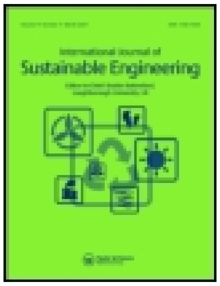

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Mechanical performance and capillary water absorption of sewage sludge ash concrete (SSAC)

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Mechanical performance and capillary water absorption of sewage sludge ash concrete (SSAC)

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Disposal of sewage sludge from waste water treatment plants is a serious environmental problem of increasing magnitude. Waste water treatment generates as much as 70 g of dry solids per capita per day. Although one of the disposal solutions for this waste is through incineration, still almost 30% of sludge solids remain as ash. This paper presents results related to reuse of sewage sludge ash in concrete. The sludge was characterised for chemical composition (X-ray flourescence analysis), crystalline phases (X-ray diffraction analysis) and pozzolanic activity. The effects of incineration on crystal phases of the dry sludge were investigated. Two water/cement (W/C) ratios (0.55 and 0.45) and three sludge ash percentages (5%, 10% and 20%) per cement mass were used as filler. The mechanical performance of sewage sludge ash concrete (SSAC) at different curing ages (3, 7, 28 and 90 days) was assessed by means of mechanical tests and capillary water absorption. Results show that sewage sludge ash leads to a reduction in density and mechanical strength and to an increase in capillary water absorption. Results also show that SSAC with 20% of sewage sludge ash and W/C = 0.45 has a 28 day compressive strength of almost 30 MPa. SSAC with a sludge ash contents of 5% and 10% has the same capillary water absorption coefficient as the control concrete; as for the concrete mixtures with 20% sludge ash content, the capillary water absorption is higher but in line with C20/25 strength class concretes performance.

Keywords: sewage sludge ash; XRD; XRF; TGA; concrete; compressive and flexural strength

1. Introduction

The worldwide production of sewage sludge from waste water treatment plants is increasing all over the world. This kind of sludge includes the solid material left after sewage treatment processes. Sludge treatment involves various steps: thickening, anaerobic digestion, mechanical dewatering and possibly drying (Van de Velden *et al.* 2008). The total production of sewage waste for the USA and the European Union (EU) approaches 17 Mt of dry solids per year (7 Mt in the USA + 10 Mt in the EU; EUROSTAT 2005). According to Baeyens and Van Puyvelde (1994), specific sludge production in waste water treatment is 50 g of dry solids per capita per day. Other authors (Davis 1996, Foladori *et al.* 2010) mention that it varies widely from 35 to 85 g dry solids per population equivalent per day while Van de Velden *et al.* (2008) mentioned it to be 70 g per inhabitant. Sewage sludge tends to accumulate heavy metals, polychlorinated dibenzofurans (PCCDFs), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and dioxins, pesticides and endocrine disruptors present in waste water, and their concentration depends on the origin of sludge (Everaert and Baeyens 2001, Fytili and Zabaniotou 2008, Van Caneghem *et al.* 2010, Chang *et al.* 2011). Domestic sources are usually associated with Cu and Zn and car washes are the largest contributors of Cr, Cd and Pb (Van de Velden *et al.* 2008). The use of thermal hydrolysis and Fenton's peroxidation can reduce the heavy metal content by over 50% (Dewil *et al.* 2006, 2007; Hwang *et al.* 2007). One of the disposal solutions for this waste is through incineration, but this leads to hazardous emissions and even if new technologies are introduced for controlling emissions, still almost 30% of sludge solids remain as ash (Malerious 2003). Fluidised bed incinerators are widely used for this purpose and their design has been recently updated (Van de Velden *et al.* 2007, 2008). Incineration destroys organic compounds, minimises odours, greatly reduces sludge volume and valorises its calorific value. Thus, the percentage of incinerated sludge is increasing all over the world (Lundin *et al.* 2004). The incineration of sewage sludge is governed by the European Directives on the Incineration of Waste (Council Directive 2000/76/EC 2000). The expected growth of world population and also the increase in the volume of waste water show that sewage sludge ash will rise at a very fast pace in the next years (Fytili and Zabaniotou 2008). For the 9 billion inhabitants expected to live on earth by the year 2050 (Bloom 2011), almost 70 Mt of sewage sludge ash could be produced every year. According to some authors the best way for the construction industry to become a more sustainable one is by using wastes from other industries as building materials (Mehta 2001, Glavind and Munch-Petersen

