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Utilization of industrial by-products for the production of controlled low strength materials (CLSM)

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Abstract

Industrial by-products were used for the production of controlled low-strength material (CLSM). CLSM, also known as 'flowable fill' is used as a replacement of compacted soil in cases where the application of the latter is difficult or impossible. The low mechanical requirements (compared with structural concrete) enable the use of industrial by-products for the production of CLSM. In this study cement kiln dust, asphalt dust, coal fly ash, coal bottom ash and quarry waste were tested for the possibility of producing CLSM with large proportions of those wastes. The results showed that in most cases, CLSM with good properties could be made with significant amounts of dust (25–50%w), especially when the dust has some cementing or pozzolanic potential as do fly ash and cement kiln dust.

1. Introduction

Large amounts of industrial waste having a granular nature accumulate every year in all industrial countries. These materials are, in general, unsuitable for use in the construction industry due either to their high content of very fine particles, or to their poor mechanical properties. Most international standards limit the content of fines (particles smaller than #200 sieve, or 0.075 mm) in concrete applications to 16% of crushed sand (preEN 12620:2000), or 7% (ASTM C33). Controlled low strength materials (CLSM), also known as 'flowable fill', can serve as an excellent means to utilize large quantities of fines without impairing its properties.

CLSM is used mainly for filling cavities in civil engineering works, in which the application of granular fill is either impossible or difficult (ACI 229, 1999). The production technology, however, is similar to the production of concrete. The mechanical strength of CLSM is generally low (unconfined compressive strength of 0.5–2 MPa) permitting re-excavation in the future, and the material is flowable, allowing perfect filling of any void. Cement content is generally in the range of 50–100 kg/m^3 of CLSM to provide the desired strength. High workability is achieved through the use of high amounts of mixing water or by using admixtures (air entraining agents, plasticizers, etc.). The cohesiveness of highly flowable concrete-like material is generally poor, leading to the risk of segregation, unless a high amount of fines is used in the mix. As the mechanical properties of the hardened CLSM are inferior to those of concrete, large amounts of fines can be used in the production of CLSM to improve the properties of the fresh mix without damaging its mechanical properties.

Coal fly ash (FA) is widely used in CLSM production. However, although approved by the departments of transportation of many US states (ACI 229, 1999), its application in CLSM is only ~1% of the 57 million tons of fly ash produced annually in the US (ACAA, 2000). Several successful applications of FA in CLSM have recently been reported (Pierce et al., 2002; Dockter, 1998; Gabr and Bowders, 2000), even with high carbon content (Ramme et al., 1995). It appears that a significant increase in compressive strength may develop in time with FA mixes that may limit future excavation if needed.

Other industrial by-products have been used sporadically in CLSM production, for example spent foundry sand (Bhat and Lovell, 1997; Tikalsky et al., 2000) and recycled glass (Ohlheiser, 1998).

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The current study was conducted in view of the need for fines in the production of CLSM and the possibility of using non-standard materials. Its goal was to identify possible by-products that can suit the production of CLSM and to study the resulting properties.

2. Experimental program

2.1. Materials

Five types of industrial by-products were identified as suitable for the production of CLSM as follows:

Cement kiln dust (CKD)—dust that is collected from the stack of cement plants. The dust contains particles stemming from clinker production.

Dust from asphalt plants (AD)—excess fine dust that is removed during the production of asphalt concrete. Its composition depends mainly on type of stone that is used as a filler.

Coal fly ash (FA)—residues collected from the exhaust gas from the combustion process of coal in power plants.

Coal bottom ash (BA)—residues collected from the bottom of the furnace burning coal in power plants.

Quarry waste (QW)—fine material from an aggregate quarry that is unsuitable for the production of concrete.

Ordinary Portland Cement (OPC) conforming to CEM II/A-V 42.5 (with up to 10% of coal fly ash) was used in all the mixes.

2.1.1. Mix composition

Table 1 presents the composition of the tested mixes. Mixes 1–7 served to test the effect of waste. The fine waste was tested together with crushed stone or with the coarser waste. With mixes 8–10 the effect of cement content in mixes containing fine materials was tested, with mixes 11–14 the effect of waste content, and with mixes 15–17 the effect of an accelerator ($CaCl_2$) were tested. The basic mix contained approximately 50 kg/m^3 cement, 500 kg/m^3 fine waste and 1200 kg/m^3 crushed sand (CS), and is designated CS/500/50 (mixes 1–3). These mixes served as reference for the further changes noted above. In the notation of the mixes the first two letters represent the type of coarse material (crushed sand: CS; bottom ash: BA; or quarry waste: QW), followed by the fine waste content and finally the cement content. Water content was adjusted to provide a constant flow of 200 mm according to ASTM D6103-97 and ranged from ~300 to ~450 kg/m^3 (Table 1).

2.1.2. Sample preparation and testing procedure

Mixes of approximately 10 l were prepared in a Hobart mixer. Water was added gradually while frequently testing the workability until the desired workability was achieved. In some of the mixes the workability improved after additional mixing, leading to higher flow values than initially measured. The properties of the fresh mix (unit weight, flow, air content, bleeding, setting time and shrinkage after 24 h) were tested immediately after mixing. 50×50×50 mm cubes were prepared for compressive strength tests, and 40×40×160 mm prisms for testing the drying shrinkage after complete drying in an oven and of swelling after

Table 1
Mix composition (kg/m^3)

No.	Cement[a]	Cement kiln dust	Fly ash	Asphalt dust	Bottom ash	Quarry waste	Crushed sand	Water
1	54			535			1280	320
2	53	525					1260	325
3	53		525				1255	297
4	53	525			900			385
5	54			535	920			335
6	50			490		1108		372
7	45	435				1047		423
8	96		519				1219	310
9	101			517			1268	339
10	100	503					1238	339
11	45			1089			455	426
12	43	1022					426	457
13	45		951				440	419
14	53	318					1467	313
15	53	525					1260	325
16	100	503					1238	339
17	100	503					1238	339

[a] CEM II/A-V 42.5.

re-wetting. Table 2 lists the relevant standard for each testing method.

The specimens were demolded after 1–3 days, when enough strength had been obtained for proper demolding, i.e. without damaging the specimens. During that time the moulds were kept in plastic bags. After demolding the specimens were stored again in sealed plastic bags in which water was sprayed occasionally to ensure 100% humidity, while preventing the complete wetting of the specimens. The compressive strength was tested at ages 7, 28 and 90 days and the other properties of the hardened mix were tested at age 90 days.

The wastes (apart from the quarry waste) were tested for leaching of metals according to EPA-TCLP 1311-92 procedure, with and without acid extraction. Leaching of the CLSM prepared with these wastes was tested after 1 year after being stored in air from age 3 months.

