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Production of non-constructive concrete blocks using contaminated soil

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ABSTRACT

In this research, a heavily contaminated humus-rich peat soil and a lightly contaminated humus-poor sand soil, extracted from a field location in the Netherlands, are immobilized. These two types of soil are very common in the Netherlands. The purpose is to develop financial feasible, good quality immobilisates, which can be produced on large scale.

To this end, two binder combinations were examined, namely slag cement with quicklime and slag cement with hemi-hydrate. The mixes with hemi-hydrate proved to be better for the immobilization of humus rich soils, having a good early strength development. The heavily contaminated soil with 19% humus (of dm) could not be immobilized using 398 kg slag cement and 33 kg quicklime per m^3 concrete mix (binder = 38.4% dm soil). It is possible to immobilize this soil using 480 kg binder (432 kg slag cement, 48 kg quicklime) per m^3 of mix (58.2% dm). An alternative to the addition of extra binder (slag cement with quicklime) is mixing the soil with sand containing particles in the range of 0–2 mm. This not only improved the compressive strength of the immobilisates, but also reduced the capillary absorption. All the mixes with the lightly contaminated soil were cost-effective and suitable for production of immobilisates on a large scale. These mixes had good workability, a good compressive strength and a low capillary absorption. The leaching of all mixes was found to be much lower than allowed by the regulations. Given these results, the final mixes in the main experiment fulfilled all the financial and technical objectives.

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1. Introduction

In the Netherlands, there is a large demand for primary construction materials. At the same time, many locations in the Netherlands are contaminated and need to be remediated according to the national environmental laws [1,2]. Since the amendment to the National Waste Management plan in 2005, immobilization is considered to be equivalent to remediation of waste [3]. Immobilization of contaminated soil can be a partial solution for both needs. Immobilization also fits the sustainable building concept, because waste materials are re-used, so less primary construction material is needed.

The Netherlands Building Material Degree [2], which applies to stony materials, distinguishes two categories of construction materials: shape retaining and non-shape retaining materials. The successful production of a non-shape retaining building material using contaminated dredging sludge and the binders slag cement and lime was presented by Brouwers et al. [4]. Shape-retaining materials need to have a volume of at least 50 cm^3 and maximum weight loss of 30 gr/m^2 during the diffusion-test [2]. An additional problem with the immobilization of soil is the possible presence of humus with the soil. Humus can retard the hydration of cement and can have a negative influence on the characteristics of a mix.

The immobilisates need to be able to replace products which are made from primary raw material. Therefore, the immobilisates need to fulfil, besides the leaching limits, the same requirements as products based on primary materials. In this case, where a mega/lego block is produced, at least a compressive strength of 25 N/mm^2 is required. The requirement of 25 N/mm^2 was given by the producer of the mega blocks as their requirement for the production on large scale. These mega/lego blocks are used as separation walls in concrete factories for resources and storing locations to separate different kind of resources, soil and rubble.

In addition, the immobilisate needs to represent a financially feasible solution, which means that the profit on producing the immobilisate must be the same or better than that of the primary product. Furthermore, this production of the immobilisates should be possible on a large scale. So, financially feasible solutions and production on a large scale are both important criteria for the design of the mix.

The research is executed in cooperation with two companies which are in involved in the production of concrete blocks and the remediation of contaminated soil, which are searching for more financial attractive and better ways to process contaminated soils. The research consists of two parts: the main experiment and

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an additional experiment. The main experiment focuses on the immobilization of two soils. One soil is contaminated with lead and cadmium, while the other soil is contaminated with arsenic, chromium, copper, lead, nickel, zinc, and mineral oils. In the additional experiment, the influence of humus on the immobilization process is studied. Both soils are extracted from contaminated sites within the Netherlands and are representative for the soil types common in the Netherlands. One of the soils is selected because it has a high organic matter, which is common in certain regions of the Netherlands. It is known that organic matter has an influence on the hydration of binders. The first step is to characterize the soils both physically (particle size distribution and dry matter) and chemically (chemical composition). This characterization is described in Section 2. The chemical composition and especially the contaminations of the soils have an influence on the choice of the binders. Therefore Section 3 describes, based on a literature research, the choice of two binder combinations and two binder amounts for the immobilization of the soils. This selection aims to provide the best fit between contaminations and the stabilization/solidification potentials of the binders. Using the selected binder, a first series of explorative tests are performed in order to identify the possible problems of the chosen binders (Section 4). The next step is the determination of the water need of the mixes (Section 5.1). This is needed because high water/binder have a negative influence on the strength of the product, but a too low water/binder ratio will result in problems during mixing. The results of this determination have been used to modify the mix design for the mortar tests (Section 5.2). The mortar tests consist of test on compressive strength, tensile splitting strength, leaching and financial feasibility.

Table 1
Physical and chemical characterization of soils.

Parameter	D-soil (%)	J-soil (%)
Dry matter (dm)	94.8 m/m	63.6 m/m
Organic matter (H)	2.4 dm	19.0 dm
Lutum (L)	7.9 dm	2.4 dm
$CaCO_3$	1.6 dm	17.0 dm

Subsequently, based on the results of the mortar tests, the final binder combination is chosen. This binder combination is used for the production of the ultimate concrete mix. In this mix also a coarse aggregate is added in order to improve the performance. These concrete mixes are tested on compressive strength, tensile splitting strength, leaching and financial feasibility (Section 7). Finally, Section 8 give the financial analysis or economics of all mixes made during the research.

The major input variables for this research are the physical and chemical characterization of the used soils. The main output variables are the compressive and tensile splitting strength, leaching of contaminations, the financial feasibility and possibilities of large scale application of the findings in practice.

2. Materials and methods

2.1. Materials

Two soils are used within this research. The physical characteristics of both soils, henceforth named D- and J-soil, are presented in Table 1 and the particle size distribution is presented in Fig. 1. The D-soil is poor in humus, clay containing and sandy soil. The J-soil is a humus rich, clay containing and sandy soil and comes near to a peat soil. Both soils are common soil types in the Netherlands.

Besides the physical characteristics, the environmental characteristics are important. In the Netherlands, soil is considered as a non-shaped material, while concrete is categorised as a shaped material. The methods for the determination, when a material may be used, are different for both categories. The determination of the leaching, the leaching limits and the composition limits differ for these two categories.

For non-shaped material, the leaching is determined using a column test, which is described in the standard NEN 7343. The BMD [2] distinguishes four categories of non-shaped material, The distinction is made based on two parameters: immission and composition [4].

In this research a shaped material is produced. For a shaped material, the leaching is measured by the diffusion-test, which is described in standard NEN 7345. For the mix design, only the composition is used, because the composition is a measure for the availability of heavy metals for leaching. Since the calculation methods differ for both categories of materials, a comparison of the immission of soil (non-shaped) and immission of product (shaped) is not possible. Therefore immission is very difficult to use for the mix design.

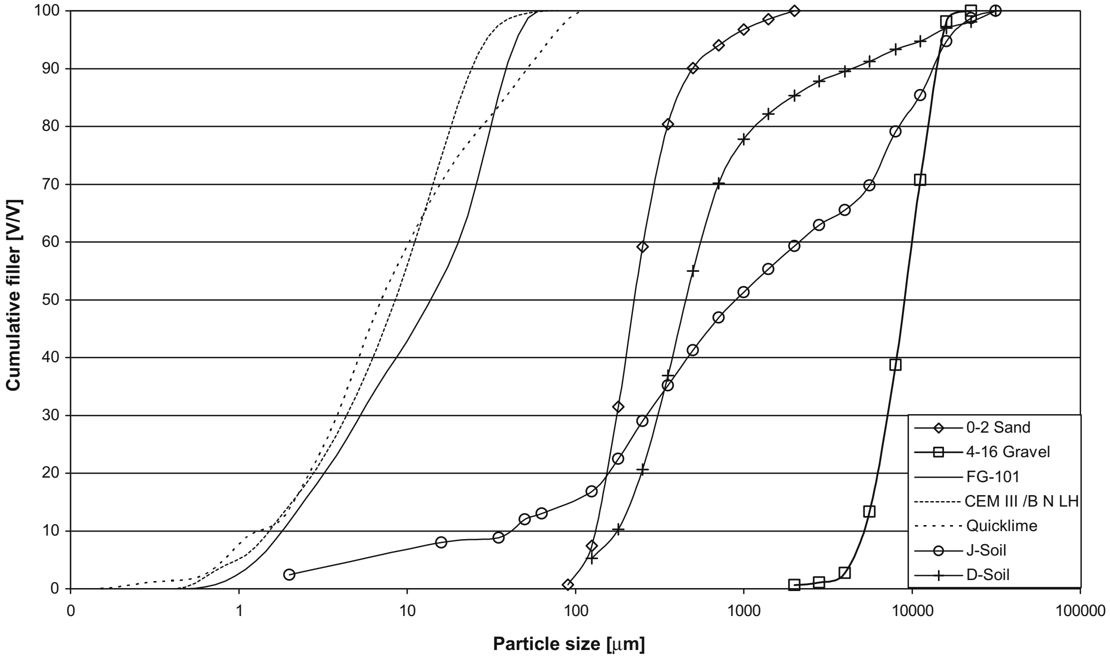

Fig. 1. Particle size distribution of the applied soils, binders, and aggregates.

Table 2a
Contaminant concentrations D-soil.