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2002, Sarkar and Roumain 2003, Meyer 2009, Khatib 2009). Therefore, if we think of the areas needed for sludge ash disposal, we clearly understand the importance of reusing sewage sludge ash in concrete. Since global Portland cement demand will increase almost 200% by 2050 from the 2010 levels (Taylor and Gielen 2006), this means that concrete structures are expected to increase in a similar trend. Investigations on sewage sludge ash concrete (SSAC) have already been reported by several authors. The results show that sewage sludge ash reduces workability (Monzo *et al.* 2003) and decreases the mechanical performance (Valls *et al.* 2004). Contradictorily the same authors who report a serious decrease in mechanical strength state that SSAC does not show a durability reduction (Yague *et al.* 2005). Mun (2007) studied the performance of concrete with lightweight aggregate using sewage sludge. The samples were tested for leaching heavy metals in accordance with Korean standard leaching test and the Environmental Protection Agency (EPA) test. The results show that no toxic heavy metals with the highest sewage sludge contents were detected from any of the manufactured lightweight aggregates. Cioffi *et al.* (2011) also studied the use of sewage sludge to produce lightweight aggregates with acceptable physical and mechanical properties as well as leaching behaviour. Several authors confirm the capacity of cementitious matrices to immobilise these wastes (Saikia *et al.* 2008, Horiguchi *et al.* 2011, Wu *et al.* 2011). Recent investigations show that the partial replacement of cement by sewage sludge ash led to substantial retardation of hydration rates (Rodriguez *et al.* 2010). Nevertheless, further investigations are needed regarding SSAC. According to Cyr *et al.* (2007), 'The inherent variability of this kind of residue remains one of the most important reasons for avoiding a systematic generalization of the results.' This study aims to evaluate the mechanical performance and capillary water absorption when using sewage sludge ash of a water treatment plant in Iran.

2. Experimental

2.1 Materials, mixture design and concrete mixing

2.1.1 Sewage sludge

The sludge was prepared from a sewage treatment plant of Alborz Industrial City. The characteristics of sewage and chemical properties of sludge are presented in Table 1. The sludge ash is mainly composed of SiO_2, CaO and Al_2O_3. The SiO_2 content is near the maximum and CaO and Al_2O_3 contents are below the average as in the review of Cyr *et al.* (2007). The SO_3 content is well below the mean value and the P_2O_3 content is slightly above the minimum. The sludge was also analysed by X-ray fluorescence (XRF) (Table 2). Chlorite peaks observed by others were not detected (Mun 2007, Rodriguez *et al.* 2010). Due to high weight loss on ignition (LOI) of the sludge and negative effects of oils and fats on concrete performance, heat treatment process was done on the sludge for up to 650°C. The reason for using this temperature relates to the fact that it was enough to remove the organic matter from the dry sludge. Besides, calcination costs increase exponentially with temperature. The most important change which was visually observed was the change in sludge colour from white-creamy to grey. In order to determine the mineralogical composition, the representative samples were analysed by X-ray diffraction (XRD) (Figure 1 and Table 3). The specific gravity of the sludge ash was 1.8 g/cm^3. The results showed that calcite and dolomite of two crystalline phases were removed from the sludge. This is attributed to the removal of CO_2 from the sludge by

Table 1. Properties of sewage of a treatment plant of Alborz Industrial City.

