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Waste Materials in Construction: Putting Theory into Practice

Inorganic immobilisation of waste materials

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ABSTRACT

Inorganic immobilisation uses cement to solidify certain waste materials. Water is added to the cement in a ratio between 0.4 and 0.6. The calcium-silicates of the cement react with the water to a calcium-silicate-hydrate-gel (CSH-gel), lime and heat. This gel is able to cling aggregates together. The result is a hardened product, including some pores. Pores larger than 20 nm are called capillary pores, smaller than 20 nm are called gel-pores. The concrete is characterised by a high pH about 13.

The effectiveness of immobilisation techniques is a relation of immobilisation and leaching mechanisms, degradation mechanisms, economic and environmental merit and application potentialities. Because of the high pH most heavy metals show good immobilisation properties, except molybdene and chromium (VI). Other components of the waste material are hard to immobilise, such as anions and organic compounds. Therefore additives may be used. Oxidants can start a REDOX-reaction with the anions and organic compounds are used to bind the organic components. Once the product is put into practice, the effectiveness of the technique depends on leaching mechanisms: surface release, diffusion and dissolving. Especially diffusion is important for immobilisation. Diffusion is caused by the presence of water in the pores of the material and concentration variations between the material and the medium. Degradation mechanisms, important for inorganic immobilisation, are erosion, wet/dry-periods, temperature changes and freeze/thaw-periods [25]. These influences can cause the formation of cracks. Economic merit is not often given. It can be divided in benefits and costs of the used and produced materials, disposal, transport, labour, energy, aftercare and investments. Like economic merit ,the environmental merit is not simply given. An important factor is the priority list of Lansink. The benefit of the technique is the replacement of primary materials by secondary materials. Furthermore other aspects have to be considered, such as the use of energy, the release of components and the use of materials. The effectiveness of immobilisation is last but not least dependent on the application potentialities. The application of immobilised products, both the disposal and useful application, needs after-care. This means, control of the product is required.

Furthermore, the effectiveness of inorganic immobilisation depends on the used waste material. Some material have more opportunities than others. Desired properties of the waste material are: high content of heavy metals, low content of anions and organic compounds. Moreover, it is desirable to minimise the pretreatment of the waste. Currently used waste materials for inorganic immobilisation are: filter dust, coal ashes, MIP-fly ash, residues from burning of coal, sewage sludge, lime sludges, fluorgypsum waste, arsenical waste, slag and dust from steel making.

It can be concluded that inorganic immobilisation can show good encapsulation properties for certain waste types. Especially these waste types, containing heavy metals. Degradation of the product is mostly caused by the formation of cracks. Therefore, after care of the product is required.

INTRODUCTION

Inorganic immobilisation is based on cement as solidifying agent. In addition of water cement hydrates to a cement gel, that is able to cling aggregates together. The result is a hardened product, which can chemical and physical encapsulate certain hazardous waste materials.

This technique is widely developed in several countries, such as the United States of America and Japan. However, in the Netherlands, little applications of this technique are known due to legislative restrictions in the past. Current changes in legislation are helping to put developed processes into practice and thereby requiring a research to the advantages and disadvantages of inorganic immobilisation techniques. The scope of this article is a 'state of the art' of immobilisation based on cement.

The scope of paragraph 1 are properties of concrete relevant to inorganic immobilisation. In paragraph 2 the effectiveness of inorganic immobilisation techniques is given. This paragraph contains encapsulation mechanisms, degradation mechanisms, application potentialities, costs and environmental aspects. Paragraph 3 deals with required properties for the waste materials. Chemical and physical properties of the waste material will be related to the effectiveness of the immobilisation. The last paragraph presents the advantages and disadvantages of inorganic immobilisation.

1 RELEVANT PROPERTIES OF CONCRETE

Composition

Concrete is made up of cement, aggregate, water, air and additives. Currently used cement types in the Netherlands are: Portland cement, blast furnace slag cement and Portland fly ash cement. The clinker consists of the following minerals: $3CaO.AlO_3$, $3CaO.SiO_2$ and $2CaO.SiO_2$. In the presence of water, $CaSO_4.2H_2O$ (gypsum) and/or $CaSO_4$, $3CaO.AlO_3$ reacts to $CaO.Al_2O_3.3CaSO_4.32H_2O$ (ettringite). This ettringite forms a layer on the cement aggregates and thereby delays the hydration reaction of cement.