Chemical	Measured (mg/kg)	S1 (mg/kg)	S2 (mg/kg)	<S1	S1-S2	>S2
Arsenic	14	19.1	36.3	X		
Barium	68	89.7	280.2	X		
Cadmium	20	0.5	7.7			X
Chromium	28	65.8	250.0	X		
Cobalt	15	9.4	112.3		X	
Copper	27	21.2	111.8		X	
Mercury	0.2	0.2	7.6	X		
Lead	140	60.3	376.0		X	
Molybdenum	3	10.0	200.0	X		
Nickel	22	17.9	107.4		X	
Zinc	150	77.3	397.5		X	
Mineral oil	49	12	120		X	
Sum PAK	2.1	0.24	9.6		X	

Table 2b
Contaminant concentrations J-soil.

Chemical	Measured (mg/kg)	S1 (mg/kg)	S2 (mg/kg)	<S1	S1-S2	>S2
Arsenic	320	25.7	48.7			X
Cadmium	12	0.9	14.0		X	
Chromium	370	56.8	215.8			X
Copper	1400	31.0	163.7			X
Mercury	0.2	0.2	8.3	X		
Lead	4700	76.7	478.2			X
Nickel	70	13.4	80.4		X	
Zinc	8500	95.2	489.3			X
Mineral oil	1700	116.5	1165			X
Sum PAK	4.9	2.33	93.2		X	

Table 3
Physical properties, chemical composition and standard strength development of CEM III/B 42.5 N LH (ENCI, 2006).

Properties		
Begin binding	230	Min.
Specific surface	475	m^2/kg
Specific density	2950	kg/m^3
Loose bulk density	1050	kg/m^3
Hydration heat (isotherm)	<270	J/g
C-value	1.50	–
Composition		
Chloride level (Cl^-)	0.05	% m/m
Na_2O equivalent	0.6	% m/m
Portland cement clinker	26	% m/m
Blast furnace slag	72	% m/m
Other ingredients	2	% m/m
Standard strength		
2 days	12	N/mm^2
7 days	36	N/mm^2
28 days	59	N/mm^2

Table 4
Properties hemi-hydrate.

Properties		
Degree of purity	>95	%
Dissolvability (gypsum in 100 ml water)	>300	g
Water/gypsum factor	<0.33	
Crystal water	<6.20	%
Begin binding	4–9	Min.
pH value	7–9	
Bulk density	1250–1450	kg/m^3
Specific density	2720	kg/m^3
Degree of whiteness	>40	%

Table 5
Properties quicklime.

Component	Notation	(% m/m)
Loss on ignition		2.5
Silicium dioxide	S	1.2
Aluminium oxide	A	0.22
IJzer (III) oxide	F	0.21
Magnesium oxide	M	1.5
Calcium oxide	C	95.3
Free calcium oxide	C	92.7

Two limits (SC1 and SC2) are available for the composition of non-shaped material. Both limits depend on the physical parameters of the soil. This means that the two used soils have different limits. In Tables 2a and b the composition of soils is described as well as the modified composition limits. The D-soil only contains one pollutant, which renders it Not Applicable: cadmium is above the so called SC2-level. The J-soil contains arsenic, chromium, copper, lead, zinc, and mineral oil levels that are above the SC2-level. These pollutants render this soil Not Applicable as well.

In this research a third soil is composed which consists of half J-soil and half sand with particles in the range of 0–2 mm (0–2 sand). This soil has a lower humus level and is used for the additional experiments in order to measure the effect of humus on the hydration and immobilization. This soil is named the J½-soil.

Besides the soils, some other materials are used like binders and aggregates. The used binders are slag cement, quicklime and hemi-hydrate. The slag cement used for this research is a CEM III/B 42.5 N LH. Table 3 describes the physical properties, chemical composition and strength development of this slag cement [5]. Table 4 shows the physical properties of the hemi-hydrate, while Table 5 shows those of quicklime. Fig. 1 shows the particle size distribution of the different binders and the two aggregates used within this research.

2.2. Test methods

The mortar mixtures are mixed with Hobart mixer, while full concrete mixtures were mixed by using a force mixer. The samples have been vibrated on medium speed on a vibration table, in order to reduce the air-content. All samples have been demould after 24 days and stored under water of 20 ± 1 °C.

For the research six test methods are used to evaluate the developed mixes: (1) slump flow, (2) V-funnel, (3) compressive strength, (4) tensile splitting strength, (5) capillary absorption, and (6) diffusion/leaching. The slump flow, V-funnel, compressive strength, tensile splitting strength are described in more detail in Brouwers and Radix [6]. In this Section the spread-flow test, capillary absorption and diffusion/leaching tests are described.

The spread-flow test is a common way to assess the water demand of pastes and mortars. This yields a relation between relative slump flow (Γ) and water/powder ratio of the paste (V_w/V_p). The powders are defined here as all particles smaller than 125 μm. The test is executed analogously to Domone and HsiWen [7] and ordinary tap water is used as the mixing water in the present research. The relation between V_w/V_p and Γ is described by

$$\frac{V_w}{V_p} = E_p \cdot \Gamma + \beta_p \tag{1}$$

This method was originally developed for powders only [8]. But the same procedure can be applied on mortar mixes with the use of the same Heagermann cone. Besides the determination of relation between relative slump flow (Γ) and water/powder ratio (V_w/V_p), it is also possible to do this for the water/solid ratio. Solids means in this case the powders and sand in de mix, i.e., all solids in case of mortars.

The relative slump (Γ), used in for spread-flow test is determined with Eq. (2), whereby d_1 and d_2 are the maximum diameters, rounded off at 5 mm, and d_0 is the base diameter of the Haegermann cone

$$\Gamma = \left(\frac{d_i}{d_0}\right)^2 - 1 \quad \text{with } d_i = \frac{d_1 + d_2}{2} \tag{2}$$

The capillary absorption is measured, analogous to Brouwers and Radix [6], Audenaert et al. [9], and Zhu and Bartos [10]. Prior to the experiment, the concrete cubes (of age 28 days) were dried in an oven at 105 ± 5 °C during 48 h, and cooled down during 24 h at room temperature. Then, the cubes were placed on bars with a diameter of 10 mm, so that the water level is 5 ± 1 mm above the lower horizontal face of the cube. The mass increase of each cube is measured after 0.25, 0.5, 1, 3, 6, 24, 72, and 168 h. Furthermore, the height of the capillary rise is measured on the four vertical side faces (in the centre of the side) of each cube; the mean values of each cube, H. There is a linear relation between the capillary rise and the square root of time [6,9,10]

$$H = H_o + \mathrm{SI}T^{0.5} \tag{3}$$

In this equation is H the height of the capillary rise, H_0 the intersection with the y-axis [mm], SI the sorption-index [mm/h$^{0.5}$] and and T the time (h). The SI is a measure for the uptake of water by a concrete surface exposed to rain for instance. In Audenaert et al. [9] it can be found that SI should be smaller than 3 mm/h$^{0.5}$.

Finally the leaching of the hardened product is measured by the diffusion-test (NEN 7375). The cubes are places in 1 (in case mortar cubes) and 7 l (in case of concrete cubes) of acid water of pH 4. The acid water is replenished after 0.25, 1, 2.25, 4, 8, 16, 36, and 64 days. This water is analysed on the concentration of heavy metals. From this leached amount the immission can be calculated according to NEN 7375 and BMD. Further details of the followed calculation procedure can be found in de Korte [11].

3. Previous research

In this section, previous research will be recapitulated in five subsections: (3.1) the use of (contaminated) soil for the production of concrete blocks, (3.2) influence of contaminations on the immobilisation; (3.3) possible binders, (3.4) the amount of binder which is needed, and (3.5) the composition of the binder. This information will serve as a basis for the new mix designs developed and tested here, presented in the next section.

3.1. The use of (contaminated) soil for the production concrete blocks

This section will focus on the use of (contaminated) soil for the production concrete blocks from the point of the view of the scientific literature. Contaminated soil is used for the production of concrete blocks in several studies. For instance Hago et al. [12] point out that organic and inorganic wastes can be stabilized by using fly ash, lime, Portland cement or a combination of these materials. This often results in a pozzolanic reaction that prevents or minimizes the release of contaminants into the environment by producing a solid mixture, decreasing surface area for contaminant transport, improving handling characteristics and reducing mobility of the contaminants into a less toxic form.

The use of soils in concrete also introduces some challenges. The main challenge is the presence of organic matter in the soil. Organic soils can retard or prevent the proper hydration of binders such as cement in binder–soil mixtures [13]. Clare and Sherwood [14] and Maclean and Sherwood [15] suggested that the retardation of the hardening of organic soil–cement mixture is due to the retention by the organic matter of the calcium ions, liberated during the hydrolysis of the cement particles. Therefore, only part of the calcium released during hydration is available for the pozzolanic reaction, and this is believed to be the reason for the difficulty encountered in immobilizing organic soils. Another part of the explanation is that the humic acid reduces the pH of the soil, which has influence on the hydration rate of the binders. This will result in lower strength development in organic-rich soils compared to organic-poor soils.

Another challenge is the fineness of the soils. A very fine soil will lead to high water need [16] and therefore a lower compressive strength. The fine particles are commonly clay particles. Walker and Stace [17] point out that 5–10% cement is sufficient to stabilize soils with clay mineral contents less than 15–30% for non-constructive applications. They point out that the mortar compressive strength decrease with increasing clay content. The compressive strength drops from 9 N/mm^2 for 9% (m/m) clay to 5 N/mm^2 for 30–40% (m/m) clay.