3. Results

3.1. Waste properties

Fly ash, asphalt dust and cement kiln dust have a very fine particle size, whereas bottom ash and quarry waste are coarser. Fig. 1 presents the sieve analysis of the materials. The content of the fine material passing the 0.075 mm sieve (#200) was approximately 85% of the FA and AD and only 55% of the CKD. The CKD is still relatively fine with all particle sizes being smaller than 1.18 mm (#14). The BA particle size ranges uniformly from 0.15 to 9.5 mm. The QW contains a relatively large amount of very fine particles (22% passing the 0.075 mm sieve). The fraction that passes the 0.075 mm sieve was tested for the Atterberg limits (ASTM D4318). The results (liquid limit 42%, and plastic limit 16%) indicated the presence of some clay that affects the properties of the mix as will be further discussed.

Table 2
Standards for the testing methods

Test procedure	Standard
Flow	ASTM D6103-97
Air content	ASTM C231-97
Unit weight	ASTM D6023-96
Bleeding	ASTM C232-99
Setting time	ASTM C403-99 (initial setting time was determined at pressure of 0.69 MPa)
Compressive strength	IS 26 Part 4 (similar to ASTM 4832 but on cubes)
Total absorption	ASTM C642-97
Shrinkage and swelling	Direct measurement
Early age shrinkage	IS 1920 Part 1
Leaching	EPA TCLP 1311

ASTM—American Society for Testing and Materials; IS—Israeli Standard; EPA—US Environmental Protection Agency.

3.2. Fresh mix

3.2.1. Water demand

The amount of water needed for a constant flow of the fresh mix was in the range of 297–457 kg/m^3 (Table 1). The amount of water depends on the amount of fine material in the mix but also on its shape. Mixes 1–3, for example, contain the same amount of fine waste (AD, CKD and FA, respectively) and crushed sand. The water needed for the AD and the CKD was similar (320 kg), while approximately 10% less water was needed for the mix containing FA (Fig. 2). The shape of the particles seems to affect the water demand, as a smaller quantity of water was needed for the rounded particles of FA than for the angular particles of AD and CKD. Increasing the fine waste content from 500 to 1000 kg/m^3 significantly increased the water required for a constant flow from 300–320 kg/m^3 to 426–455 kg/m^3 (Fig. 2). Increasing the cement content from ~50 to ~100 kg/m^3 was accompanied by an equivalent reduction in the content of the crushed sand. As a result the total content of fines was slightly increased, leading to a moderate increase in the water demand (Fig. 2). Replacement of the crushed sand with either bottom ash or quarry waste led to an increase in the water demand. The increased water demand for the bottom ash is a result of its porous nature; part of the water is needed for void filling and another part is due to the rougher surface. The large amount of fines in the QW (Fig. 1) is the direct reason for the increased amounts of water, as explained before.

3.2.2. Bleeding

The increased amounts of water may lead to the concern of high bleeding and high sedimentation of the fresh mix. Fig. 3 presents the total bleeding from the various mixes. High bleeding values were observed with the mixes containing fly ash (FA), being almost twice the values obtained for the AD mixes and more than three times larger than those of the CKD mixes. Large bleeding values are expected for the fly ash mixes, due to the spherical shape of the fly ash particles and their delayed setting (Ravina, 1990). However, the reason for the difference between the AD and the CKD mixes is not clear, as smaller values would have been expected for the AD mixes, resulting from their finer particle size. It is possible that the cementing capacity of the CKD enhances the thickening of the mix at an early age, helping to reduce the bleeding in these mixes.

3.2.3. Setting time

The standard test method ASTM C403 for measuring the setting time of concrete that was used in this study measures the setting time under laboratory conditions only, and it enables the comparison between different mixes. In actual field casting of CLSM, test method

ASTM D6024 is preferred as it takes into account field parameters, such as absorption by the surrounding soil, evaporation, etc. Fig. 4 presents the result of the setting time tests. Long setting times compared with that of ordinary concrete were observed for the various mixes. Mixes containing fly ash and crushed sand exhibited the shorter time of 15 h regardless of the cement content (either 50 or 100 kg/m^3 of cement). The mixes prepared with AD or CKW exhibited $\sim$30 and 18 h for cement contents of 50 and 100 kg/m^3, respectively, regardless of the waste type. As the cement is the main component that dominates the setting time for these mixes, reduced setting time is expected as its content increases. However, when fly ash in large quantities ($\sim$500 kg/m^3) is used, it contributes to the setting process by shortening the setting time, and the change in the cement content is less dominant. This phenomenon is contrary to the setting process in ordinary concrete in which large quantities of fly ash together with large quantities of cement (compared with CLSM) extend the setting time of concrete (Ravina, 1990).

Increasing the quantities of the fine waste slightly increased the setting time of the FA and CKD mixes, but significantly increased the setting time of the AD mixes (Fig. 4), probably because AD is completely inert as distinct from the other two materials.

Replacing the crushed sand with bottom ash reduced the setting time of the mixes due to the contribution of the bottom ash to the chemical process involved in setting. However, when the quarry waste was used, the setting time significantly increased, due to the high content of fine materials, which produced an effect similar to that of AD noted before.

The effect of an accelerator was tested on a limited number of mixes containing asphalt dust (AD), crushed sand and cement content of 100 kg/m^3. $CaCl_2$ was used as an accelerator, at 2 and 5% by weight of cement. The reductions in the setting time were 14 and 35%, respectively. The effect of the accelerator was studied in another phase of the study, but the results here indicate a good possibility to control the setting time through the chemistry of the cement, despite its relatively low content.

3.2.4. *Volume changes at early age*

The volume changes were measured at two ages: 24 hours after mixing (during setting, Fig. 5) and at age 90 days. Fig. 5 presents the sum of the length changes as measured from the gages (the bottom part of the bar) and the sum of cracks width (upper part). Only a few fine cracks were detected in the base mixes containing fly ash or asphalt dust. Wider cracks were observed in

