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1 Colour, compressive strength and workability of mortars with an iron rich 2 sewage sludge ash

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5

6 **Abstract**

7 This paper reports a study of the colour, compressive strength and workability of mortar when cement is
8 partly replaced by sewage sludge ash (SSA). In the study, an iron rich SSA was dry milled into six different
9 fractions. The results showed that the colour, compressive strength and workability parallel to one another
10 gradually changed when the particle sizes of the SSA decreased. The milling of the SSA altered the
11 performance of mortars to the extent that the compressive strength and workability were comparable to the
12 performance of ordinary mortar. At the same time, the colour also changed from grey to a reddish colour. As
13 the change in colour may be of importance for application, it is suggested to include colour as experimental
14 parameter in future work.

15

16 **Keywords:** mortar, sewage sludge ash, colour, compressive strength, workability

17 **1. Introduction**

18 Negative environmental effects and overexploitation of available resources, due to a growing human
19 population, is a problem faced by the construction industry. Not only has the construction industry a high
20 demand for materials, but 10% of the global emission of CO₂ is due to provision of construction materials of
21 which cement alone is accountable for approximately 85% [1]. The growing demand for reduced emissions
22 of CO₂ is urging the cement and concrete industry to find new less CO₂ intensive materials, which allows
23 substituting cement in blended cement and concrete.

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24 The cement and concrete industry have for a long period of time played the role of scavengers by retrieving
25 waste from other sectors to be utilised in blended cement and concrete production [2]. This has led to
26 conditions where 20 -70 % of cement is replaceable with these silico-aluminate materials, which have filled
27 out the function as supplementary cementing material (SCM) [3]. But in order to achieve higher rates of
28 cement substitution it is, as suggested by Scrivner et al [4], necessary to develop and use new SCM, which
29 also are locally available. Sewage sludge ash (SSA) could be such a local available resource suitable for
30 SCM. Sewage sludge ash derives form incineration of sewage sludge, which is a waste handling option used
31 at water treatment plants to deal with large volumes of sludge.

32 Extensive research has investigated the possibilities of utilizing SSA not only as SCM in blended cement but
33 in a wide range of building materials such as bricks, tiles, pavers, light aggregates but also for substitution
34 for cement in concrete and mortar [5,6]. The majority studies conducted, which have tested the effect of SSA
35 in mortar, have reported that the compressive strength decreases, when using SSA as partial cement
36 replacement [5-7]. In order to be qualified as SCM a key question of interest, which have been addressed in
37 previous works, is whether SSA possess pozzolanic activity and therefore belongs to the group of pozzolans
38 like other residues such as blast furnace slag, silica fume and coal fly ash [7-11]. In the review by Cyr [7] the
39 oxide content of SSA found in literature were compared. The analyses of the content taken from 46 studies
40 showed that content of SiO_2 and Al_2O_3 were in average less than 50 %. This means that material parameters
41 important for the reactivity in general are lower in SSA than in other known pozzolans. In two studies by Pan
42 et al. [12] and Donatello et al. [11] the SSA was milled to obtain finer particle sizes. The pozzolanic activity
43 of un-milled and milled SSA was determined by Strength activity Index (SAI) [11,12] and Frattini Test [11].
44 In the Frattini test the reactivity of the pozzolane is measured by monitoring the removal of $\text{Ca}(\text{OH})_2$ from a
45 solution of cement and the pozzolane in focus, whereas the SAI is an indirect method that determines the
46 activity of the pozzolane by determination of the compressive strength of the test mortar. The results of the
47 studies showed that the pozzolanic activity of SSA increased as the SSA was milled. However, Donatello et
48 al. [11] also showed that the assessment method used to determine the pozzolanic activity provided different
49 results. With the Frattini test pozzolanic activity was only detected for milled SSA, whereas the SAI showed

50 pozzolanic activity in both un-milled and milled SSA. Another important parameter for the performance of
51 mortars with SSA is the morphology and fineness of the SSA. Results from the studies by Pan et al. [12] and
52 Donatello et al. [11] showed a connection between decreasing particle sizes of SSA and improved
53 compressive strength development of mortars with milled SSA. Both studies also found that even though the
54 particles sizes of the SSA decreased due to the milling, the specific surface area of the SSA did not increase
55 to the same extent. Therefore it was found that the SSA's were characterised by having many open pores
56 trapping water, which effected the workability of the mortar and thereby also the hydration process due to
57 lower available water in the system [11].