For the practical use of soil for the immobilization, the concrete blocks need to show sufficient compressive strength, high durability, and low leaching of heavy metals. Shan and Meegoda [18] show the possibility to produce concrete blocks with soil with compressive strength of more than 25 N/mm^2. Guettala et al. [19] has done research to the durability of stabilized earth concrete under both laboratory and climatic conditions exposure. They noted that all treated walls showed no signs of deterioration after 4 years of exposure in real climatic conditions. They used between 5% and 12% (m/m) of binder based on the soil. They found a compressive strength between 15.4 N/mm^2 for 5% (m/m) cement and 21.5 N/mm^2 for 8% (m/m) cement with 4% (m/m) lime. These compressive strengths are close to the required compressive strength in this research. Yin et al. [20] for instance shows that a contaminated soil from a scrap metal yard with high amount of heavy metals could be immobilized successfully. The leaching of the treated materials was low as well for the leaching of crushed materials as for the whole blocks. Yin et al. [20] showed that stabilization is effective since the amount that is leaching is very small compared to the amount available according to the composition of the soil. Besides this, the compressive strength reached 22 N/mm^2 with 50% (m/m) of binder based on the soil.

Based on these results from literature, it could be concluded that contaminated soil could be used for the production of concrete blocks with a compressive strength of 15–20 N/mm^2, high durability and low leaching of heavy metals. In the present research a concrete with compressive strength of 25 N/mm^2 is aimed at, since this was the requirement of the producer involved in the project.

3.2. The influence of contaminants on immobilisation

The contaminants' characteristics influence the degree to which immobilization is possible. Arsenic, lead, chromium and cadmium are solvable in acid environments. Arsenic and lead are amorphous, which mean that they are soluble in both acidic and base environments. Immobilisates which are produced using cement have a high pH. This means that heavy metals are soluble and available for leaching. The leaching behaviour strongly depends on the valence of the metal. Both arsenic and chromium have more than one valence. Chromium (III) is for instance easier to retain than chromium (VI) [21].

Heavy metals also influence the hydration of cement. Copper, lead and zinc will retard the hydration of cement [21]. Chromium shortens the gel fibres and increases the matrix porosity [22].

The way heavy metals are incorporated in the hardened product differs from case to case. Cadmium, zinc, and arsenic can replace calcium within CSH [23]. Chromium and lead are absorbed within the CSH-binding, but nickel cannot be absorbed within the CSH-binding [24]. Chromium (III) can replace aluminium within the CAH-binding [25]. The different binders have a different oxide composition and therefore they have a different level of bindings. This means that the most suitable binder can be selected based on the required bindings.

3.3. Possible binder combinations

In this section the feasible binder combinations are described. The first and most known binder is ordinary Portland cement (OPC). Portland cement is suitable for immobilization of most heavy metals. Pure blast furnace slag is more suitable for the immobilization of heavy metals in humus rich soils. The use of slags results in a lower porosity and permeability compared to the use of Portland cement. A lower porosity normally results in a lower level of leaching. However, a major disadvantage of the use of slag is the slower reaction rate. This reaction rate decreases further due to the presence of heavy metals and humic acid. Hence, an initiator could be needed when slags are deployed. The main reason is the absence of a calcium source within slag [26]. Possible initiators are quicklime, anhydrite, and hemi-hydrate. The advantage of the use of calcium sulphates is the possible formation of ettringite. Ettringite can fill the pores between the soil particles and so decrease the porosity and permeability. A lower porosity will result in a lower level of leaching [21].

Portland cement also acts as activator for slag. The combination of Portland cement and slag, i.e., slag blended cement, results in a higher compressive strength and better immobilization than when Portland cement is used only. The combination of Portland cement and slag has the same effect as when blast furnace slag cement is used. For instance, the combination of 25% Portland cement and 75% blast furnace slag has the same composition as many available blast furnace slag cements.

Another possible binder is pulverized fly ash (PFA), although it is less suitable than blast furnace slag. For the immobilisation of cadmium and copper, PFA is less suitable [27]. For chromium, PFA is completely unsuitable, because it appeared that no strength development took place at all [22]. PFA combined with Portland cement is suitable for the immobilization of copper but unsuitable for lead [28]. Besides, as PFA reacts slowly, the strength development is slow too. So fly ash can better not be used for the immobilization of heavy metals.

The combination of calcium sulfoaluminate cement (CSA) and hemi-hydrate can be used instead of blast furnace slag. In a ratio of 70/30 CSA/hemi-hydrate it is suitable for all heavy metals except six valence chromium. For six valence chromium, a ratio of 80/20 is suitable. The combination of CSA with hemi-hydrate can result in the formation of ettringite. Ettringite can fill the pores between soil particles and therefore results in lower porosity and permeability, and also a lower level of leaching [27]. A disadvantage of the combination of CSA with hemi-hydrate is the introduction of more sulphate into the mix. Ettringite and gypsum are dissolved at low pH values, which results in the release of sulphate. The leaching of this sulphate is also regulated in the Building Material Degree. This problem also exists with the combination of blast furnace slag and hemi-hydrate. However, in the case of blast furnace slag cement and hemi-hydrate the problem is smaller due to a lower amount of sulphate in the binder.

3.4. Required binder amount

In this section the determination of the amount of binder per m^3 of concrete is described. An amount of 250 kg binder per m^3 concrete mix is currently used for the production of concrete blocks by Dusseldorp Group. According to Axelsson et al. [29], between 100 and 200 kg/m^3 is needed for the immobilisation of mud, 150–250 kg/m^3 for peat and 70–200 kg/m^3 for hydraulic filling. Nijland et al. [30] used 250 kg/m^3 for the immobilisation of contaminated clay. Yin et al. [20] used 900 kg/m^3 for the immobilization of contaminated soil from metal scrap yard. Shan and Meegoda [18] used 480 kg/m^3. Walker and Stace [17] used 250 kg/m3 for soil with less then 15% clay minerals. Guettala et al. [19] used 150 and 225 kg/m^3 for production of earth block using a sandy clayed (non-contaminated) soil.

Based on these finding, here also a binder level of 250 kg/m^3 is included. The binder amount of 350 kg is selected as well to overcome the possible negative effects of heavy metals and humus. A binder amount of 500 kg is introduced to investigate if the addition of extra binder can neutralize the possible negative effect of large quantities of humus. Hence, in this research, binder amounts of 250, 350, and 500 kg/m^3 are selected. These amounts correspond with 13.6, 21.9, and 26.7% (m/m) on dry matter of D-soil. While the amount of 350 kg for the J-soil corresponds to 38.4% and 500 kg with 58.2% dm.

3.5. The composition of the binder

This section summarizes possible binder combinations that will be used in this research. The first binder combination is slag cement and quicklime. This ratio is set to 90/10. Brouwers et al. [4] researched the immobilization on heavily contaminated (Class 4) dredging sludge. The ratio of 90/10 slag cement/quicklime gave good results. This finding is compatible with Janz and Johansson [31], who point out that the optimal mix lies between 60–90% slag cement and 40–10% quicklime.

The choice of a ratio of 60/40 slag cement/hemi-hydrate is based on the research of Huang [32]. This ratio was confirmed by the research of Peysson et al. [27]. Peysson et al. [27] indicated that 70% CSA and 30% gypsum is a suitable binder for the immobilization of most heavy metals. CSA itself also contains calcium oxide and sulphate. Because of that, the levels of calcium and calcium sulphate are higher than at the same ratio of slag cement and hemi-hydrate. In order to compensate this, here the proportion of hemi-hydrate is increased to 40%.

4. Exploratory tests

As a preparation for the main-research, some exploratory tests were done to identify possible problems which could arise with the application of soil in concrete mixes.

In these exploratory tests, two mix designs were tested on workability, air-content, compressive strength and leaching. The main difference between both mix designs was the binder combination. The first combination concerned blast furnace slag cement and quicklime and in the second combination blast furnace slag cement and gypsum were involved. Both these mixtures were based on the results from the literature research. The first tests showed that water present within the soil was insufficient for reaching a good workability. Therefore the addition of extra water and superplastizer was needed and the standard mixtures from literature were modified in order to reach a good workability. Table 6 shows the composition of these mixtures made during exploratory tests.

Table 6 also shows the results of the fresh mixes. The tests on hardened concrete show small differences between both mixtures.

Table 6
Composition (in kg/m^3) and measured properties concrete cubes exploratory research.

	D-HG-250 v	D-HK-350 v
Mix design		
Blast furnace slag cement	193.5	332.8
Quicklime	–	37.0
Gypsum (hemi-hydrate)	129.0	–
Mix water	197.8	282.9
Superplastizer-solution	0.0	1.5
DD ISM soil dry	1544.6	1324.1
DD ISM soil water	84.7	72.6
Total mass	2149.7	2050.9
Hardened properties		
Density		
7 days	2079	
28 days	2083	2072
Compressive strength		
7 days	12.6	
28 days	19.9	20.6
Tensile splitting strength		
28 days	2.20	3.14

Both mixtures do not fulfil the requirement for the 28 days compressive strength of 25 N/mm^2. The low compressive strength of both mixtures can be explained by a too high water/binder ratio. But also the particle size distribution of the mixture is not optimal. Therefore the packing of the mix is not optimal, which will result in a lower compressive strength [33]. The current particle size distribution is missing particles in the coarser range. Therefore the mixtures in the pre-research can be characterized as being more a mortar then a concrete. But the required compressive strength was for a concrete. In order to get a concrete a courser aggregates should be added. The problem of the high water/binder ratio is addressed in the mortar tests, while the problem of the particle size distribution was tackled in the concrete tests.

The mixes were also evaluated in regard to their environmental performance. Tables 7a and b show the calculated immission (I_{bv}) according to the Dutch standard NEN7375. This immission is calculated for the leaching during the diffusion-test. The detailed computation procedure can be found in de Korte [11]. The third column of both tables shows the maximum limit of immission according to Dutch law.

Both tables show that the measured immissions during diffusion-test were lower than the maximum allowed immissions according to Dutch law. The immission of sulphate for D-HG-250 v approaches the limits. This is caused by the dissolution of gypsum during the diffusion-test. Furthermore the heavy metals seem to be better retained by the combination of blast furnace slag cement and quicklime.