Water is added to the cement to react with the calcium-silicates and form a calcium-silicate-hydrate-gel (CSH-gel) and lime. An example of the reaction of $3CaO.SiO_2$ with water is:

$$2\,(3CaO.SiO_2) \quad + \quad 6\,H_2O \quad -> \quad 3\,CaO.2SiO_2.3H_2O \quad + \quad 3\,Ca(OH)_2$$

During the reaction, the content of unhydrated cement decreases and the content of CSH-gel increases, which leads to a decrease in volume. The second objective of the addition of water is the increase in the workability of the concrete. Water surrounds the cement particles and aggregates. In the final product, water can be present in the concrete under several conditions. In the capillary pores[1] water can be present as water vapour. Above the saturation pressure condensation will occur. The saturation pressure increases with decreasing pore size. Some water is not physically bound to the surface of the solid material. This water is called 'free water'. Free water exists in the larger gel pores and the capillary pores due to condensation. In addition, water is often adsorbed to solid materials in the smaller gel pores. Water can also form a layer between components of the CSH-gel.

Aggregates, such as river gravel and river sand are added to the cement paste. Important factors of the aggregates are the weight, shape and particle size distribution. In some cases, additives are used to improve the workability of the concrete or to decrease the Water/Cement-ratio. After casting of the concrete, the concrete will be vibrated for proper compaction. Air decreases the strength of the concrete, by forming pores in the concrete. However, in special cases air is consciously brought into the cement gel by means of air entraining agents. Concrete thereby becomes more resistant to freeze/thaw(salt)-periods, due to these pores.

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[1]An explanation of capillary and gel pores will be given later in this paragraph.

Strength
Strength develops in time and continues to increase for years. This process will be accompanied by a gradual change in pore size distribution.

Pores
Pores in the CSH-gel take approximately 25% of the total volume of CSH-gel, the gel pores. They are defined as pores smaller than 20 nm. Pores larger than 20 nm are called capillary pores. During the hydration reaction the capillary pores diminish, due to the growth of cement hydrates. An increase in capillary pores is responsible for a decrease in strength and durability, as well as for an increase in permeability of the final product. However, capillary pores will always be present in cement. The pores are due to the presence of water.

W/C-factor
An important factor in the properties of cement is the Water/Cement-ratio. Especially, the strength depends on the W/C-factor. A higher W/C-factor includes a lower strength. The reason for this is that cement of W/C-factor above 0.38 will always consists of capillary pores. Besides that, too little water will make mixing difficult [17]. A typical W/C-factor lies between 0.4 and 0.6.

Hydration heat
The hydration reactions are exothermic and thereby the setting of cement is accompanied by the formation of heat. Heat is transported from the centre of the matrix to the surface. This results in temperature gradients, which can cause cracks in the case of bulk concrete.

pH
The pH of the cement product is high, approximately 13. The pH depends on the cement type. Furthermore, the development of OH^- concentration in the pore water is a function of the W/C-factor [8]. A high W/C-factor results in a lower pH, as shown in the following figure.

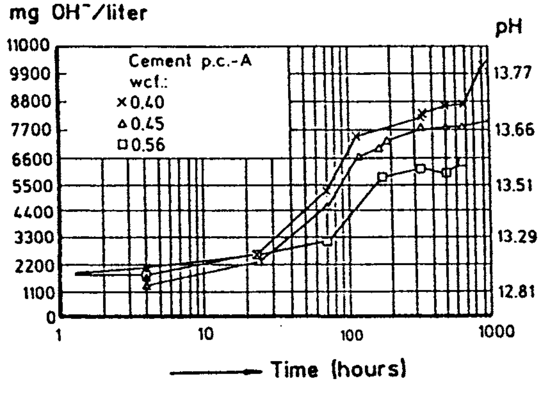

Figure 1: development of the OH^- concentration in the pore water as a function of the W/C-ratio

2 EFFECTIVENESS OF INORGANIC IMMOBILISATION

The effectiveness of immobilisation can be measured by the encapsulation of components of the waste material. The more components are encapsulated, the more effective the technique is. Therefore, immobilisation and leaching mechanisms will be described. Furthermore, the environmental and economic merit and application potentialities contribute to the effectiveness of inorganic immobilisation.