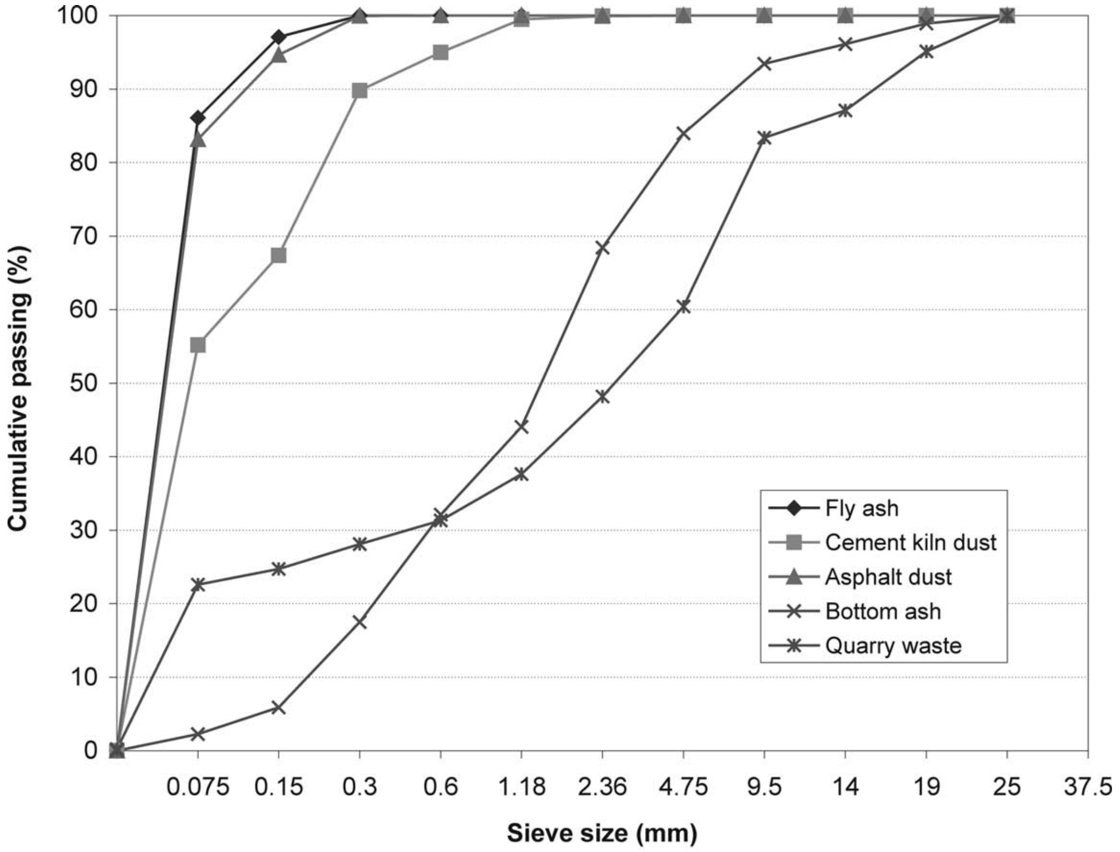

Fig. 1. Sieve analysis of the tested materials.

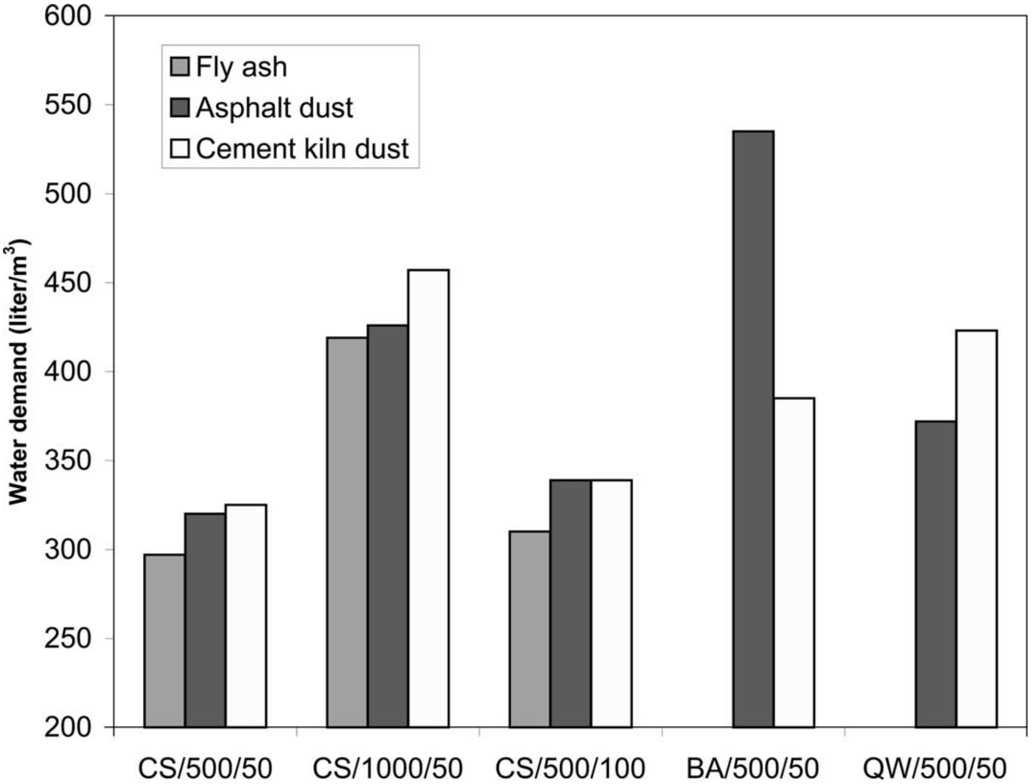

Fig. 2. Effect of fines type and cement content on the water demand (l/m^3). CS—crushed sand, BA—bottom ash, QW—quarry waste, mix code: coarse fraction/fine waste content/cement content.