Rate	Property
Temperature (°C)	Varies
Colour	Dark green
Ec (μ s/cm)	1800
PH	7.6
Ph[a]	7.2
BOD (mg/l)	1200
BOD[a] (mg/l)	130
COD (mg/l)	2000
COD[a] (mg/l)	195
TSS (mg/l)	1400
Phosphate (mg/l)	60
Nitrate (mg/l)	10
Sulphate (mg/l)	183
Azotes (mg/l)	44
NH_4 (mg/l)	28
Suspended solids (SS, mg/l)	40
Detergent (mg/l)	14.2
$No_2 + No_3$ (mg/l)	10
TDS (mg/l)	980

[a] After digestion.

Table 2. XRF analysis of dry sludge.

Elements	Percentage
LOI[a]	21.3
Na_2O	0.436
MgO	2.194
Al_2O_3	8.962
SiO_2	54.545
P_2O_3	1.303
SO_3	0.171
K_2O	1.79
CaO	7.337
TiO_2	0.2
Fe_2O_3	0.927
Zn	0.149
Br	0.541
Sr	0.031
Zr	0.114

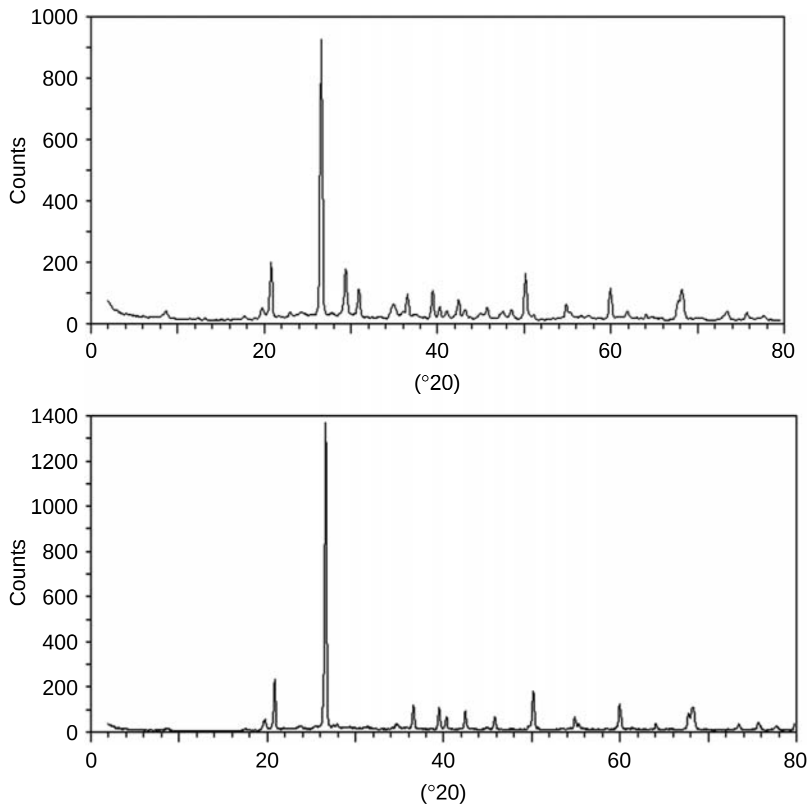

Figure 1. XRD diagram of dry sludge: before and after calcinations.

calcination. Probably calcite and dolomite crystals changed to calcium and magnesium oxides in dry sludge. Also, an additional crystalline phase appeared in the sludge composition (i.e. illite). Its chemical structure is close to that of muscovite. It is clear that calcination not only eliminates organic matter but also changes the crystalline phases. To investigate generation of pozzolanic activity in dry sludge after heat treatment, thermo-gravimetric analysis (TGA) was carried out using an STA-499C instrument. The sludge was analysed for up to 650°C for a temperature rate of 10°C per minute. Results are shown in Figure 2. The activity of the sludge sample was 37.86% which is much lower than the activity of natural pozzolans (i.e. 70%). On the basis of this finding, it was concluded that this particular sludge ash has a very low chemical activity and it can only act as filler or aggregate in concrete depending on their particle size. The fineness rate of sludge ash was also measured by a 45 μm sieve (mesh 325). The results indicated that 51.5% of sludge remained on the sieve.