5. Mortar experiments

In this section the results of the experiments on mortar are described. The purpose of the mortar test is to solve the problem with the high water/binder ratio found in the exploratory tests by determining the water demand of the mixtures in order to achieve acceptable compressive strength. Therefore, the experiments on mortar are divided into two parts. The first part is the determination of the water demand in order to find the optimal balance between good flowability and low water content in order to achieve a high compressive strength and low leaching properties. The second part concerns the production of mortar cubes ($50 * 50 * 50\ mm^3$). The mix used for casting these mortar cubes was based on the results of the water demand part. The compressive strength, capillary absorption and diffusion of these mortar cubes will be determined. The results of the main and additional experiment are incorporated in this section. Section 5.3 will address the main findings of the additional experiment. The derived water demands from this sections are used in the mix design of the full concrete in Section 6.

Table 7a
Leaching data D-HG-250 v (in mg/m^2).

	I_{bv} (mg/m^2)	I_{max} (mg/m^2)
Sulphate	84.047	100.000
Cadmium	0.51	12
Chromium	2.82	1500
Copper	1.95	540
Nickel	2.70	525
Lead	13.18	1275
Zinc	10.24	2100
Cobalt	1.70	300
Arsenic	8.77	435

Table 7b
Leaching D-HK-350 v (in mg/m^2).

	I_{bv} (mg/m^2)	I_{max} (mg/m^2)
Sulphate	6.995	100.000
Cadmium	0.04	12
Chromium	0.13	1500
Copper	0.04	540
Nickel	0.11	525
Lead	0.42	1275
Zinc	0.14	2100
Cobalt	0.06	300
Arseen	0.84	435

5.1. Water demand

The water demand determination was carried out using the slump flow test for the mortar mix. This mortar mix includes binders, soil (fraction that passes the 4 mm sieve) and sand. The soil was sieved in order to make it possible to use a small mortar mixer. The D-soil could be sieved wet, but for the J-soil this was not possible. The J-soil is therefore dried during 24 h at 105 ± 5 °C. Before using this soil for the mortar mixes, the amount of water evaporated during drying was re-added, and mixed with the soil. These soil–water mixes stood for 30 min, so the soil could absorb the water. By doing so a wet soil could be simulated, which is closer to the practice since a wet soil will be used in the immobilization process.

The mixes are displayed in Tables 8a and b. The slump flow was measured for different water/powder ratios (m/m) and with differed amounts of superplasticizer (Glenium 51), based on the mass of powders in the mix. The mass of powders is the sum of all particles smaller than 125 m present in the mix. The function of a superplasticizer is to reduce the quantity of water while maintaining the same workability.

The relative slump flow is plotted against the water/powder ratio to construct the spread-flow line. The relative slump flow is computed with Eq. (2) with d_1 and d_2 as the diameters of the slump flow and d_0 the base diameter of the Haegermann cone. The water demand (β_p) of a mix is the interception point of the linear regression function based on these results [8], as shown in Fig. 2 (see also Section 2 and Eq. (1)). In Fig. 3 and Table 9, the water demands of mixes for different amounts of superplastizer are shown.

The different binder types all had their specific water demand. The mixes with slag cement and hemi-hydrate had a lower water demand (β_p measured as water/powder ratio) than the mixes with slag cement and quicklime. Also, the mixes with 350 kg binder had a lower water demand (β_p) than mixes with 250 kg binder. This lower water demand for higher binder amounts is partly caused by the chosen definition of water demand. Water demand is de-

Table 8a
Composition (in kg/m^3), fresh and hardened properties of D-mixes (mortar).

	Present mix	D-HK-250 m	D-HG-250 m	D-HK-350 m	D-HK-500 m	Unit
Mix design						
Slag cement		195.3	130.2	303.3	360.5	kg/m^3
Portland cement	250					kg/m^3
Quicklime		21,7		33.7	40.1	kg/m^3
Hemi-hydrate			86.8			kg/m^3
D-soil (dry)		1590.2	1598.8	1538.2	1499.5	kg/m^3
Sand	1950	0	0	0	0	kg/m^3
Water D-soil		87.2	87.7	84.4	82.2	kg/m^3
Superplasticizer		4.7	4.9	6.4	7.2	kg/m^3
Mix water	125	214.2	206.6	195.3	190.3	kg/m^3
Fresh properties						
Slump flow		108–109	107–108	139–140	107–110	mm
Relative slump flow		0.177	0.156	0.946	0.177	
Hardened properties						
Compressive strength						
7 days		1.91	3.09	8.31	10.05	N/mm^2
28 days		4.77	4.57	8.55	23.62	N/mm^2
Density						
7 days		1647	1603	1773	1941	kg/m^3
28 days				1761	1968	kg/m^3

Table 8b
Composition (in kg/m^3), fresh and hardened properties of J-mixes (mortar).

	Present mix	J-HK-350 m	J-HG-350 m	J$^1/_2$-HK-350 m	J$^1/_2$-HG-350 m	J-HK-500 m	Unit
Mix design							
Slag cement		298.4	198.2	408.4	259.7	431.7	kg/m^3
Portland cement	250						kg/m^3
Quicklime		33.2		45.0		48.0	kg/m^3
Hemi-hydrate			132.1		173.1		kg/m^3
J-soil(dry)		863.2	854.4	590.7	559.7	823.8	kg/m^3
Water J-soil		494.7	489.7	338.5	320.8	472.2	kg/m^3
Sand 0–2				590.8	559.6		kg/m^3
Sand + gravel	1950						kg/m^3
Superplastizer		8.4	8.5	9.0	8.9	10.5	kg/m^3
Mix water	125	44.6	47.8	36.9	78.5	32.8	kg/m^3
Fresh properties							
Slump flow		103 – 104	100 – 103	148–149	109–110	152–146	mm
Relative Slump flow		0.071	0.030	1.205	0.188	1.220	
Hardened properties							
Compressive strength							
7 days			0.75	2.27	3,81		N/mm^2
21 days						5.68	N/mm^2
28 days		0.68	1.64	7.33	6.51	6.64	N/mm^2
Density							
7 days		1640	1600	1868	1799	1707	kg/m^3

fined as the volume of water in de mix divided by the powder volume. Mixes with a higher binder content also have a higher powder content and hence, at same water content a lower water/powder ratio. But this effect can not explain the difference completely, because the total amount of water in the mixes is lower at higher binder contents. A possible explanation could be that the soil absorbed some of the mix water, so it is not available for enabling flowability. The mixes with higher binder content have namely a lower soil content. The mixes with J½ had a lower water demand than the normal J-mixes, which could be expected as J½ contains less fines. Section 6 contains a more detailed analysis of this effect/phenomenon.

5.2. Mortar cubes

The mixes for mortar cubes were based on the results from the water demand study. A relative slump flow of 0.2 and a superplasticizer use of 15 g/l powder formed the two constraints used for the mix designs. The mix compositions are presented in Tables 8a and b.

The hardened mortar was tested for compressive strength, density, leaching and capillary absorption. The last two properties could only be measured for the mixes containing slag cement and quicklime, because hemi-hydrate and gypsum readily dissolve when they come into contact with water.

The results of the experiments are presented in Tables 8a and b. A difference in the flowability was visible during the mixing. First, the mix was very dry and after a few minutes the mix became flowable. This time gap can be explained by the time the superplasticizer needs to form a thin layer around the particles [34], as is shown by i.e., Brouwers and Radix [6].

In Table 10, a comparison between the quicklime and hemi-hydrate mixes is presented. The mixes containing quicklime had a lower early strength than comparable mixes with hemi-hydrate. The mix with quicklime could be crushed manually. These effects became very clear when the humus content of the soil was in-

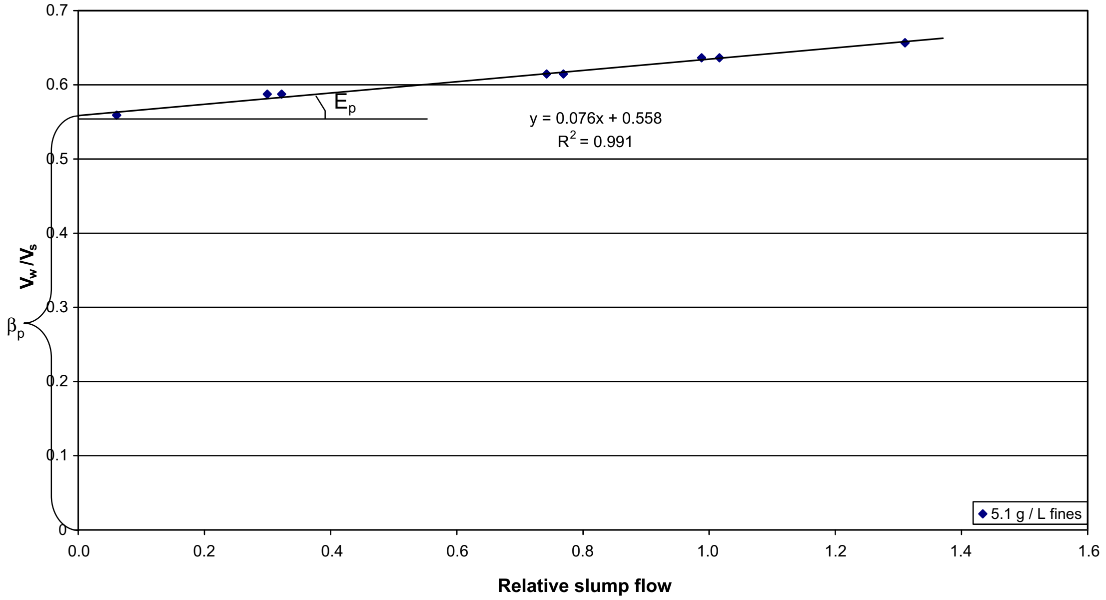

Fig. 2. Spread-flow line for D-HK-250 m for three amounts of superplastizer.