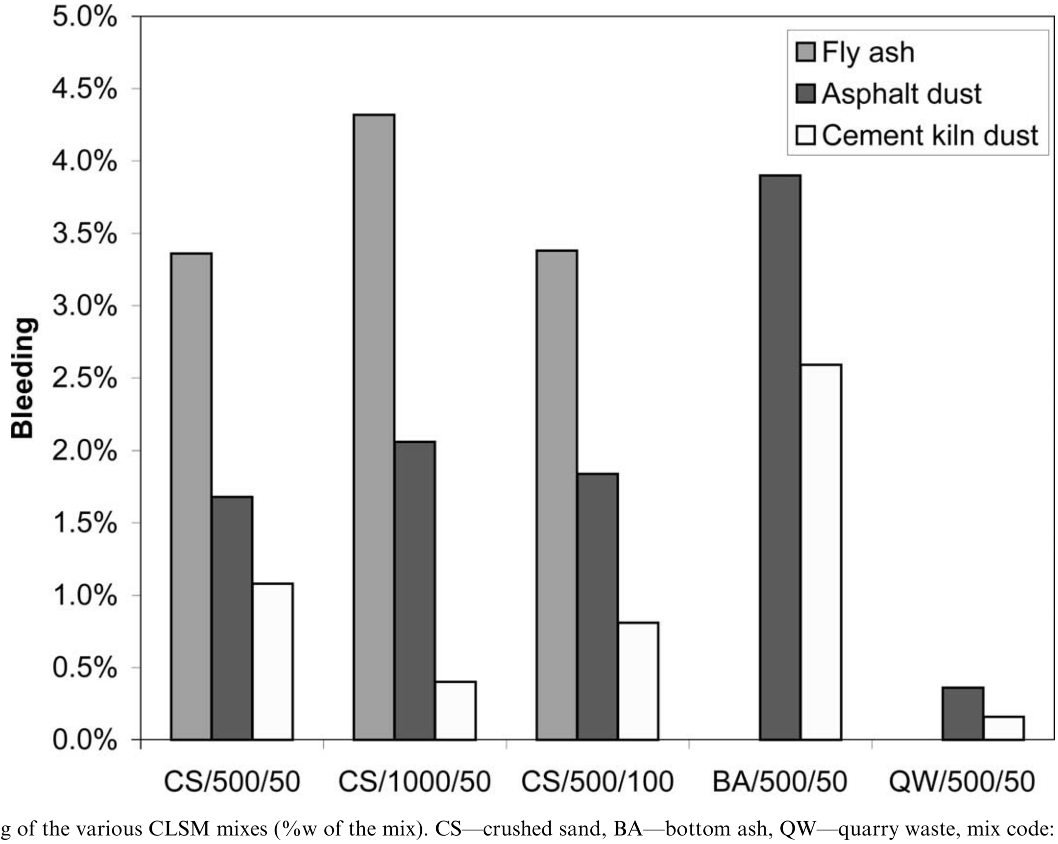

Fig. 3. Bleeding of the various CLSM mixes (%w of the mix). CS—crushed sand, BA—bottom ash, QW—quarry waste, mix code: coarse fraction/fine waste content/cement content.

the CKD mix exhibiting somewhat larger shrinkage (see Fig. 6). Doubling the fine waste content increased the volume changes and the tendency to crack; the shrinkage of the mixes containing FA and AD increased by ~75%, but that of the CKD mix increased by almost 300% (all compared with the base mixes). This tendency towards larger values of the CKD mixes was seen in all the combinations of mixes containing CKD (Fig. 5), mainly in the mixes containing large amounts of CKD alone or in combination with quarry waste with its high fines content. In all the mixes increasing the cement content reduced shrinkage and the tendency to cracking; while increasing the fine content by using quarry waste significantly increased the shrinkage, probably due to the clay present in the fines of that waste.

It appears that the early age shrinkage is inversely related to the bleeding of the mix (see Fig. 3). The setting time was found to be very long with bleeding that may extend throughout that time. The mixes with large bleeding values that extended through the setting time (FA and AD) exhibited lower shrinkage and cracking tendency. This phenomenon can be explained in a manner similar to that of plastic shrinkage in ordinary concrete (Soroka, 1993). The CKD mixes with relatively very little bleeding exhibited the largest shrinkage since the water dried out from the bulk of the material rather than from the surface. As long as there was enough water available for evaporation from the surface (the bleeding water), shrinkage was small, as in the FA and AD mixes.

3.2.5. Unit weight

The unit weight of all the mixes was ~2200 kg/m^3 regardless of the type of aggregate or dust used (with the exception of the bottom ash mixes), indicating similar air entrainment. A lower unit weight however was measured for the bottom ash mixes (~1850 kg/m^3), due to the porous nature of the bottom ash.

3.3. Hardened mix

3.3.1. Strength

The compressive strength of the mixes at age 28 days is presented in Fig. 7. The high compressive strength obtained by the mixes containing fly ahs is clearly shown, resulting probably from the pozzolanic activity of this material. A relatively high compressive strength was measured in the case of the CKD mixes, affected by the residual cementing properties CKD is known to possess (Corish and Coleman, 1995). The AD mixes that have no cementing or pozzolanic properties exhibited the lowest strengths of all. The strength level of the AD mix (CS/500/50) is low compared with that of other mixes made with first-class materials reported in the lit-

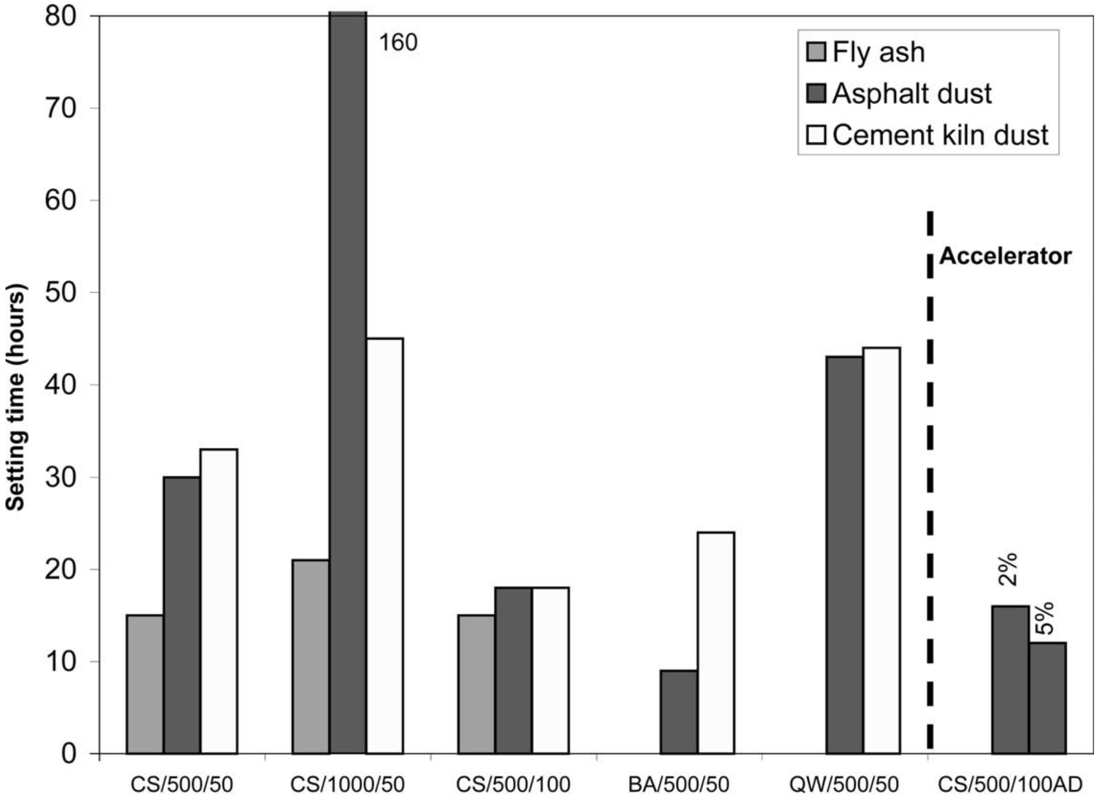

Fig. 4. Setting time (h) of the mixes. CS—crushed sand, BA—bottom ash, QW—quarry waste, mix code: coarse fraction/fine waste content/cement content.