58 Despite of numerous studies investigating the use of SSA as SCM in mortar and concrete, research has not
59 led to application of cement based materials with SSA in construction. This might be due to the uncertainty
60 to what extent SSA belongs to the group of pozzolans. However, in a Danish demonstration project *Bio*
61 *Crete* supported by EU LIFE program [13] utilisation of SSA in concrete production was tested on a larger
62 scale. During a three year project period app 28.000 m³ concrete was produced using app 2000 t of SSA in
63 total [14]. In project it was found that a high content of Fe in the SSA affected the colour of the concrete,
64 which changed from the normal grey to red tones depending on the quantities of SSA in the mix [14,15].
65 Even though the concrete produced with SSA met the technical requirements for materials to be used in
66 construction, the change of the colour was seen as an obstacle, because it restricted the application of the
67 concrete mainly to be used for hidden structures if not intentionally used aesthetically. The colour and
68 possible colouration of mortar and concrete with SSA is relevant to address and include as parameter into the
69 experimental framework in order to anticipate obstacles for its application in the build environment. The
70 focus of present study was therefore jointly to examine how the milling of SSA affected the colour,
71 compressive strength, and workability of mortar when 20 % of cement was replaced with processed SSA.

72

73

74

75 2. Materials and methods

76 2.1. Materials

77 SSA was collected at the wastewater treatment plant Biofos in Copenhagen, Denmark (February, 2013). The
78 SSA is incinerated in a fluidized bed combustor at about 850°C. The plant treats wastewater from 255.000
79 person equivalents (PE) with a subsequent ash production of app. 2500 tons annually. Phosphorous is
80 removed from the wastewater by chemical precipitation with Fe. The resulting ash therefore has a
81 characteristic red iron-oxide colour. The SSA is a mixture of at least 95 % fly ash captured in the
82 electrostatic filter and not more than 5% Air pollution control residues taken from the bag filter. It is
83 according to the European waste catalogue classified as fly ash with a hazardous substance (EWC code 19 01
84 13) [16]. The SSA was collected directly from the process line and stored in sealed plastic containers at room
85 temperature. The SSA was both used as-received and milled, and these samples are named SSA and SSA_{xmin},
86 respectively, where x is the duration of the milling.

87 For mortar preparation a Portland cement (CEM II/A-LL 52.5R) was used. This cement type has a content of
88 less than 20% limestone filler. The sand used in the experiment was a natural sea sand 0-4mm with technical
89 specification following DS/EN 12620 [17] and DS 2426 [18] In this paper, the term “test material” covers
90 SSA (as-received and milled) and test binder (cement and SSA).

91

92 2.2 Drying and milling procedures

93 The impact of drying the SSA on particle size distribution of the ash was investigated. The SSA was dried
94 for 24 h at 50° or 105° respectively. Two samples were dried at 50° or 105° before they were milled, and
95 compared with two samples which also were dried at 50° or 105° but after the milling, SSA as-received and
96 cement. A vibratory cup mill (FRITSCH - pulverisette 9) with the capacity to process a batch size of 250 ml
97 was used for milling the SSA. The SSA was placed in the grinding set which consisted of a container with a
98 ring and a puck inside. The grinding set was placed on a vibrating plate and the sample was milled by

99 centrifugal force. The samples were dried milled for 30 sec. The particle size distribution of cement, SSA as
100 -received and four milled SSA samples were analysed by laser diffractometry.

101 For the remaining part of the work, the procedure for drying and milling was: drying at 50 °C for 24 h before
102 milling. Milled SSA samples from 6 different durations were produced: 0 sec, 10 sec, 30 sec, 3min, 6 min,
103 and 10 min. Particle size distribution was measured for each fraction and they were compared to the particle
104 size distribution of cement.