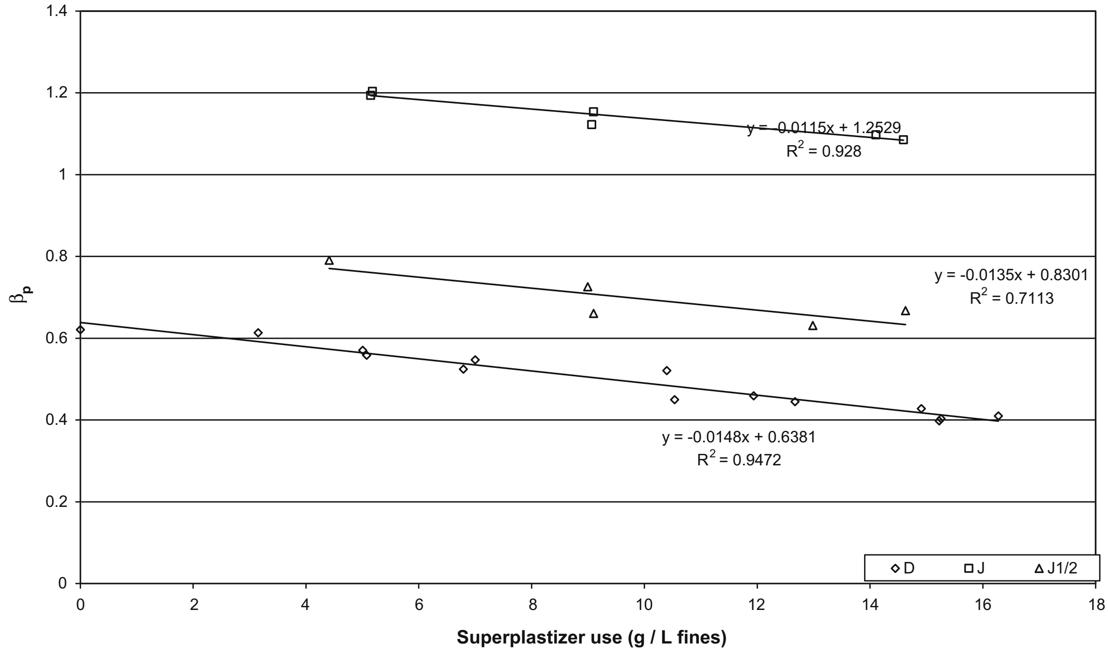

Fig. 3. β_p versus SP dosage for D-soil (215 < binder < 400 kg/m^3), J-soil (330 < binder < 480 kg/m^3) and J½-soil (430 < binder < 455 kg/m^3).

creased. The 500 kg variant of the J-soil with 19% humus could be crumbled manually after 1 day, but achieved a good compressive strength after 28 days. After 28 days, almost every mix with quicklime had a higher compressive strength than the comparable mix with hemi-hydrate. In general, the compressive strength increased when the binder amount increased. This effect was partly caused by a decrease of the water/powder ratio, which has a direct relation on the compressive strength [35] and partly to the binder as such.

A high leaching of sulphate is considered negative due to the limitations for the leaching of sulphate according to the Building Material Degree. Mixes containing gypsum, hemi-hydrate and anhydrite have a high sulphate leaching level. This was already shown by exploratory tests presented in Section 4. The solubility of gypsum, hemi-hydrate and anhydrite is relatively high, which results in a high leaching of sulphate. This means that mixes with hemi-hydrate are less suitable than mixes with quicklime.

The retention capability of heavy metals is also important for the immobilisates. Hemi-hydrate mixes can retain heavy metals better than the quicklime mixes. But here it appeared that both hemi-hydrate and quicklime were suitable for retaining heavy metals within the immobilisates (Table 11). The metal leaching was less than 5% of the limits specified by the Building Material Degree. The possibility that leaching of sulphate was masked by the leaching of the heavy metals has to be taken into account.

Both the hemi-hydrate and quicklime mixes had a sustainable shape retention during exploratory tests in Section 4. The tested

Table 9
Superplastizer versus β_p.

	SP (g/l fines)	β_p
D-HG-250 m	16.3	0.410
	6.8	0.524
	11.9	0.459
D-HK-250 m	10.4	0.521
	14.9	0.428
	5.1	0.558
	15.3	0.403
D-HK-350 m	7.0	0.547
	3.2	0.613
	12.7	0.445
D-HK-500 m	10.5	0.450
	5.0	0.570
	15.2	0.398
	0.0	0.621
J-HK-350 m	9.1	1.154
	5.1	1.194
	14.1	1.098
J-HG-350 m	9.1	1.122
	5.2	1.204
J½-HK-350 m	14.6	1.086
	4.6	0.664
	9.1	0.661
	13.0	0.631
J½-HG-350 m	9.0	0.726
	14.6	0.667
	4.4	0.791

Table 10
Performance overview of binders on most important aspects.

Aspect	Quicklime	Hemi-hydrate
Early strength		+
Final strength	+	
Leaching sulphate		–
Retaining heavy metals	+	++
Sustainable shape retaining	+	+
Humus neutralisation		+

Legend: ++ very suitable, + suitable, – unsuitable.

Table 11
Leaching results of mortar cubes D-soil (in mg/m^2).

	i_{max} (mg/m^2)	i_{bv} (mg/m^2)		
		D-HK-250m	D-HK-350m	J-HK-500m
Sulphate	100,000	30,352	52,080	10,158
Cadmium	12	0.04	0.05	0.07
Chromium	1500	0.04	0.04	1.40
Copper	540	0.11	0.10	14.00
Nickel	525	0.11	0.11	3.50
Lead	1275	0.45	0.45	3.50
Zinc	2100	0.37	0.38	1.40
Cobalt	300	0.07	0.07	1.40
Arsenic	435	0.84	0.84	3.50

quicklime mortar cubes also retained their shape during the diffusion-test. The mixes with hemi-hydrate were not tested for this aspect, as they would dissolve.

5.3. Additional experiment

The mixes with hemi-hydrate appeared to be more suitable for immobilisation of humus rich soils. This effect becomes apparent at humus levels of 9.5% and 19%. There was a threshold visible for the mixes with a high humus level. The compressive strength of the 350 kg variants is lower than 1.7 N/mm^2, while the 500 kg variant has a compressive strength of 6.7 N/mm^2. This was also the compressive strength for a mix containing half soil and half 0–2 sand (J½) and 350 kg binder. So an alternative to reducing the humus content by mixing with sand was the use of more binder (Table 12). But humus also increases the capillary absorption, and this was not reduced by adding extra binder (Fig. 4). From these capillary absorption tests it follows that capillary absorption increases when the level of humus is increased. From the financial point of view, adding extra binder is more desirable (Section 8). This is because the soil used in the mix does not need to be remediated, which generates revenues as remediation costs of soil can be avoided. By the application of the soil in the mix, there is no need for this remediation, so the saved cost of remediation can be seen a revenue. On the other hand, the addition of sand will lead to extra costs.

6. Analysis of the water demand

In Section 5.1 it was observed that the water demand of a mix decrease when the binder content increases. This is contrary to what would be expected, namely that a higher powder content results in a higher water demand. A possible explanation could be that the soil was finer than binder, but this was not the case (Fig. 1). In this section the relationship between water demand and the properties of the mixes is examined in more detail.

6.1. Spread-flow analysis

As discussed in Section 2, there is a relation between relative slump flow (Γ) and volume-based water/solid ratio (Fig. 2). The β_p of the different mixes at different amount of superplasticizer (SP) is shown in Fig. 3. Having a closer look at Fig. 3, it can be noticed that the β_p of three soils are independent of the used mix design, which differs in amount of binder and binder combination. It furthermore appears that for each soil β_p depends linearly on the applied superplastizer dosage only.

6.2. Void fraction

For every soil a spread-flow line can be drawn, yielding β_p and E_p (Fig. 2). In order to analyse the lines, in the soil volume distinction is made between the mineral and organic matter volumes, since these two parts have a different specific density. The mineral phase has a density between 2650 and 2750 kg/m^3, while organic matter has a density of 1480 kg/m^3. Table 13 shows the used specific densities for the calculation. It is also possible to calculate the void fraction based on the β_p of the mixes. According to Brouwers and Radix [6] this can be done by

$$\phi_{\text{water}}(\Gamma = 0) = \frac{V_w}{V_{\text{total}}} = \frac{V_w}{V_w + V_s} = \frac{\beta_p}{\beta_p + 1} \tag{4}$$

In which β_p is the interception of the spread-flow line with the abscissa. From Section 6.1 it is known that β_p depending linearly on the applied superplasticizer (SP) dosage. Therefore the void fraction

Table 12
Comparison between different alternatives for immobilization of soil with high humus content.

	Mix with 0–2 sand	Extra binder
Compressive strength	+	+
Capillary water absorption	+	–
Financial feasibility	–	+

Legend: ++ very good, + good/better, – bad/less.