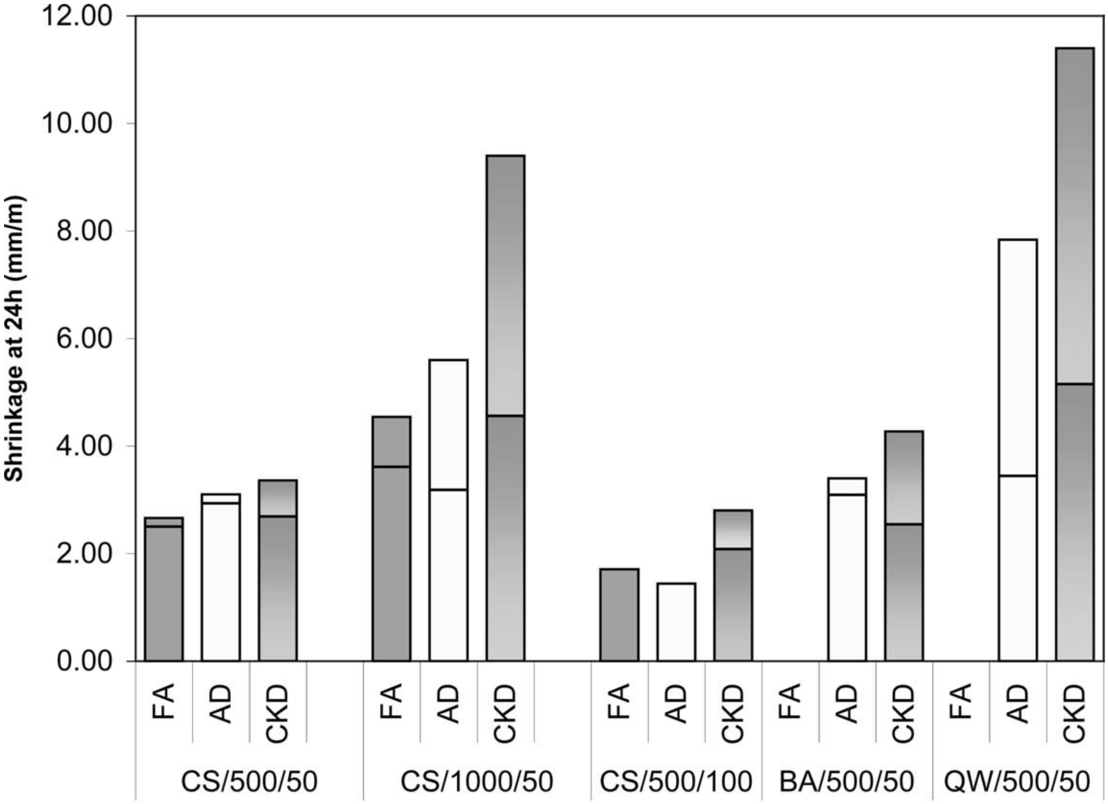

Fig. 5. Shrinkage during the first 24 h (mm/m). The bottom part of the columns represents the gage reading, and the upper part-the total crack widths. FA—fly ash, AD—asphalt dust, CKD—cement kiln dust, CS—crushed sand, BA—bottom ash, QW—quarry waste, mix code: coarse fraction/fine waste content/cement content.

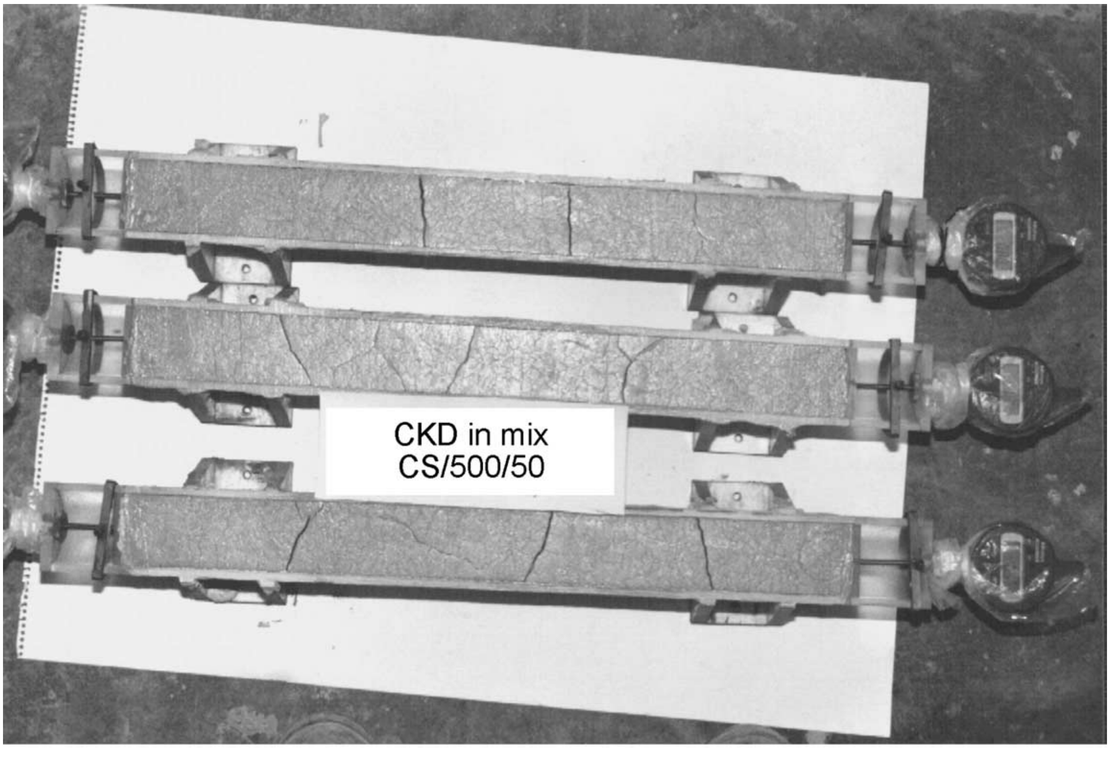

Fig. 6. Test procedure for early-age volume change.

erature (Clem et al., 1994), indicating that large proportions of inert fine waste may lead to a reduction in strength. Increasing the fines content from 500 to 1000 kg/m^3 somewhat reduced the compressive strength, resulting probably from the increased water demand when a large amount of fines is used, as discussed before.

Increasing the cement content from 50 to 100 kg/m^3 increased the 28 day compressive strength of the FA and CKD mixes by ~100% and of the AD mix by ~300% (Fig. 7). In the former, the content of the cementing/pozzolanic materials is large hence, increasing the content of the cement alone in those mixes has less effect on the strength than in the AD mix in which the cement is the only cementing material.

Replacing the crushed sand with bottom ash (BA) that may have some pozzolanic activity (to a lesser extent than the fly ash due to its smaller surface area and composition) led to some increase in the 28 day compressive strength. The replacement with quarry waste had a small and insignificant effect.