Immobilisation mechanisms

The effectiveness of encapsulation depends on the immobilisation mechanisms during and after the cement production. Firstly, the physical mechanisms will be considered. Secondly, the chemical mechanisms are described and finally the use of special additives is related to the desired encapsulation of components.

Physical mechanisms can be divided in hardening of the concrete and porosity of the concrete. Fine particles (less than 74μm) weaken the bounding between waste particles and the cement by coating the larger particles [17]. This coating inhibits chemical binding of the contaminants. Pretreatment of the waste may be required to reduce the fine particle concentration.

As said before, pores are always present in the final product. The leachability of components is increased by the increase of the porosity. Furthermore, a high content of soluble salt in the matrix may lead to an increase of the porosity of the matrix, due to the leaching out of these contaminants [6].

Chemical mechanisms of immobilisation of the waste are due to the chemical attraction of the surface atoms and of the precipitation of hydroxides. Most cations, such as heavy metals are insoluble at pH 8-10. They are immobilised by the precipitation of metalhydroxides. Above and below this pH range the solubility increases. Figure 2 shows the solubility of cations in relation to the pH. At the high pH of concrete, most cations are not in its least soluble state. Ions, such as molybdene and chromium (VI) are mobile at high pH, due to a low chemical retention, see figure 4. Although chromium and molybdene show high leachability, some heavy metals can be bound to the CSH-gel by adsorption and chemisorption. Metal ions may be incorporated into the crystalline structure of the cement [17].

Anions are difficult to immobilise, f.e. cyanide, chloride and bromide. They do not precipitate with hydroxide and often are not bound into the crystalline matrix [22]. Exceptions of anions that can be immobilised are sulfates and sulfites. Organic compounds may delay the setting time. Besides that, organic compounds show less fixation in the matrix [22]. Moreover, organic compounds can increase the mobility of other compounds [6]. Organic compounds may be decomposed at high pH. This will lead to soluble organic compounds. Trace elements, both organic and inorganic, can be bound to the organic compounds and thereby leave the matrix [6]. Volatile organic compounds, but also inorganic volatile compounds such as mercury, can release the matrix during mixing. Oil and grease cause the coating of waste particles and thereby weaken the bond between particle and cement [17]. Pretreatment may be required.

Additives

Because of the described immobilisation mechanisms, some cations, anions and organic compounds are hard to immobilise. Therefore, additives are used in order to optimise the immobilisation. In the following, the common additives are given and related to the desired encapsulation mechanism.

In order to optimise the hydration reaction, pozzolanic materials, such as blast furnace slag and cement-kiln dust are added. Pozzolanic materials need an additional calcium source

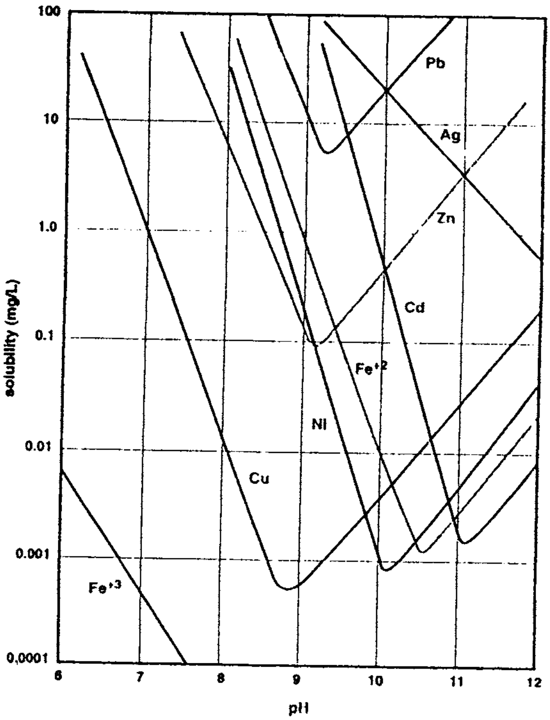

Figure 2: typical solubility curve for metals over a range of pH

in order to start the hydration reaction. Therefore and for the formation of ettringite, an external calcium source is required, like $CaCO_3$, $CaCl_2$ or $CaSO_4$. NaOH and MgOH may be used for to optimise the hydration reaction.