Table 3. XRD analysis.

Before calcination	After calcination
Quartz (SiO_2)	Quartz (SiO_2)
Muscovite [$KAl_2(Si_3Al)_{10}(OH,F)_2$]	Muscovite [$KAl_2(Si_3Al)_{10}(OH,F)_2$]
Calcite ($CaCO_3$)	Illite [$KAl_2(Si_3Al)O_{10}(OH)_2$]
Dolomite [$CaMg(CO_3)_2$]	

2.1.2 *Mixture design and concrete mixing*

For the production of concrete specimens, Portland cement Type II of ABYEK Cement Production Co. was used along with both gravel and sand from Rahsar Company. Figure 3 shows the particle size distribution of sand, fine and coarse gravel. To improve concrete workability, a Melcrete super-plasticiser was used. A reference mixture (control) and three more mixtures according to the sludge ash content (5%, 10% and 20%) were investigated. The sludge ash percentage relates to cement mass, for indicative purposes only. Two water/cement (W/C) ratios were used (0.45 and 0.55). Table 4 presents the concrete mixture proportions per cubic metre of concrete. The specimens were left for 1 day in the mould at laboratory conditions (23 ± 2°C). Then they were removed and immersed in water until tested under compression. Figure 4 shows the density of concrete mixtures. Mixtures with W/C = 0.45 and with a 5% sludge ash content show a decrease in density of about 5%. Increasing the sludge ash content to 10% or even 20% changed concrete density only to a minimum level (6% reduction). This means that sludge

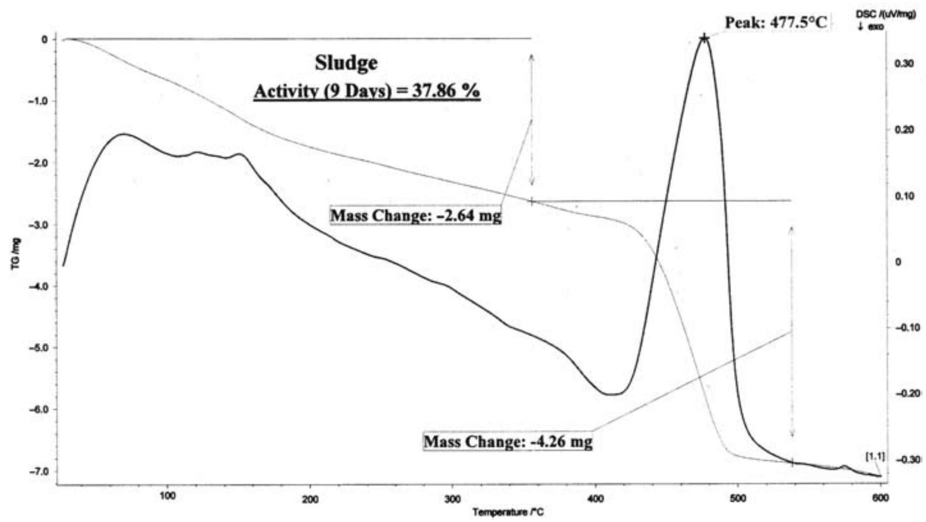

Figure 2. Thermal analysis of the dry sludge.

incorporation below 20% does not have a marked effect on density. As for mixtures with W/C = 0.55, sludge incorporation leads to a concrete density reduction between 2% and 6%. This relates to the fact that sand has a higher density than the sludge ash.