The development of strength at higher ages may cause problems in accessing equipment buried in the CLSM (pipes, tanks, etc.). The results presented in Fig. 8 show a significant increase in the compressive strength with age when materials with pozzolanic/cementing activity are involved. Mixes with fly ash, CKD, or bottom ash exhibited a significant increase in compressive strength from age 28 to 90 days. This trend was observed in all the mixes except the AD ones. The strength of the AD mix remained constant from age 7 days and onwards for the mixes with the lower cement content (Fig. 8) and somewhat increased in those mixes having the higher cement contents (0.9, 1.5 and 2.1 MPa at ages 7, 28 and 90 days, respectively). These results strengthen the assumption of a limited effect of the cement when mixed with large quantities of inert fine waste.

3.3.2. Total water absorption

A total water absorption of ~15% was measured for the mixes made of crushed sand and 500 kg/m^3 of fine waste (Fig. 9). Increased values, of ~25%, were measured for the mixes containing higher quantities of fines (CS/1000/50), or other coarse materials (BA and QW). The mixes containing CKD always exhibited the highest values.

It seems that the parameters that led to increased water demand also influence the total absorption, which significantly increased as the amount of fines was increased (either fine waste or QW fines) or by using a porous material (BA). An increase of 100 l/m^3 of water (the difference between Mix #1 and #11, for example) may lead to 10% increase in the porosity of the hardened CLSM and hence to increased absorption.

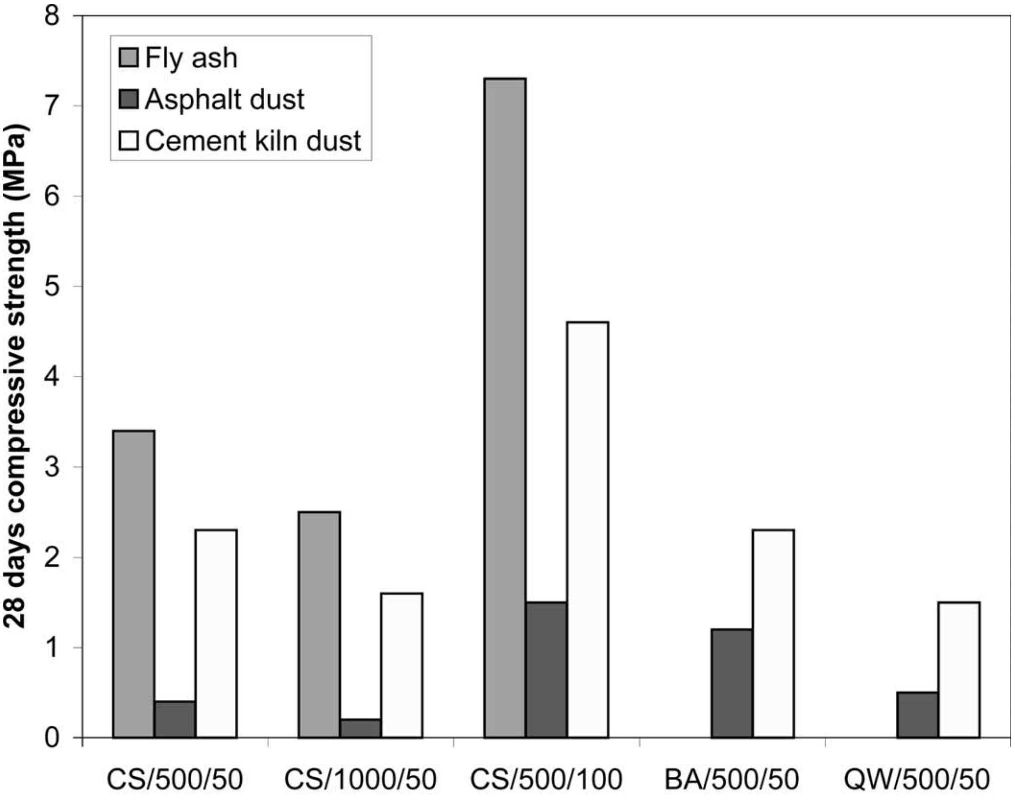

Fig. 7. Twenty-eight day compressive strength (MPa). CS—crushed sand, BA—bottom ash, QW—quarry waste, mix code: coarse fraction/fine waste content/cement content.

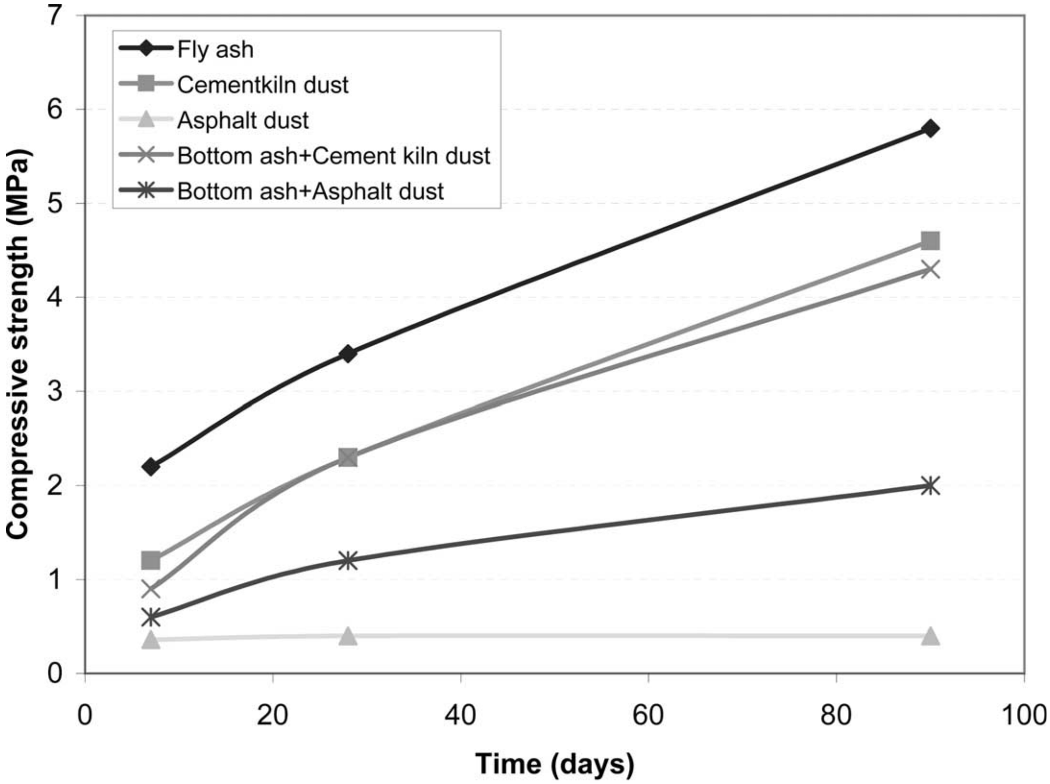

Fig. 8. Development of compressive strength (mixes with cement content of ∼50 and ∼500 kg/m^3 of fine waste).