105

106 2.3 Analytical procedures

107 The concentrations of the trace elements Ni, Cr, Cu, Zn and Pb in the test samples were measured after the
108 pre-treatment procedure described in DS/EN 259 [19]: 1.0 g material and 20.0 ml (1:1) HNO₃ was digested
109 at 200 kPa (120 °C) for 30 min. The digested suspension was filtered through 0.45 µm filter paper, and the
110 filtrate analysed by ICP–OES (Induced coupled plasma – optical emission spectrometry). The equipment
111 used for the analyses was a Varian 720-ES.

112 The water content of the test samples were measured as weight loss by drying at 105°C for 24 hours. The pH
113 was measured by suspending 10.0 g of test material in 25 ml distilled water. After 1 h agitation pH was
114 measured directly in the suspension. Loss on ignition (LoI) was determined as weight loss after 30 minutes at
115 950 °C. Solubility in water was evaluated by suspending 100 g test material in 500 ml distilled water. After
116 agitation for 1 min and settling, the water was decanted and 500 ml new distilled water was added. This was
117 repeated and the ash was washed three times. Finally the suspension was filtered, dried and weighed, and the
118 solubility expressed as weight loss by this procedure.

119 The buffering capacity of the test materials was determined by firstly preparing a suspension of the test
120 material mixed in water (6.7 % w/v) secondly stirring the suspension for 30 min before pH was measured.
121 Successive 10 ml of concentrated HCl were made every 30 min and pH was measured thereafter. This was
122 repeated every 30 min until pH was below 2 [20]. The analyses conducted comprised, besides a

123 characterisation of SSA as received (SSA) and cement, also an analysis of Test Binder (80 wt % cement and
124 20 wt % SSA.)

125 Major oxide composition and Cl content in SSA and cement was found by X-ray fluorescence (XRF) on
126 powder samples by an external laboratory. Images of particle morphology were made using a scanning
127 electron microscopy (SEM) of a small sample placed directly on carbon tape. The SEM apparatus used was a
128 FEI Quanta 200. It was equipped with a large field detector and x-ray cone and the accelerating voltage of
129 the SEM was 15 kV. Particle size distribution of the test materials was determined by a laser diffractometry
130 and the apparatus a Malvern Mastersizer 2000.

131

132 2.4 Mortar preparation and compressive strength test

133 The mortar preparation followed the procedures as described in DS/EN 191-3+A3 [21] except for the sand,
134 where the 0-2 mm sand prescribed was replaced by coarser sand with a grain size distribution between 2- 4
135 mm. This sand was chosen to have a coarser consistency, closer to that of concrete, but still manageable at
136 laboratory scale.

137 In the experimental 20 wt % of the cement was replaced by SSA. This percentage was chosen in order to
138 obtain results that would clearly show what effect milled SSA had on colour, compressive strength
139 development and workability. The same percentage of cement replacement was used in two studies in which
140 milled SSA was tested for pozzolanic activity [11], setting time and workability [12]. 20 % of cement
141 replacement can also be seen as an appropriate starting point for dealing with the environmental implications
142 of cement production. Seven experimental mortars were produced, five with substitution of milled SSA, one
143 with substitution of un-milled SSA (0sec) and one control sample without SSA (Ref) No additional water was
144 added to any of the test samples. A description of the different mortars is shown in Table 1. The mixing,
145 casting procedures and the moulds used were as prescribed by DS/EN 191-3+A3[21]. The mortar samples
146 were removed from the moulds after 24 h, placed vertically in a water bath 20 °C and cured for 28 days.
147 Each prismatic mould produced 3 specimens measuring 160mm x 40mm x 40mm which after curing were

148 cut into 6 equal test samples measuring 80mm x 40mm x 40mm. A Toni 3000 compression machine was
149 used for the determination of the compressive strength. The halved samples were loaded side faced with a
150 momentum of 2400 N/s. Detection of fracture was set at 2%.