3. Experimental procedures

3.1 *Compressive strength*

Compressive strength was determined following ASTM C39/C39M. The test was done on $15 \times 15 \times 15\,\mathrm{cm}^3$ specimens. Compressive strength for each mixture was obtained from an average of three cubic specimens determined at the age of 3, 7, 28 and 90 days.

3.2 *Flexural strength*

The compressive strength was determined following ASTM C78. Compressive strength for each mixture was obtained from an average of three cubic specimens determined at the age of 28 days.

3.3 *Capillary water absorption coefficient*

The capillary water absorption coefficient was carried out according to C1585 ASTM and using $10 \times 10 \times 10\,\mathrm{cm}^3$ specimens with a 28-day curing age. Preparation of test specimens was done as follows: after drying in an oven at 105°C for 48 h, the specimens were made waterproof along the lateral surface with a fine layer of silicon in order to

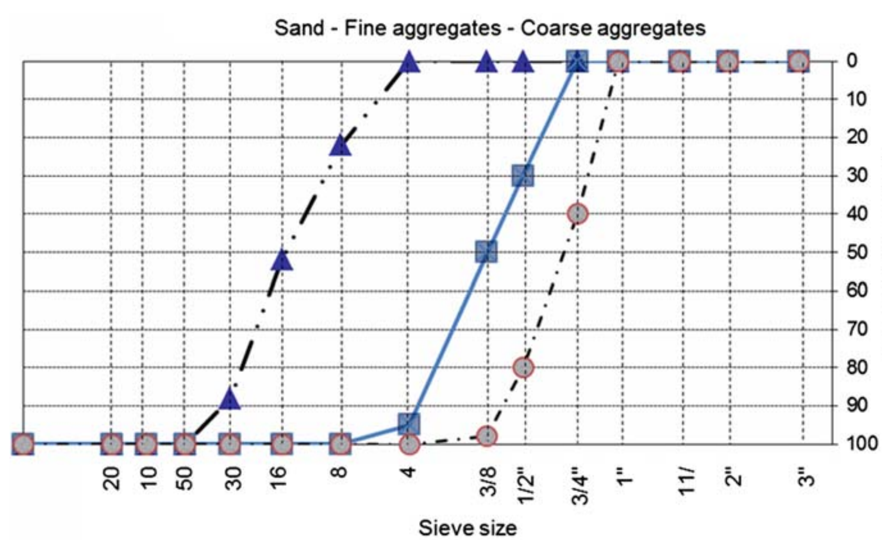

Figure 3. Particle size distribution of aggregates.

Table 4. Concrete mixture proportions per cubic metre of concrete.

Mixtures	Cement (Kg)	Gravel (Kg)	Sand (Kg)	Sludge (Kg)	Super plasticiser (Kg)	Water (l) W/C = 0.55	Water (l) W/C = 0.45
Control	360	861	852	0	3.6	198	162
SSAC-5	360	861	852	18	3.6	198	162
SSAC-10	360	861	834	36	3.6	198	162
SSAC-20	360	861	798	72	3.6	198	162

reduce water evaporation and guarantee capillary water absorption. The test specimens were then placed inside desiccators, for some hours, to allow hardening of the silicon. The capillary water absorption was obtained from an average of three specimens. The capillary water absorption coefficient corresponds to the slope of the curves representing water absorbed per unit area versus square root of time.