Ohter additives are useful for the immobilisation of inorganic compounds: soluble silicates, reducing agents, oxidants and clay. Soluble silicates, such as silica gel ($Na_2Si_4.xH_2O$), can chemically bind inorganic contaminants. However, a common disadvantage of these additives is an increase of volume [17]. Reducing and oxidising agents, such as Fe^{2+}, Fe^{3+}, Mn^{4+}, SO_4^{2-} are added in order to precipitate salts [14]. A REDOX-reaction will lead to less soluble salts and thereby diminish the leaching out of salts through the pores. An example is the reduction of ferric (II) to ferric (III) and the oxidation of chromium (VI) to chromium (III). Chromium (III) is less soluble than chromium (VI). Clay is added to absorb inorganic compounds and excessive free water. It is also used as absorbent of organic compounds.

Organic compounds can be immobilised in the cementious matrix by addition of certain absorbents, such as the previous mentioned clay and active coal [10,18]. By means of clay, organic compounds are absorbed in the matrix by non-ionic forces. Soluble organic compounds with carboxyl and hydroxyl groups, can be fixed at the Ca^{2+}-ions. They thereby become insoluble. Organic, particularly aromatic, substances can be immobilised by absorbing on a layered clay mineral. The clay is therefore modified with alkyl ammonium, which increases the adsorption surface. The surface has no longer hydrophilic but organophilic conditions. After adsorption of the organic compounds, the clay is mixed with a hardenable inorganic binder, f.e. $Ca(OH)_2$ or Ca^{2+}-containing cement. Other techniques consists of the addition of an absorbent, others than clay [3,16]. A possibility is mixing the waste with a binder and then granulate. The granulates are contacted with solvent to extract hydrocarbons. Or the organic waste may be dispersed in water containing a cationic ammine as an emulsifier. Subsequently, the emulsion is mixed with cement. The last technique for organic waste materials is to saturate the waste material with water and mixing it with an inorganic hydraulic binder [21]. Because of the high pH some organic compounds will vaporise.

Leaching mechanisms
Once the immobilised product is put into practice, the isolation of contaminants from the environment can not totally be guaranteed. The mechanisms that contribute to the release of these contaminants are caused by the presence of water in the pores or on the surface of the product, due to the following mechanisms: surface release, dissolving and diffusion. Figure 3 shows these three mechanisms.

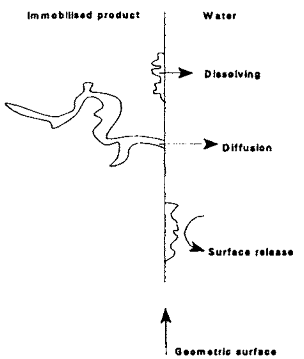

Figure 3: leaching mechanisms

Surface release is characterised by a short leaching out of contaminants in the first period of the application of the product. High soluble components at the surface of the product dissolve into the surrounded media. However, this leaching mechanism is important in organic immobilisation techniques and vitrification, inorganic immobilisation shows little surface release. Over a longer period, the rate of dissolving of contaminants is almost constant. An example is the release of Ca^{2+} from stabilised gypsum. However, this mechanism does not contribute much to the total leaching out of contaminants.

The most important mechanism is diffusion [6]. Diffusion is caused by the presence of water in the pores of the material and concentration variations between the material and the medium. As shown in the following formula, the diffusion capacity can be related to the tortuosity and the chemical retention.

$$L = \frac{f^2 \cdot D_0}{R \cdot \tau}$$

L	flux (m^2/s)
f	availability (-)
D_0	average diffusion coefficient (m^2/s)
R	chemical retention (-)
τ	tortuosity (-)

The tortuosity of an immobilised product indicates the path length of the ion through the pores [6]. A low tortuosity means a small diffusion path and thereby a high leaching rate of the component. Some immobilised products show low tortuosity compared to most building materials, such as concrete and bricks [6].

While tortuosity is a measure for the physical resistance of a component to diffusion, chemical retention is a measure of the hindrance of diffusion due to chemical interactions. Chemical retention is highly correlated to the pH in the pores. A typical relation between pH and some metals is shown in figure 4.

