials and eastates- Leaching tests- Detirmination od the availability of inorganic constituents for leaching from construction materials and wste meterials*.
- PlanEnergi. (n.d.). Long Term Solar and Solar District Heating: A presentation of the Danish pit and thermal energy storages. Energy Technological Development and Demonstration Program.
- (2018). *PLAXIS 2D Material Models Manual*.
- Rönqvist, H. (2010). *Predicting Surfacing Internal Erosion in Moraine Core Dams*. Stockholm: KTH.
- Šinkovičová, M., Igaz, D., & Kondrlova, E. (n.d.). Soil Particle Size Analysis by Laser Diffractometry: Result Comparison with Pipette Method. *IOP Conference Series: Materials Sience and Engineering*.
- Soil Management*. (2018, October 10). Retrieved from How to Determine the Permeability of Soil: <http://www.soilmanagementindia.com/soil/permeability-of-soils/how-to-determine-the-permeability-of-soil/13521>
- Swedish Geotechnical Institute. (2006). *Handbok: Slaggrus i väg- och anläggningsarbeten*. Linköping: Statens Geotekniska Institut.
- Sysav. (2011, 08 29). Produktinformationsblad Slaggrus.
- Thermtest: Thermophysical Instruments*. (2018, October 10). Retrieved from Assessing the Thermal Properties of Dry and Saturated Soils Using the TLS-100 Portable thermal Resistivity Meter: <https://thermtest.com/applications/soil-thermal-conductivity-tls>

- Todorovic', J. (2006). *Pre-Treatment of Municipal Solid Waste Incineration (MSWI) Bottom Ash for Utilisation in Road Construction*. Luleå.
- Vaitkus, A., Grazulyte, J., Vorobjovas, V., Sernas, O., & Kleiziene, R. (2017). Potential of MSWI bottom ash to be used as aggregate in road building materials. *The Baltic Journal of Road and Bridge Engineering*, 77-86.
- Van den Heede, P., Ringoot, N., Beirnaert, A., Van Brecht, A., Van den Brande, E., & De Schutter, G. (2015). Sustainable high quality recycling of aggregates from waste-to-energy, treated in a wet bottom ash processing installation, for use in concrete products.
- Xia, Y., He, P., Shao, L., & Zhang, H. (2016). Metal distribution characteristic of MSWI bottom ash in view of metal recovery. *Journal of environmental sciences*, 178-189.

INVESTIGATION METHODS OF MSWI BOTTOM ASH PROPERTIES FOR USE IN EMBANKMENTS

Properties of MSWI bottom ash have been investigated based on previous research. There is a large variation properties based on the origin of the bottom ash. Therefore, if the bottom ash will be used for construction of PTES embankment engineering properties of the specific bottom ash used have to be determined to ensure the stability of the embankment.

MSWI bottom ash has also high leaching potential. Therefore weathering will be necessary to reduce the mobility of the contaminants. Additional pre-treatment methods may also be needed. It may also be necessary to install additional liners on the downstream face to limit MSWI bottom ash exposure to precipitation.

In addition to determining bottom ash properties it is equally important to determine the properties of the underlying material. As foundation of the embankment experiences a change in initial stress state under additional load stability problems may arise during construction as well as service time.

Energiforsk is the Swedish Energy Research Centre – an industrially owned body dedicated to meeting the common energy challenges faced by industries, authorities and society. Our vision is to be hub of Swedish energy research and our mission is to make the world of energy smarter!