4. Results and discussions

4.1 Compressive strength

Figure 5 shows the results of compressive strength of concrete mixtures with a W/C = 0.55. For a hydration period of 3 days, no significant differences were noticed between the control mixture and the mixtures with 5% and 10% replacements of sand by sludge ash. The mixture with 20% replacement shows a 20% decrease in the compressive strength. Beyond 7 days curing until 28 days, the concrete mixture with a 5% content of sludge ash shows almost no compressive strength loss. Mixtures with 10% sludge ash have a 10% compressive strength loss and similar performance occurs to the concrete mixture with a 20% sludge ash content, meaning that strength loss is proportional to the sludge ash mass replacement. The mixture with 20% sludge ash content shows an increase in the compressive strength with curing time, and at 90 days the strength almost reaches the same compressive strength as the mixture with just 10% sludge ash content. This could be attributed to a minor pozzolanic effect as reported by other authors (Cyr *et al.* 2007) or to the fact that sludge ash particles could behave like extra sites for the nucleation and growth of hydration products, thus enhancing the overall hydration process (Neville 1997, Moosberg-Bustnes *et al.* 2004, Dyer *et al.* 2011). Results show that concrete mixtures with 5% or even 10% sludge ash show minor compressive strength loss. Even the use of a 20% sludge ash content leads to a compressive strength above 25 MPa for 28 days curing. Figure 6 shows the results of the compressive strength of concrete mixtures with a W/C = 0.45. The results show that the reduction in water leads to an overall increase in compressive strength associated with a denser microstructure. The mixture with

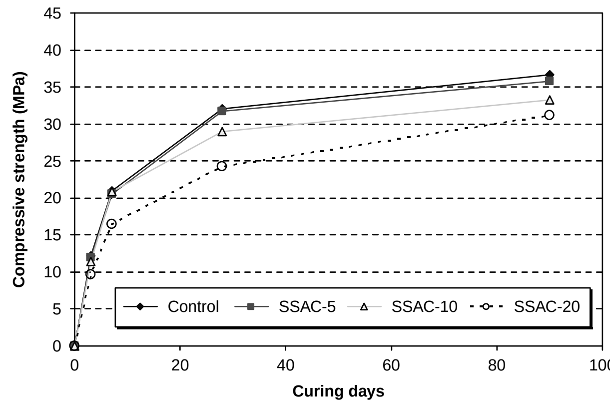

Figure 5. Compressive strength of concrete mixtures with W/C = 0.55.

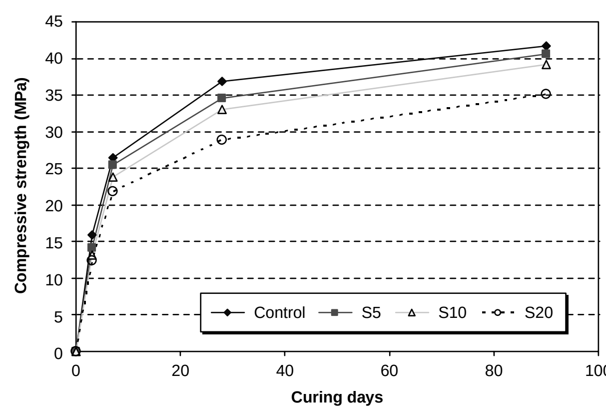

Figure 6. Compressive strength of concrete mixtures with W/C = 0.45.

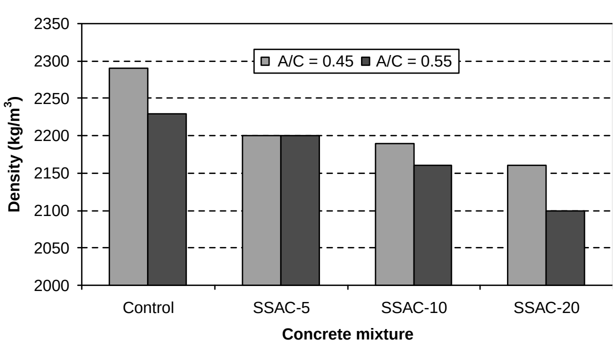

Figure 4. Density of concrete mixtures.