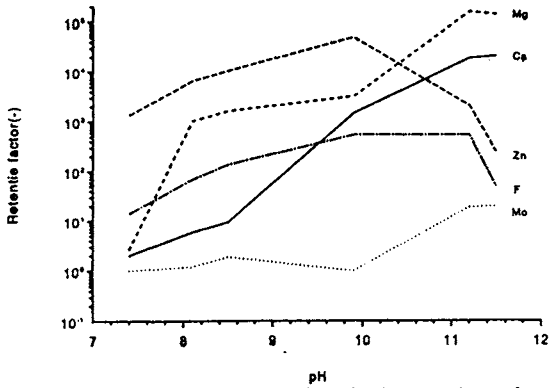

Figure 4: relation between chemical retention of certain elements and pH from the environment

Leaching test

To test the leaching behaviour of immobilised products, several test methods are suggested. Dutch legislation concerning building materials and landfill prescribes column tests, diffusion tests and availability tests. The first step in the column test is to fractionise the product to particles smaller than 4 mm and to put them in a column [11]. Acid water (pH = 4) is lead from the bottom to the top of the column. After certain periods, the liquid is tapped of. These periods correspond to specific water/material ratios (L/S = 0.1, 0.2, 0.5, 1.0, 2.0,5.0 and 10.0). This column test gives insight into the leaching behaviour of a fractionised waste over a short period (5 year) and moderate period (< 50 years). Another test, the cascade-test, gives information about the long term leachability. A column, water/material ratio of 100 kg/kg, is therefore shacked. The disadvantages of these tests is that the material has to be fractionised, while the aim of immobilisation is to encapsulate hazardous components in a compact matrix.

The second test, diffusion test, is specific for materials larger than 40 mm, like monoliths of immobilised waste. The product is surrounded by water of pH = 4. At certain time intervals, corresponding to L/S = 0.25, 1, 2.25, 4, 9, 16, 36, 64, the water is tapped of and purified. The concentrations of the percolates are determined. The results of the tests give insight into the contribution of diffusion to the total release of components.

The aim of the third test, the availability test, is insight into the leaching of inorganic components of a material under extreme circumstances [24]. The material is first pulverised until 95% of the material is smaller than 125μm. It is presumed that diffusion can take place through the whole material. During 3 hours, the material is washed with water (pH = 7) and after that washed with acid water (pH = 4). The ratio between water and material is each time 50. The composition of the percolate is determined and translated to the amount of leached components.

These test methods are not capable of measuring the leaching behaviour of organic compounds. Therefore, Dutch legislation is based on the organic composition of an immobilised product. However, these composition demands in Dutch legislation contradict the aim of immobilisation. Not the composition of the product but the leaching behaviour is a measure of the effectiveness of immobilisation.

Degradation mechanisms

Besides leaching mechanisms, other degradation mechanisms may effect the immobilised product. This gives an indication of the durability of the product. Durability is defined as the resistance to chemical, physical and mechanical influences. A product is durable when no intolerable decrease of relevant properties is caused by the influences. Figure 5 shows these external influences.

Inorganic immobilisation products are mostly sensitive to erosion, wet/dry-periods, temperature changes and freeze/thaw-periods [25]. Erosion is defined as the degradation of material due to moving media, such as wind, rain and rivers [5]. The wind contains fine particles, that deteriorate the surface [6]. Also, human activities can effect the surface, by walking and driving. The erosion sensitivity depends on the strength level of the product. Products with high strength have high resistance to erosion.

Wet/dry periods are characterised by the transportation of water between the environment and the immobilised product [6]. This may lead to (re)crystallisation. In addition, wet/dry-periods causes shrinkage or swelling of the material. Shrinkage is due to the release of water from the pores and the release of adsorbed water. Because of increased surface tensions, due to the release of water, the surfaces attract each other. This leads to shrinkage. The extent of shrinkage highly depends on the W/C-factor and the cement contents. Shrinkage is from major importance for products with high amounts of clay. This can cause the formation of cracks on the surface of the product. The opposite mechanism appears in the presence of water, the wetting periods. Although this mechanism is much faster than shrinkage, shrinkage is the major cause for the formation of cracks during wet/dry-periods.