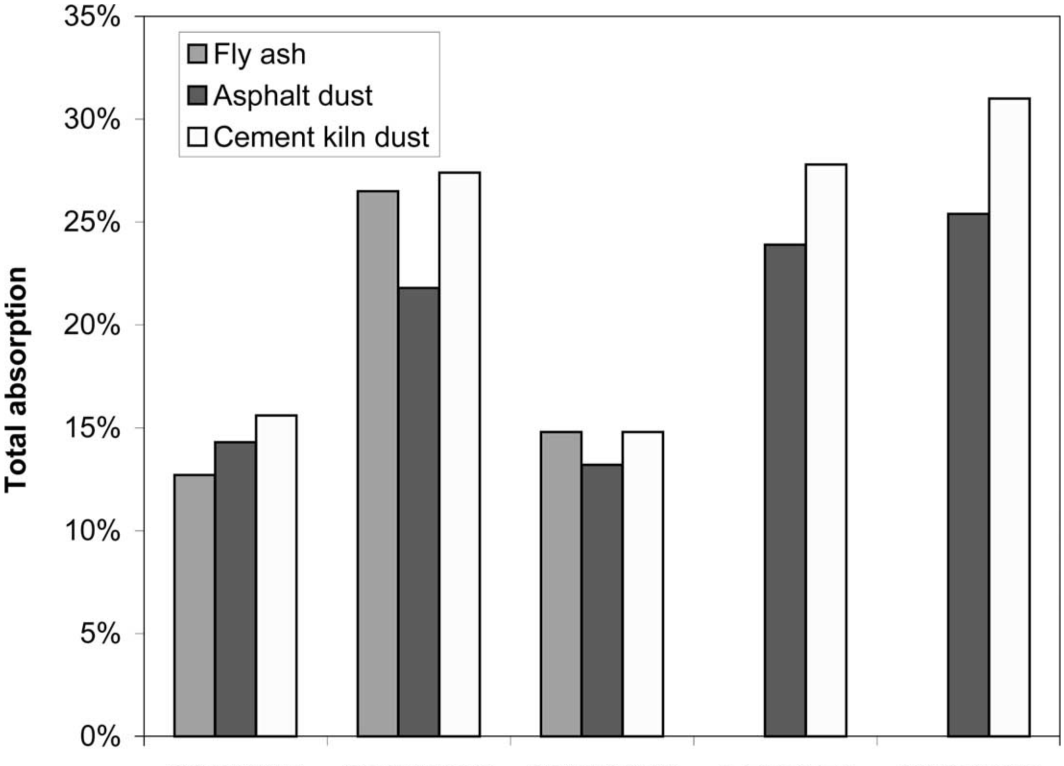

Fig. 9. Total water absorption of mature CLSM. CS—crushed sand, BA—bottom ash, QW—quarry waste, mix code: coarse fraction/fine waste content/cement content.

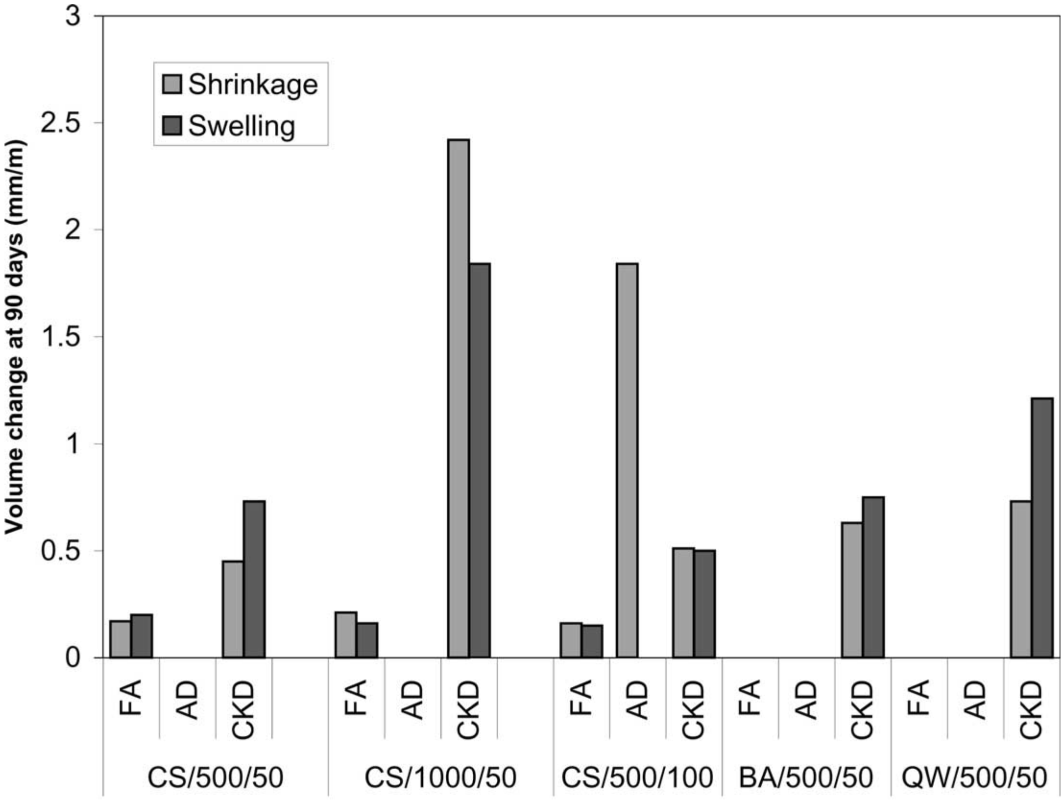

Fig. 10. Volume changes at 90 days (mm/m). FA—fly ash, AD—asphalt dust, CKW—cement kiln dust, CS—crushed sand, BA—bottom ash, QW—quarry waste, mix code: coarse fraction/fine waste content/cement content.

3.3.3. *Volume changes at 90 days*

The volume change of the mature CLSM was relatively small (approximately 0.5 mm/m) with similar values of shrinkage due to complete drying, and swelling due to complete saturation thereafter (Fig. 10). Mixes containing CKD exhibited relatively higher values, probably resulting from the mechanism of water retention that occurred at an early age, as discussed above.

Relatively large volume changes accompanied by very low strength led to partial or sometimes complete disintegration of the mixes containing AD (Fig. 11). The large values of Mix CS/500/100 with AD, which preserved its integrity during the drying process due to its large cement content, can probably give an indication of the order of magnitude of the true values.

The relatively small values of volume changes due to the drying/wetting cycle indicate that significant volume changes due to wetting and drying are not expected, and the risk of the development of lateral pressure on buried elements is not likely to occur.

3.3.4. *Leaching of trace elements*

Leaching tests were carried out on selected specimens only. The results shown in Fig. 12 are of the FA mix CS/500/50 that exhibited the highest, i.e. the worst, leaching values (compared with neat fly ash). The figure shows a significant reduction in the leaching of most of the tested metals. The only exception was the increase of Fe resulting from the presence of iron in the cement and in the crushed sand. Similarly, the reduction in the leaching of aluminum was relatively small, probably also because of the presence of this component in the cement and the crushed sand.