151

152 Table 1 Recipe for reference and test mortars

Mortar sample	SSA duration of milling	cement	SSA	sand	water
REF	÷	450 g	÷	1350 g	225 g
0SEC	0 sec	360 g	90 g	1350 g	225 g
10SEC	10 sec	360 g	90 g	1350 g	225 g
30SEC	30 sec	360 g	90 g	1350 g	225 g
3MIN	3 min	360 g	90 g	1350 g	225 g
6MIN	6 min	360 g	90 g	1350 g	225 g
10MIN	10 min	360 g	90 g	1350 g	225 g

153

154

155 2.5 Workability

156 The flow value expresses the workability of mortar with un-treated and milled SSA. Preparation of mortars
157 followed DS/EN 191-3+A3(DS 2009) and the tested mortars are those listed in Table 1. The flow value was
158 determined according to DS/EN 1015-3[22]. A truncated conical mould (50 mm high, internal diameter 100
159 mm at the bottom and 70 mm at the top) was uniformly filled with mortar. The mould was removed, and the
160 mortar exposed to jolting by slowly raising the mould 2 cm vertically and dropping it, 15 times at a rate of
161 one pr. second at a flow table. The mean diameter (d_{mean}) from two measurements of the subsequent mortar
162 diameter in two directions at right angles was found. The procedure was repeated twice for each mixture.

163 The flow value is defined as D_{mean} of second measurement and accepted, if D_{mean} differs less than 10 %
164 between the two mixtures.

2.6 Colour samples

165 The seven mortars in Table1 were prepared for the production of samples for colour evaluation. The mixing
166 followed the same procedures as for compressive strength testing. However, the moulds used were three

167 compartment moulds made from film faced ply wood where each compartment had the internal dimensions
168 100x100x30mm. The mortar was uniformly distributed in the mould by means of a vibrator table, covered in
169 plastic and kept in the wooden mould for 24 h. The samples were ejected and stored at room temperature
170 without any exposure to daylight.

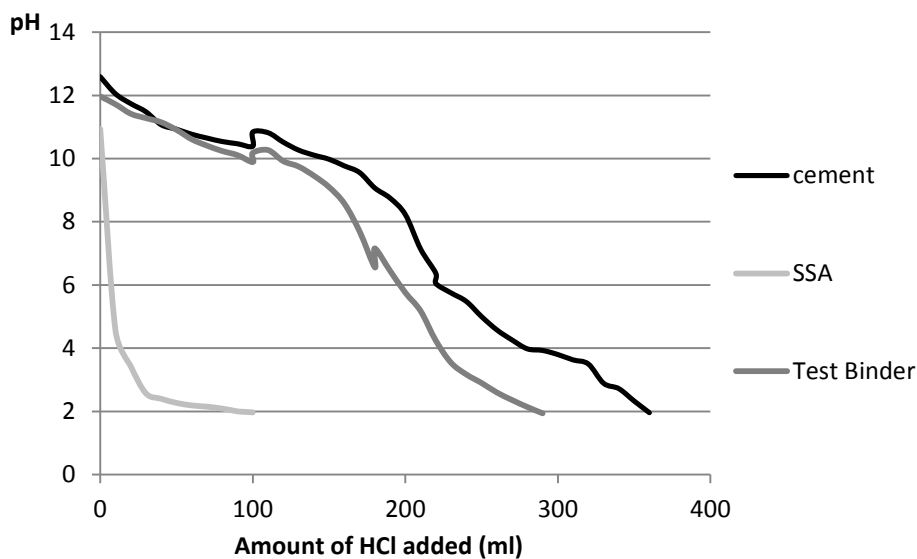
171

172 3. Results

173 3.1 Material characteristics

174 The characteristics of the test materials: SSA, SSA_{10min}, cement, Test Binder (80 wt % cement and 20wt %
175 SSA) are shown in Table 2. The results show that all test materials were alkaline. However, the pH of SSA
176 was 9.9 against pH 12.6 for both cement and test binder (Table 2). This finding was supported by findings
177 provided by the determination of the buffering capacity (Figure 1). The graphs monitoring the buffering
178 capacity of cement displays a high resistance against acidification as the pH dropped slowly. Even though
179 the buffering capacity of SSA was significantly lower in comparison to cement, the buffering capacity of the
180 test binder was relatively high and to some extent comparable to the buffering capacity of cement.

181 Figure 1 Buffer capacity of SSA, SSA_{10min}, cement and Test Binder



182

183

184 The SSA had a water soluble fraction of about 1.5% per weight (Table 2). Determination of water solubility
 185 gave negative values for cement and for the test binder. The negative values represent an increase in mass
 186 due to the hydration process. The values found display that the hydration process of the test binders was less
 187 reactive as these values were less negative than for cement.