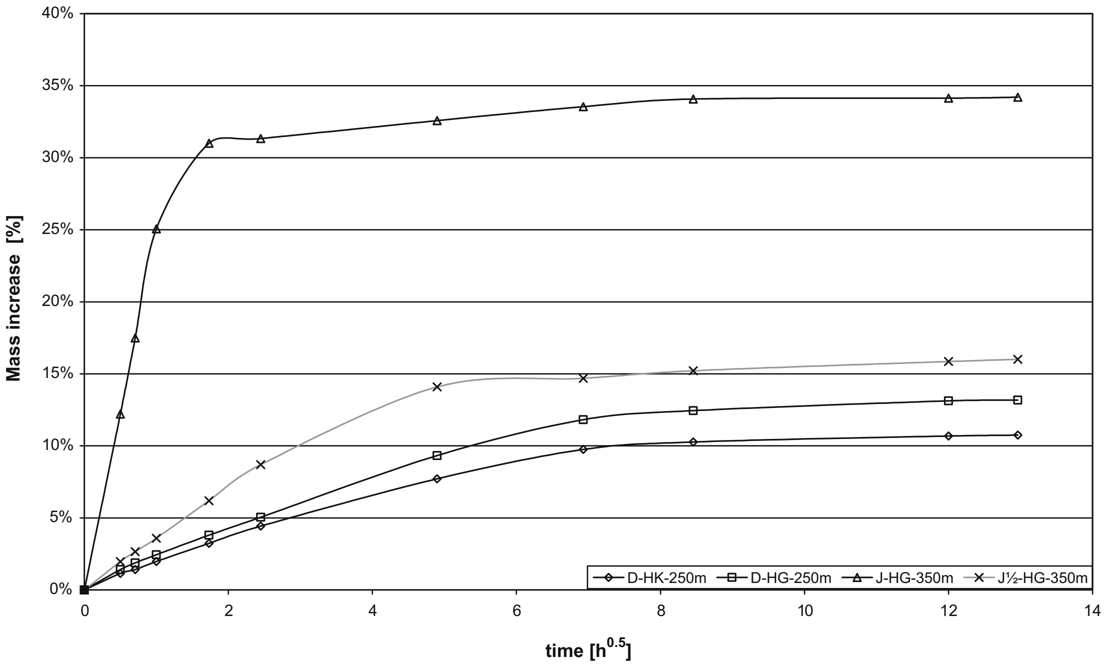

Fig. 4. Capillary water absorption of the mortar cubes.

Table 13
Specific densities of employed materials.

Component	Specific density (kg/m^3)
Slag cement	2950
Quicklime	3345
Hemi-hydrate	2700
Mineral fraction D-soil	2736
Mineral fraction J-soil	2679
Sand	2650
Organic matter	1480

is depending on the SP dosage. This is shown in Fig. 5. It appears that for each soil the void fraction depends linearly on the applied superplasticizer dosage.

6.3. Particle packing theory

The packing of a granular mix is closely related to the particle size distribution. Continuously graded granular mixtures are often based on the Fuller parabola. The cumulative finer fraction is given as

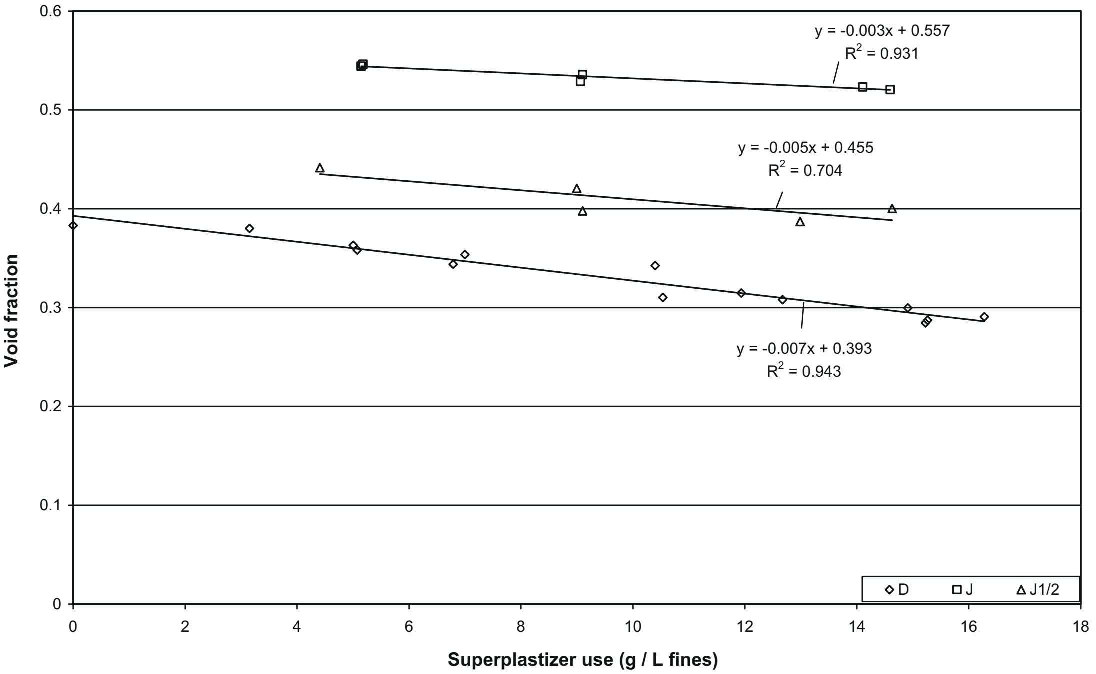

Fig. 5. Void fraction versus SP dosage for the three employed soils.

$$F(d) = \left(\frac{d}{d_{\max}}\right)^{0.5} \tag{5}$$

where d is the sieve term and $d_{\max}$ represents the maximum sieve size (i.e., where 100% passing takes place). The introduction of a distribution modulus q by Andreasen and Andersen [36] and a minimum particle size by Plum [37] led to an alternative equation, which reads as follows:

$$F(d) = \frac{d^q - d_{\min}^q}{d_{\max}^q - d_{\min}^q} \tag{6}$$

It is believed that values of q that range from 0 to 0.28, lead to optimum packing [35]. Hummel [38] mentioned an optimum distribution modulus of 0.4 for spherically shaped aggregates and 0.3 for more angularly shaped aggregates. According to Brouwers [39] several researchers refer to a distribution modulus of 0.37 for spatial grain distribution in order to obtain optimal packing and therefore minimum void fraction.

Using the particle size distribution of the mixes, the distribution modulus is assessed using fitting minimizing the sum of the squares of the residuals (RSS). Table 14 shows the calculated distribution moduli for all mixes, for which holds $d_{\max} = 2.8$ mm and $d_{\min} = 1$ µm based on Fig. 1 for all solids. The distribution modulus versus the void fraction is shown in Fig. 6. The relation between both characteristics can be described according to a quadratic function. The void fraction is minimal at a distribution modulus of about 0.29. This is line with the range which is mentioned by previous authors [35,38,39].

Table 14
Fitted distribution modulus of the mortar mixtures.

Mix	q	R^2
D-HK-250 m	0.335	0.737
D-HG-250 m	0.333	0.737
D-HK-350 m	0.291	0.762
D-HK-500 m	0.269	0.774
J-HK-350 m	0.124	0.932
J-HG-350 m	0.121	0.932
J-HK-500 m	0.066	0.937
J½-HK-350 m	0.194	0.837
J½-HG-350 m	0.190	0.842

7. Concrete mix results

The results of the mortar research were used for the preparation of the concrete mixes. In this part of the research, only D-soil is used. A combination slag cement and quicklime forms the basis of the mixes. This binder combination performed well on all aspects during the mortar tests and does not have major drawbacks. Better results are to be expected from this combination compared to the binder combination slag cement with hemi-hydrate, for instance in regard to leaching (Sections 4 and 5.2) and financial aspects (Section 8).

Concrete is distinct from mortar because of the presence of bigger aggregates. The concrete mix consisted of 70–75% mortar and 25–30% coarse aggregates [6]. The concrete mixes are based on the mortar mixes D-HK-350 m and D-HK-500 m (Table 8a).

Based on these two mix definitions, a preliminary mix was designed. This mix was optimized to meet two objectives. The first objective was the optimisation of the particle size distribution. This means a minimization of the sum of absolute deviations from the modified Andreasen and Andersen line with $q = 0.35$, $d_{\min} = 1$ µm and $d_{\max} = 16$ mm. The second target was to design a mix which is more cost-effective than the present one (Section 8).

Table 15 shows the composition of the concrete mixes. In Fig. 7, the particle size distribution of the final mixes is shown. The deviation of the mixes from the modified Andreasen and Andersen line is shown in Table 15. These mixes were selected (out of a number of possible mixes) because they had an acceptable deviation from target function (the modified AA-line) and lowest costs.