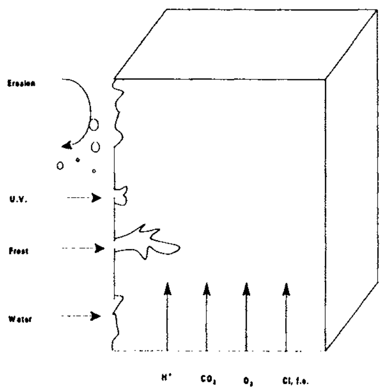

Figure 5: degradation mechanisms

Temperature changes has been mentioned before in relation to the formation of heat during hydration. The same argumentation can be followed here. Temperature changes of the environment causes temperature gradients in the immobilised material. This can lead to the formation of cracks.

Freeze/thaw-periods can also contribute to micro- and macro-cracks formation. Due to freezing periods, the water in the pores can be frozen. Because of the increase of volume, the pores will expand. Water that is not frozen is pressed into smaller pores and causes press-tensions. Another mechanism is the crystallisation of the water vapour in the concrete to form ice. Due to the lower vapour tension of ice in comparison to water, water vapour moves to the ice. This leads to the growth of the ice in the larger pores and the decrease of water in the smaller pores. This mechanism also leads to the formation of cracks in the material. A specific case of freeze/thaw periods is the presence of thawing salt. Thawing salts lead to the decrease of the freezing point of water, depended on the concentration of salts. In the centre of the material the concentration of salts is lower than on the surface. Temperature gradients and these concentration gradients may causes the surface and the centre to freeze. The isolated water, between the ice zones, presses on the surface, which will lead to degradation of the surface [2].

Application potentialities

Before a useful application can be chosen, the product has to be tested on legislation concerning building materials. The aim of legislation concerning building materials is to promote the recycling of secondary building materials combined with the aim to control the leaching out of hazardous components. In order to determine the suitability of building materials, the leaching behaviour of the inorganic components and the organic composition of the material must be determined. If application is allowed, the destination of the product partly depends on the strength of the product. Compared to 'traditional' concrete, compressive strengths of immobilised products have decreased by a factor 10 [25]. The immobilised products may be used in f.e. sound walls.

However, most of the immobilised products are not allowed to be used as building materials. In that case, legislation concerning the disposal of waste becomes active. This legislation is also based on the leaching behaviour of inorganic components in the waste.

C_2-waste: waste that is very harmful. At this moment, there is one C_2-landfill and in the near future no new disposal will be built. Some C_2-waste materials are or will be prohibited to be disposed of, such as fly-ash from Municipal Incineration Plants (MIP). With permission of the specific foreign country, the waste may be exported.

C_3-waste: waste that has high leachability of inorganic harmful components. The waste must be isolated from the soil.

C_4-waste: this waste has moderate leachability of inorganic components. Some adaptations are needed to minimise the leaching out of components to the soil.

Both useful application and disposal require more or less after-care of the immobilised product. In case of disposal, isolation, control and managing activities are required. When a product is usefully applied, the demolish of the object needs to be controlled.

Costs

Economic merit depends on the benefits and costs of the used and produced materials, disposal, transport, labour, energy, aftercare and investments. Some benefits can be obtained if the immobilised products can be usefully applied. Costs of transport, energy and labour are almost the same as for primairy materials. The disposal of the immobilised products may give some benefits. The benefit of the promotion of the waste material from C_2-disposal to C_3-disposal is approximately f75.-/ton, from C_2- to C_4-disposal f200,-/ton. The total cost of the inorganic immobilisation of MIP-fly ash is estimated between f60,- and f180,- /ton fly ash [27]. In most cases the economic merit for both disposal and useful application is low or negative.

Environmental aspects

Inorganic immobilisation techniques are meant to contribute to the environmental merit of the waste. Therefore, a comparison is needed between other possible treatments of the waste material and inorganic immobilisation. In Dutch legislation the priority list of Lansink gives a first indication of the environmental merit of immobilisation. This priority of waste managements is as follows:

1. prevention
2. recycling;
3. useful application;
4. treatment;
5. combustion;
6. disposal.