188 The chemical analysis showed that the concentration of trace elements Cu, Zn and Pb were significantly
 189 higher in the test binders than in cement due to the higher concentration levels in the SSA. The
 190 concentrations of Cr and Ni, on the other hand, were only slightly elevated in the test binder compared to
 191 cement, as the concentration of these trace elements were less than half and half, respectively, in the SSA
 192 compared to cement.

193

194 Table 2 Characterisation of SSA, SSA10min, Cement and Test Binder

	SSA	Other SSA ^a Mean	cement	Test Binder
water content %	0.63 ± 0.13	-	0.28 ± 0.11	0.24 ± 0.09
water solubility %	1.27	-	- 3.56	- 1.93
pH	9.9 ± 0.00	-	12.6 ± 0.02	12.6 ± 0.01
Loss on ignition (%)	1.35 ± 0.04	-	7.04 ± 0.09	5.81 ± 0.05
Major oxides (%)				
Al ₂ O ₃	5.1	14.2	4.91	4.95 ^b
CaO	23.8	14.8	65.7	57.5 ^b
Fe ₂ O ₃	15.7	9.2	5.43	7.48 ^b
K ₂ O	1.57	1.3	0.81	0.96 ^b
MgO	2.32	2.4	0.53	0.89 ^b
MnO	0.09	0.3	0.04	0.05 ^b
Na ₂ O	1.15	0.9	0.67	0.77 ^b
P ₂ O ₅	20.2	11.6	0.23	4.22 ^b
SiO ₂	17.1	36.1	20.1	19.5 ^b
SO ₃	2.02	2.8	4.74	4.2 ^b
TiO ₂	0.83	1.1	0.35	0.45 ^b
Cl	0.01	-	0.1	0.08 ^b
trace elements (mg/kg)				
Ni	57.5 ± 1.53	671	27.0 ± 5.55	35.6 ± 1.15
Cr	38.7 ± 0.76	452	26.0 ± 4.85	30.7 ± 2.11
Cu	688 ± 17.3	1962	67.5 ± 13.1	183 ± 8.12
Zn	1930 ± 26.8	3512	115 ± 22.0	415 ± 17.0
Pb	144 ± 2.00	600	21.6 ± 4.49	46.3 ± 1.56

195 ^a Mean values of oxide and heavy metal content in SSA samples reported in Cyr et al

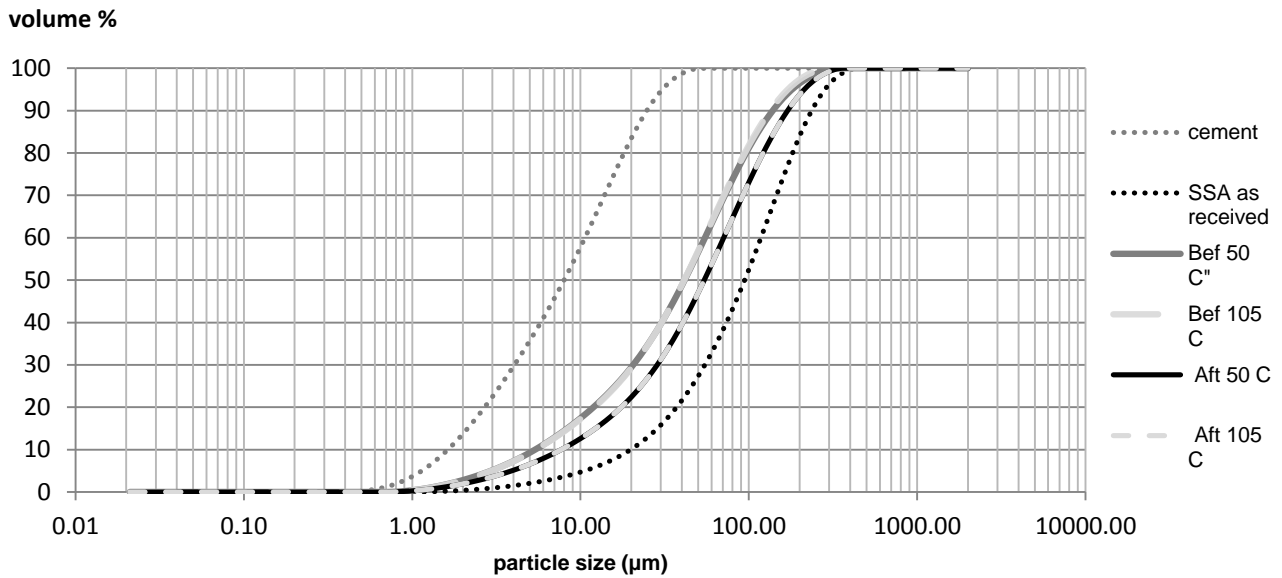
196 ^b calculated oxide content on basis of the detected content values of SSA and cement