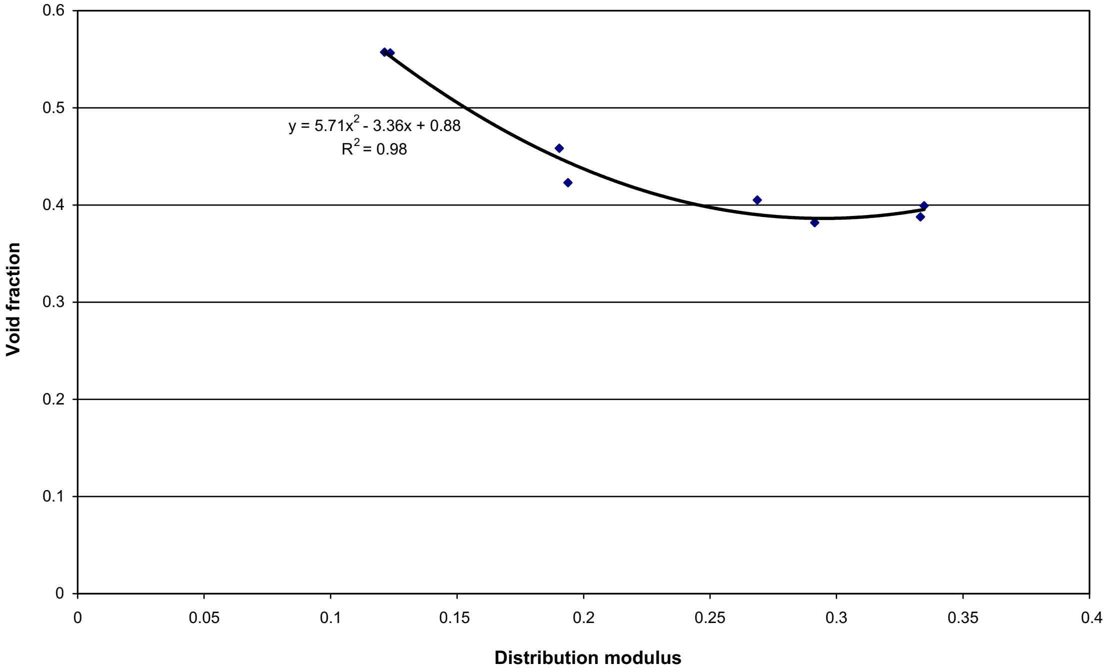

Fig. 6. Derived void fraction ($\beta_p/(\beta_p + 1)$) and distribution modulus at $\Gamma = 0$ and SP = 0.

Table 15
Mix design (in kg/m^3), deviation from modified Andreasen and Andersen line, fresh and hardened properties of the final concrete mixes.

	D-HK-350 e	D-HK-500 e
Mix design		
Slag cement	209.5 kg/m^3	274.9 kg/m^3
Quicklime	23.3 kg/m^3	30.6 kg/m^3
Hemi-hydrate		
Dry D-soil	1104.0 kg/m^3	1143.7 kg/m^3
Water D-soil	60.6 kg/m^3	62.7 kg/m^3
Gravel 4–16	740.7 kg/m^3	621.8 kg/m^3
Water extra	138.0 kg/m^3	141.2 kg/m^3
SP-solution	4.4 kg/m^3	5.4 kg/m^3
Distribution modulus		
$\sum$ |PSD-AA|	1.040	1.160
$\sum$ (PSD-AA)^2	0.089	0.156
Fresh properties		
Slump flow	280–280 mm (Batch 1) 220–220 mm (Batch 2)	200–200 mm (Batch 2) 510–520 mm (Batch 2)
Relative slump flow	0.96 (Batch 1) 0.21 (Batch 2)	0 (Batch 1) 5.63 (Batch 2)
V-funnel	13 and 14 s. (Batch 1)	15 and 13 s. (Batch 2)
V-funnel after 5 min	25 s. (Batch 1)	16 s (Batch 2)
Hardened properties		
Compressive strength		
Estimated (Eq. (7))	33.2 N/mm^2	38.5 N/mm^2
Estimated (cement content method)	31.4 N/mm^2	41.2 N/mm^2
Measured	18.6 N/mm^2	30.3 N/mm^2
Tensile splitting strength		
Estimated (Eq. (8))	1.93 N/mm^2	2.52 N/mm^2
Measured	1.96 N/mm^2	2.66 N/mm^2
Density		
Calculated	2280 kg/m^3	2280 kg/m^3
Measured	2093 kg/m^3	2206 kg/m^3
Air-content		
Invoked at mix design	1% V/V	1% V/V
Derived from real density	9.2% V/V	4.2% V/V

7.1. Tests on fresh concrete

The fresh concrete tests can be divided into slump flow and V-funnel tests. Two batches were made of each mix. The results of these tests are presented in Table 15. The mixes were designed for a relative slump flow of 0.2. The relative slump flow and V-funnel time differed considerably between the batches. The second batch of D-HK-500 e was almost self-compacting, whereas the first

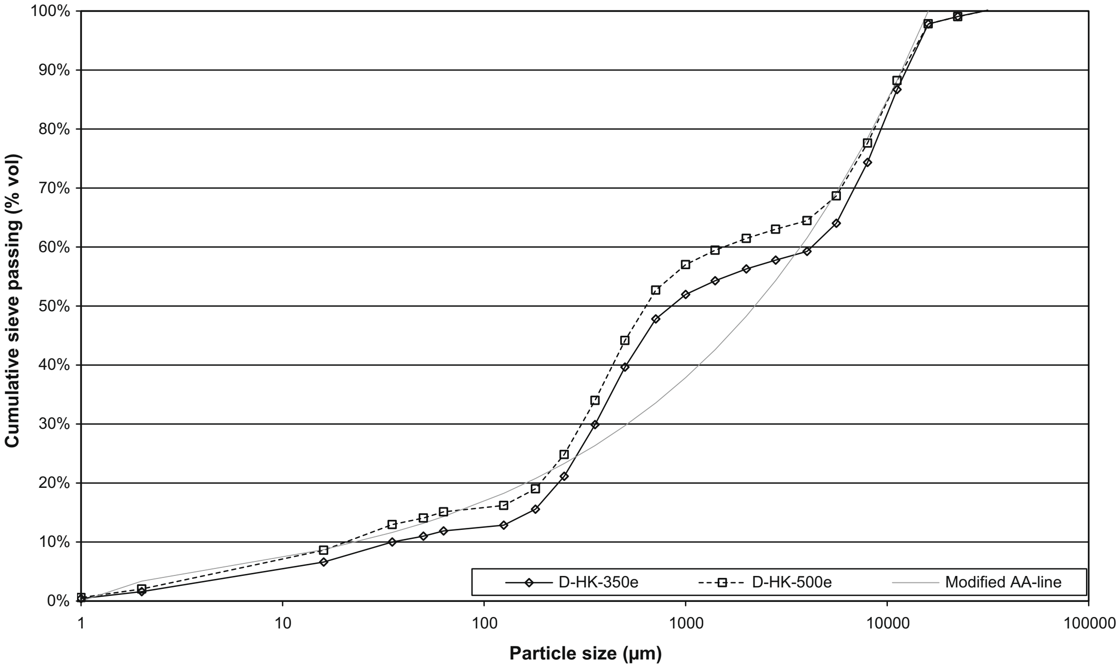

Fig. 7. Cumulative finer function of final mixes ($q = 0.35$, $d_{min} = 1$ μm and $d_{max} = 16$ mm).

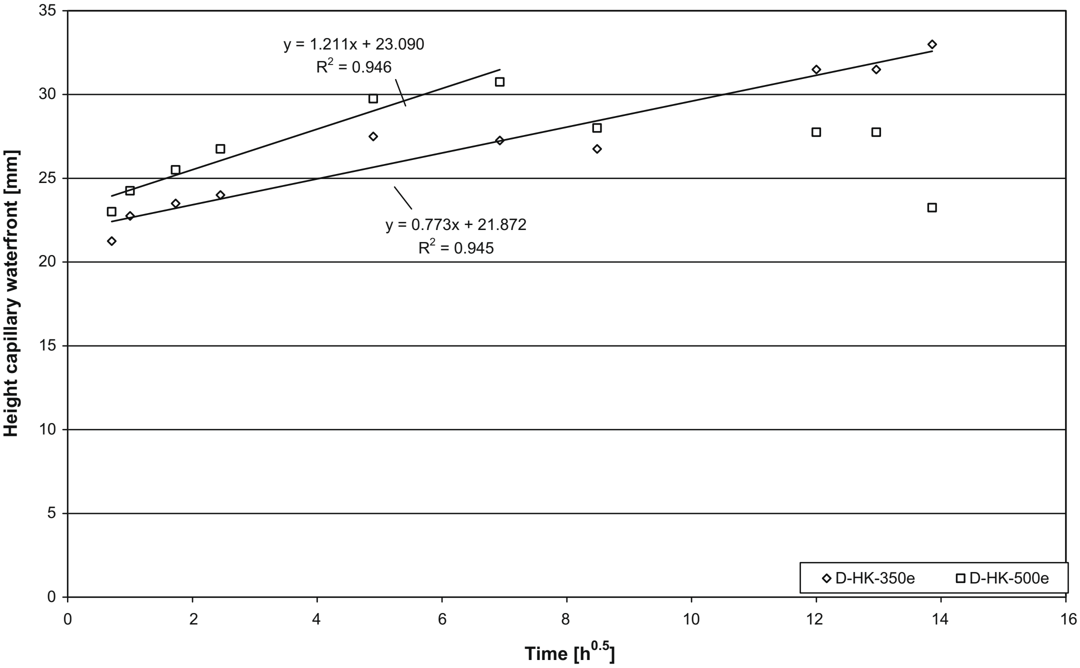

Fig. 8. Height capillary water absorption front in time.

batch was completely unflowable, this is due to fluctuations in the soil composition. These differences can be explained by the heterogeneity of the soil. For instance the amount of powder (all particles smaller than 125 μm) in the soil differs, resulting in a change in the water/powder ratio and the superplastizer content on powder. But differences in the sulphate level can also result in a different flowablity and workability. Fluctuations in the flowablility and workability of a mix can cause problems, when the mix is used in a production line. A solution for this problem is homogenizing of the soil prior to treatment, in order to reduce fluctuations in the composition of the soil and so fluctuations in the flowability and workability.

7.2. Results on hardened concrete

This section deals with the results of the hardened concrete tests, which can be divided into compressive strength, flexural strength, density, capillary absorption, and leaching.