Immobilisation techniques can be placed on the fourth level and in most cases have to be compared with disposal of the waste. Most hazardous waste materials, such as hazardous sewage sludge, can not be treated otherwise or directly usefully applied. They are placed on a so called C_2-, or C_3-landfill. An useful application of this immobilised waste material therefore seems to contribute to the environmental merit.

However, a few comments have to be made. If the immobilisation technique does highly effect the environment, it is not clear that immobilisation is the right waste management. In case of inorganic immobilisation, degradation of the environment is caused by the use of energy, the use of primairy materials, the release of hazardous components during the process and the leaching out of hazardous components. Benefits for the environment are the replacement of primairy materials, such as gravel, by immobilised products and upgrading the waste material on the previous mentioned priority list of Lansink.

Inorganic immobilisation show little release of components during the process and some use of additives and energy. The environmental merit of the technique can be the replacement of primairy materials by secondary materials. So, from environmental point of view, inorganic immobilisation is a good option, when the leaching out of components can be minimised and the properties of the product fulfill demands of legislation concerning building materials. Otherwise, an environmental merit is not simple to give.

3 PROPERTIES OF RELEVANT WASTE MATERIALS

In the previous, the effectiveness of inorganic immobilisation has been considered. The effectiveness partly depends on the used additives. Besides that the properties of the waste material are an important factor in the effectiveness. Some components are good, other are hard to immobilise. In this paragraph, desired properties of the waste material are given.

Inorganic immobilisation is partly based on chemical reactions. Therefore, the following properties of waste materials are desired. Waste materials containing heavy metals, especially Pb, Cd and As are mentioned in patents. Figure 4 shows that Mo and Zn are hard to immobilise. In addition Cr^{6+} is mobile at high pH. It is therefore desirable to immobilise waste materials with high content of heavy metals, apart from Mo, Zn and Cr^{6+}. Secondly, the presence of anions is in most cases not desirable. Exceptions of anions that can be immobilised are sulfates and sulfites. Thirdly, low concentrations of organic compounds are desirable. Especially Volatile Organic Compounds can not be fixed in the solidifying matrix and can cause degradation of the immobilised product.

The effectiveness depends not only on the chemical reaction, but also on the physical encapsulation. Some properties of the waste have negative or positive influence on this encapsulation. F.e., the presence of pozzolanic or hydraulic components in the waste is preferable. On the contrary, particles with size less than 74μm, are not preferable. They weaken the bond between particle and cement.

From environmental point of view, the so called C_2-waste materials can contribute more to environmental merit than C_3-waste materials. Moreover, some C_2 -waste materials are or will be prohibited to be disposed of, such as MIP-fly-ash. Furthermore it is desirable to minimise the pretreatment of the waste. Pretreatment requires additional energy, additional primairy materials and/or may lead to a residue, that has to be treated. Pretreatment may be required f.e. when the waste material contains oil, grease and particles less than 74μm.

Other considerations for the effectiveness of immobilisation are: variations in composition, other treatments for the waste material and the amount of the production of waste.

Currently, some inorganic immobilisation techniques have been developed. Accordance to patents, the following waste materials are common: filter dust, coal ashes, MIP-fly ash, residues from burning of coal, sewage sludge, lime sludges, fluorgypsum waste, arsenical waste, slag and dust from steel making.

CONCLUSIONS

In this last paragraph the advantages and disadvantages of inorganic immobilisation will be mentioned, which are deduced from the description of the effectiveness of inorganic immobilisation in the previous paragraphs.

Because of the high pH of the product most heavy metals show good results, except from Mo and Cr^{6+}. Other components of the waste material are hard to immobilise, such as anions and organic compounds. These elements can leave the immobilised product through diffusion. Therefore, most inorganic immobilised products do not fulfill the legislation concerning building materials. Additives or pretreatment may be required to improve the immobilisation. Furthermore, immobilisation requires severe after-care of the product. However, in special cases this may lead to a decrease of economic and environmental merit of the technique. Inorganic immobilised products are highly sensitive to the formation of cracks. Especially erosion, wet/dry-periods, temperature changes and freeze/thaw-periods [25] influence the product. Besides these disadvantages, inorganic immobilisation can be a good solution for the amount of certain hazardous waste materials.

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