197

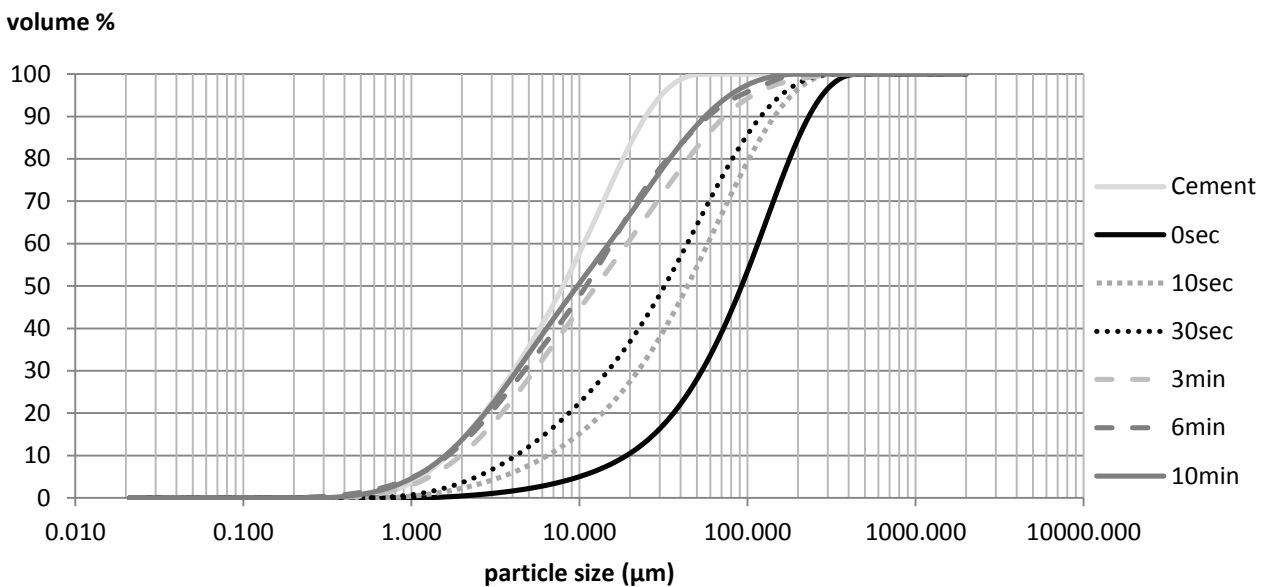
198 The distribution from XRF of the major oxides for SSA was: $\text{CaO} > \text{P}_2\text{O}_5 > \text{SiO}_2 > \text{Fe}_2\text{O}_3 > \text{Al}_2\text{O}_3$ (Table 2).
199 In comparison to mean values reported in the study Cyr et al [7] the SSA of present study had a high content
200 of P_2O_5 , relatively low content of SiO_2 and Al_2O_3 . The content of P_2O_5 was 20 % and was at the same level as
201 CaO (23.8 %) and Fe_2O_3 (17.5 %) %. When SSA and the content of four main constituents of cement: CaO ,
202 SiO_2 , Fe_2O_3 and Al_2O_3 , are compared, only the content of SiO_2 was at a comparable level to the content found
203 in cement. MgO and MnO were found to be between 2- 4 times higher in SSA than the levels found in
204 cement. Only the content of SO_3 was higher in cement than in SSA which was 2.02% against 4.74% for
205 cement. The major oxides composition for Test Binder was calculated on basis of the measured compositions
206 for the two parts SSA and cement (Table 2) and it had quite similar composition as cement. The
207 concentration of P_2O_5 was however, much higher (4.2% against 0.2%) for Test Binder due to the high
208 content in SSA. The content of heavy metals Ni, Cr, Cu, Zn and Pb were much lower than the mean values
209 reported in the study by Cyr et al [7].