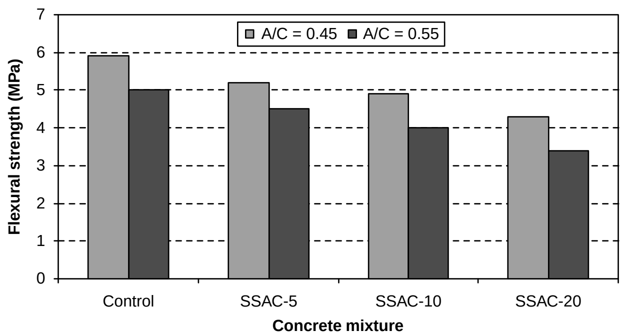

Figure 7. Flexural strength.

a 20% sludge ash content has almost 30 MPa for 28 days curing. For this hydration period, the sludge content influences the compressive strength in a proportional way. This compressive strength level is very promising when compared with the feeble performance obtained by other authors (Valls *et al.* 2004, Yague *et al.* 2005).

4.2 Flexural strength

Figure 7 shows the flexural strength of the several concrete mixtures. Results show that an increase in the sludge content leads to a decrease in flexural strength. The reduction in the W/C ratio leads to denser mixtures and higher flexural strength.

4.3 Capillary water absorption coefficient

Capillary water absorption coefficients are shown in Figure 8. Results show that using a sludge ash content of 5% or even 10% does not change the concrete capillary network. But when a 20% sludge ash content was used, the capillary water absorption coefficient almost doubles. Having said that, one must bear in mind that other authors (Pacheco-Torgal and Gomes 2006) obtain capillary water absorption coefficients between 0.85 and 2.6 $kg/m^2 h^{0.5}$, for a plain C20/25 strength class concrete, the most used strength class in Europe (ERMCO 2011). This means that the capillary water absorption coefficient associated with 20% sludge ash mixture has a good capillary water absorption performance.

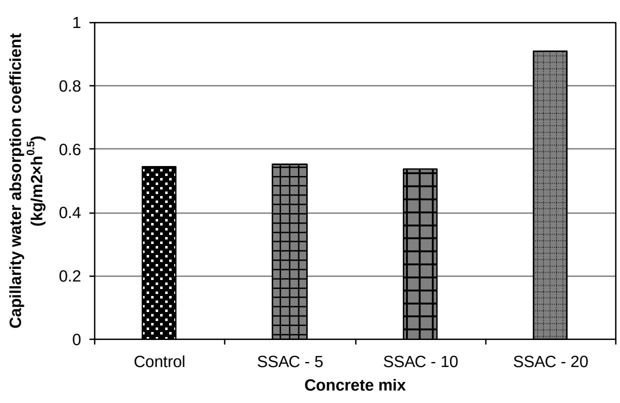

Figure 8. Capillary water absorption coefficients of concrete mixtures with W/C = 0.45.

5. Conclusions

Application of sludge ash of a water treatment plant in concrete was investigated at water to cement ratios of 0.45 and 0.55. The following conclusions were obtained on the basis of the results. Heat treatment is required to remove organic materials from the sludge. Depending on the heating temperature, some changes can be obtained in the crystalline phases. Concrete mixtures with 5% and 10% sludge ash content show minor reductions in the mechanical performance. By increasing the sludge ash content to 20%, a decrease of about 20% in compressive and flexural strengths was obtained. However, concretes containing 20% sludge ash showed acceptable mechanical performance at W/C = 0.45. This sludge ash content leads to an increase in the capillary water absorption coefficient; however, it compares favourably with the performance of a C20/25 strength class concrete. Nevertheless, for safety reasons it would be advisable to use just 10% of sludge ash. SSAC with 10% sludge ash can contribute to a reduction in sludge disposal areas in Iran. With a population of 78 million inhabitants would mean that 0.5 million tons of sewage sludge ash is to be managed each year. This amount could be easily incorporated into the Iranian annual production of 40 million tons of Portland cement concrete. Further investigations on leaching tests and ecotoxic performance are needed to ensure the environmental performance of SSAC. Furthermore, one must realise that the chemical composition of urban wastewater and of the sewage sludge may vary with time to higher heavy metal contents. This means that there is a need for new concrete conformity tests and possibly pre-treatments in order to reduce the heavy metal content.

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