The 28 days compressive strength of the D-HK-350 e mix did not fulfil the requirement of 25 N/mm^2, but D-HK-500 e did fulfil this requirement. The measured compressive strength values were lower than the expected values based on an empirical equation for the relation between compressive strength and the water/cement ratio. The compressive strength (f_c) of a concrete, with an uncertainty up to 5 N/mm^2, can be assessed by

$$f_c = \alpha N_n + \frac{\beta}{wcf} - \gamma \tag{7}$$

The α, β and γ in Eq. (7) are depending on the cement that is used. For slag cement this value are 0.75, 18, and 30 [5]. The N_n is the standard strength of the used cement after n days. In Table 3 the standard strength of the used slag cement (CEM III/B 42,5 N LH) is shown.

Another method for estimating is based on the cement content. According to Brouwers and Radix [6], 1 kg of slag cement/m^3 of concrete can contribute 0.15 N/mm^2 compressive strength. Table 15 shows the estimated compressive strength using both assessment methods, and the actually measured values. The flexural strength of the mixes was 1.96 N/mm^2 for D-HK-350 e and 2.66 N/mm^2 for D-HK-500 e (Table 15). These values were in line with the expectations for the flexural strength based on the measured compressive strength and Eq. (8). The expected flexural strength was 1.93 N/mm^2 for D-HK-350 e and 2.52 N/mm^2 for D-HK-500 e.

$$f_t = 1\text{N/mm}^2 + 0.05 f_c \tag{8}$$

The density of the mixes was lower than the expected value. This can mean a higher air-content of the mixes than expected. The

Table 16
Leaching of D-HK-350 e.

	Measured immission (mg/m^2)	Maximum immission (mg/m^2)
Sulphate	3171	100,000
Cadmium	0.04	12
Chromium	0.16	1500
Copper	0.08	540
Nickel	0.11	525
Lead	0.42	1275
Zinc	0.35	2100
Cobalt	0.06	300
Arsenic	0.84	435

Table 17
Assumed material costs (in €/ton).

Material	Costs (€/ton)
Water	1.15
Slag cement (CEM III/B 42,5 N)	80.–
Hemi-hydrate (FG-101)	25.–
Quicklime	110.–
Waterglass-solution	200.–
0–2 Sand	17.–
4–16 Gravel	18.–
Recycled aggregate	5.–
Superplastizer	300.–
Remediation of soil	−25.–

air-content can be calculated from the measured and calculated densities (Table 15). For D-HK-350 e follows an air-content of 9.2% and for D-HK-500 e 4.2%.

The capillary absorption of both mixes was lower than the requirement for self-compacting concretes (less than 3 $\text{mm/h}^{0.5}$). D-HK-350 e had a sorption-index of 0.77 $\text{mm/h}^{0.5}$ and D-HK-500 e had a sorption-index of 1.21 $\text{mm/h}^{0.5}$ (Fig. 8).

The leaching of final mixes was very low compared to the limits of the BMD. In Table 16, the results of the test are displayed for D-HK-350 e. The mixes fulfil the requirements of the BMD regarding leaching.

8. Financial analysis/economics

In this section the financial results of the produced concrete mixes are analysed. The new mixes are therefore compared with the present mix design. The new mixtures result in benefits and extra cost compared to the present situation. The total benefit can be splitted into the material benefits/costs and extra benefits. The cost of disposal of the soil can be avoided (25 €/ton), since the soil is immobilisated. This results in an extra benefit, which can be used to finance the extra material costs of immobilisation. The material benefit is defined as the original material costs minus the new material costs. So less material costs will lead to a positive material benefit and more material costs to a negative material benefit. Table 17 shows the assumed material prices. Table 18 shows the material, soil and total financial benefit of the new mixtures.

For only two mixtures, the material costs are slightly higher than the materials cost in the present situation. For the other mix designs, there is reduction of the material cost. The lower material costs are owing to the substitution of sand and gravel. The use of these resources lead to a higher material cost, while the soil leads to a benefit, due to avoiding disposal costs of the soil.

The last column of Table 18 shows the total benefit. This reveals that all new mix design are more favorable from financial point of view, then the present mix design. The mix design with half J-soil and half 0–2 sand have the poorest financial result. This is caused by a lower soil use and higher material use. These J½ -mixture had the purpose to reduce the negative effects of humus. Based on the financial results, the use of binder is more advantageous. The J-HK-500 m mix design is an example of the use of more binder to reduce the effects of humus. This mix design has a material cost comparable to the present situation, but a lower material cost compared to J½-HK-350 m. Besides, J-HK-500 m also incorporates more soil compared to the J½ mix designs, which leads to a higher benefit.

Table 18 also shows a difference between the quicklime (HK) and hemi-hydrate (HG) mix designs. The hemi-hydrate mixtures were more cost-effective than the comparable quicklime mix designs. This is mainly caused by the lower cost price of hemi-hydrate and the composition of the binder combination. The binder combination used, were 60% blast furnace slag cement with 40% gypsum and 90% blast furnace cement with 10% quicklime. Since hemi-hydrate is the cheapest binder and quicklime the most expensive of the three binders (Table 17), the binder combination with hemi-hydrate is favorable compared to the other combination.

Table 18
Indicative financial benefits for new and existing mix designs (in €/m3).

	Material (€/m^3)	Soil (€/m^3)	Total (€/m^3)
D-HG-250 v	23.84	40.73	64.57
D-HK-350 v	11.30	34.92	46.22
D-HK-250 m	23.10	41.94	65.04
D-HG-250 m	28.48	42.16	70.64
D-HK-350 m	12.65	40.58	53.23
D-HK-500 m	7.14	39.54	46.68
J-HK-350 m	12.67	33.95	46.62
J-HG-350 m	21.01	33.60	54.61
J½-HK-350 m	-7.64	23.23	15.59
J½-HG-350 m	5.39	22.01	27.41
J-HK-500 m	-0.23	32.40	32.17
D-HK-350 e	8.64	29.12	37.75
D-HK-500 e	4.44	30.16	34.60

9. Conclusions

The present research consisted of a main experiment (Sections 4, 5.2, and 7) and an additional experiment (Section 5.3). First, the conclusions of the main experiment will be given and next the conclusions of the additional experiment will be described.

9.1. Main experiment

The results of the experiments have been examined for their financial feasibility, feasibility for production on large scale, shape retaining and strength. All mixes within the experiment were more cost-effective than the current mixes with primary material. This means that the mixes are financially feasible for production of immobilisates, because the cost of materials are lower than for normal concrete blocks, since fewer primary materials is needed and the cost of remediation of the contaminated soil can be prevented.

The mixes are suitable for production of immobilisates on large scale. The design of these real mixes has been adapted to the use of wet soil, instead of the dried material within the 'normal' laboratory concrete production. The J-soil used has been dried prior to the production of mortar cubes, in order to make sieving of the soil possible. After sieving, water is added to the soil and the soil is given the opportunity to absorb this water for 30 min before the mix is made. This process has been developed in order to have a close fit between the results in laboratory and practice.

The leaching of the mixes containing D-soil was tested according to the limitations of the Building Material Degree i.e., the diffusion-test. The leaching of sulphate was near the limit for the mixes with hemi-hydrate during exploratory research, due to the solving of gypsum when in contact with water. This means that considering this aspect the mixes with hemi-hydrate are less suitable than the mixes with quicklime.

The J and D mixes were sustainable shape retaining. This means that the products can categorised as a shaped material, which also implies that the diffusion (leaching) tests are indeed applicable.

The compressive strength of the mixes containing hemi-hydrate was higher in the first days of hydration, but after 28 days the mixes containing quicklime have a higher compressive strength. The strength of the final mix D-HK-500 e (306 kg/m^3) was higher then the required compressive strength of 25 N/mm^2. The other mixes had a compressive strength of less than 25 N/mm^2. When a slightly lower compressive strength is acceptable, e.g., 20 N/mm^2, then already D-HK-350 e (233 kg/m^3) would have been sufficient. When a compressive strength of 17.5 N/mm^2 is acceptable, then the mixtures from the exploratory research are satisfactory.

Given these results, the final mixes of D-soil, quicklime and slag cement (306 kg binder) fulfilled all the objectives. So the objective of the main experiment fulfilled both the technical and financial requirements.

9.2. Additional experiment

Humus strongly influences the hydration of cement. The mixes with hemi-hydrate were more suitable for the immobilization of humus rich soils. This was due to the better strength development of these mixes compared to mixes containing quicklime. The cubes based on quicklime could easily be deformed during the first days of hydration.

Two possible ways to reduce the effects of humus were considered during this research. The first method is the mixing of J-soil with 0–2 sand to achieve a soil with a reduced humus level. The J½-soil mixes had a compressive strength hardly smaller than the comparable D-soil mixes. The second method is the use of more binder. Increasing the binder content from 331 to 480 kg/m^3 (J-HK-350 m and J-HK-500 m, respectively) gave a comparable strength development as the first method. The 28 day strength was hardly less than the compressive strength of the J½-soil mixture. Extra binder reduced the negative effect on the compressive strength, but did not reduce the higher capillary absorption of humus rich mixes. This capillary absorption was equal to the J-soil mixes. A higher capillary absorption may indicate a higher level of leaching as well.

The financial feasibility of the mixes with more binder was higher than the J½-soil mixes. This is caused by the addition of more sand than binder. But also the reduction of soil in the extra binder mixes is lower than in the half soil mixes. For the addition of soil in the mixes, a benefit is generated, as the cost for the remediation of the soil can be avoided.

Given the results, it seems that it is not possible to immobilize soil with a humus content of 19% with 331 kg/m^3 binder only. Based on the present research, two possible solutions are available to immobilize such soils. The first method is the reduction of humus content by replacing half of the soil with 0–2 sand. But from a financial point of view, it is more attractive to increase the proportion of binder. The increase to 480 kg/m^3 of binder (J-HK-350 m) is a way to achieve the required compressive strength, without reduced the high capillary absorption, which is a result of the present of humus.

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