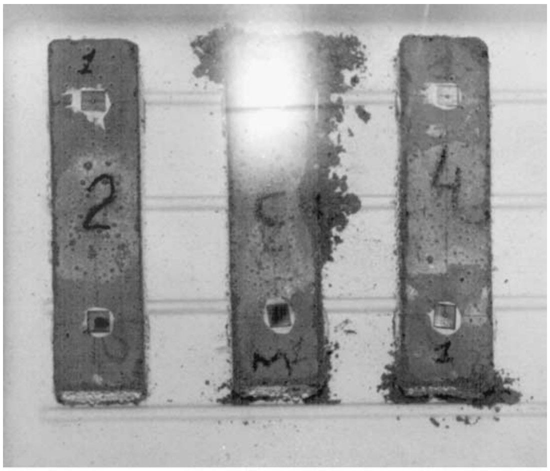

Fig. 11. Partial disintegration of AD mix CS/500/50 due to drying/wetting cycle.

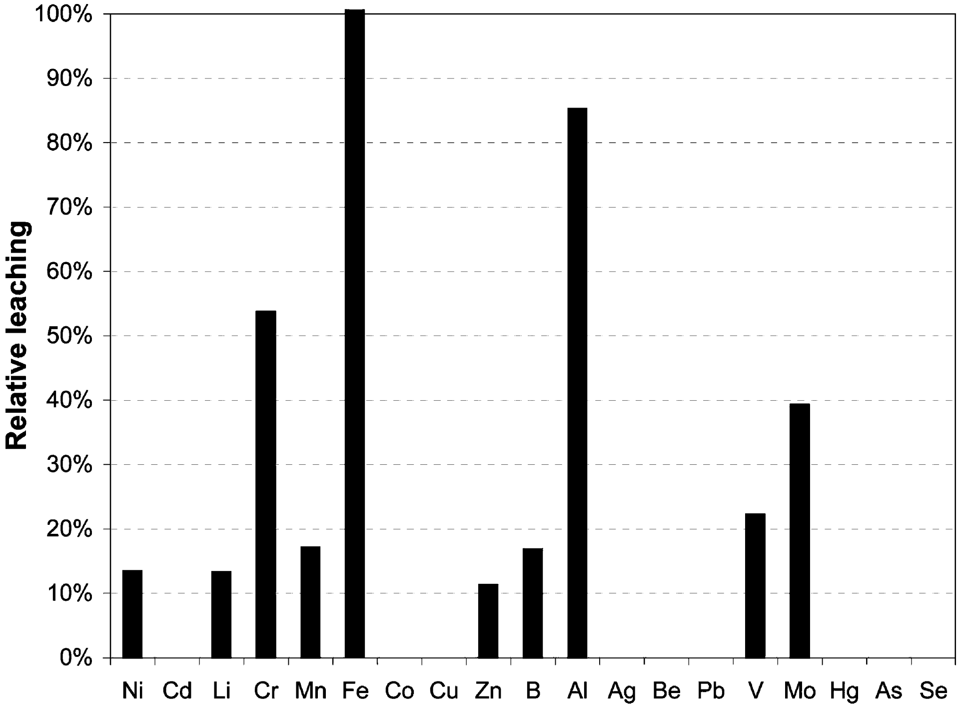

Fig. 12. Leaching of CLSM mix CS/500/50 with FA, relative to neat fly ash.

4. Discussion

The properties of the fresh mix are governed by the amount of fine waste and the shape of its particles. Large amount of fine waste increased the water demand for maintaining a constant flow, but particles of a spherical shape (such as those of fly ash) improve the workability and reduce the water demand. Bleeding is significantly higher with the round-like particles and much smaller in the case of angular particles. Using waste that contains large amounts of fines (the quarry waste that its fines contain also some clay) increases the water demand on the one hand and reduces the bleeding on the other hand. The shrinkage at an early age is reduced in the mixes with high bleeding that provides enough water for evaporation, rather than the water from within the fresh mix.

High strength is obtained in mixes that contain material with some pozzolanic activity (fly ash, bottom ash and cement kiln dust). The high strength may be a problem in mixes when re-excavation at later ages might be needed, and this should be considered. However, mixing inert material, that initially exhibited very low strength, with an active material (bottom ash) yielded a material with reasonable strength and durability.

The high strength of the fly ash mix at a late age is somewhat higher than the strength expected when considering the activation potential of the cement in the mix. Theoretically, the amount of portlandite generated during the hydration process of the cement can react with only a limited amount of fly ash, resulting in a limited addition of strength (Helmuth, 1987). The strength gain at late ages of the fly ash mixes containing 50 kg cement was larger than the strength at 28 days of the mix containing 100 kg cement, pointing on the development of another mechanism that needs further investigation.

The setting time, determined in accordance with the test procedure described in ASTM C403, is not an adequate indication for measuring the properties of very low strength CLSM, as the test result yields only small values, below the threshold value, whereas the material seems to have already started setting. In addition, the hardening of CLSM involves some loss of water to its surroundings simultaneous with the hydration of the cement. Following the ASTM procedure, therefore, may lead to an overestimation of the setting time. Additional work is needed in order to propose a better correlation between the actual setting time measured in field conditions in accordance with ASTM D6024 and its determination in laboratory conditions.

5. Summary

The properties of CLSM made with various industrial by-products were tested in the study. The tested by-products were divided into two groups: (a) cement kiln dust, coal fly ash and dust from asphalt plants in group 1, characterized by higher fine particle content; and (b) coal bottom ash and quarry waste in group 2, characterized by coarser particles. The mixes were prepared with coarse sand, fine waste, cement and water. Waste from group 2 replaced the coarse sand in some mixes.

The engineering properties, such as strength, volume change at early and late ages, bleeding, etc. were satisfactory despite the small amount of cement (50 kg/m^3) and the large amount of fine waste (500 kg/m^3). Large values of compressive strength, up to ~6 MPa, were obtained at later ages (90 days) when materials that may have pozzolanic or cementing properties were used (coal bottom/fly ash or cement kiln dust). Small values, ~0.5 MPa, were obtained when inert waste was used. However, the properties of CLSM made with inert waste can be improved by the addition of another waste that has pozzolanic/cementing properties.

Volume changes that are typical to materials containing large amounts of fines are negligible when pozzolanic/cementing materials were used. When only inert materials were used, larger values were recorded that mainly affected the wetting–drying resistance of the CLSM.

The setting time determined in accordance with ASTM 403 exhibited large values of 10–50 h. It seems that this method does not correctly represent the actual conditions in which the CLSM sets.

Leaching of most of the trace elements was reduced significantly when the waste was encapsulated in a CLSM mix.

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