210 The results of the particle size distribution analysis' seen in Figure 2 show that finer particles are obtained if
211 SSA is dried before milling regardless the applied temperature. Samples of SSA were dried either before
212 (Bef) or after (Aft) milling at 50°C and 105°C. At 50 % of volume for $\text{Aft}_{50^\circ\text{C}}$ the accumulated volume had
213 increased by approximately 10 % in comparison with $\text{Bef}_{50^\circ\text{C}}$. Thus finer particles were obtained when the
214 SSA was dried before the milling. The temperature applied did not affect the particles size distribution.
215 Based on this result, the SSA was dried at 50°C before it was milled in order to obtain the smallest possible
216 particle sizes in the remaining experiments.

217 Figure 2 Particle size distribution of cement, SSA as-received, and milled (30 Sec) SSA dried either before (Bef) or After (Aft) the
 218 milling



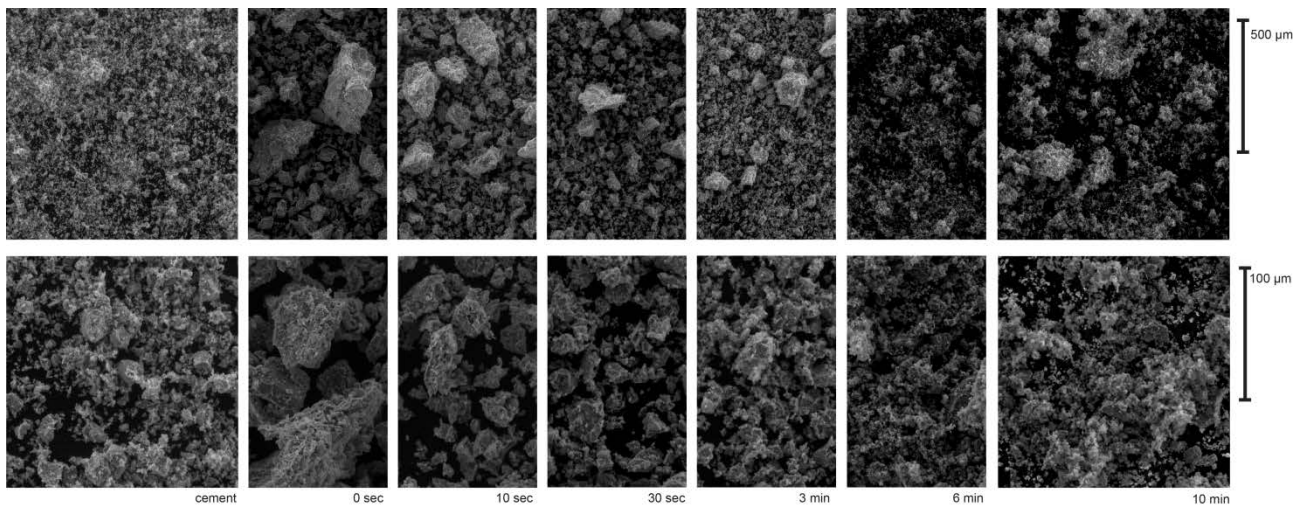
219
 220 Figure 3 Particle size distribution of cement and SSA milled in interval between 0 sec and 10 min



221
 222 The effect of the milling process for different durations was analysed by comparing the particle size
 223 distribution and morphology of the milled SSA with the particle size distribution and morphology of cement

224 (Figures 3 and 4). The effect of milling SSA can be seen in Figure 3. A comparison of the particle size
 225 distribution for the milled SSA shows that the slopes of the curves and the medium size particles (d_{50}) move
 226 closer to that of cement when milling time reached intervals between 3- 10 min, and further decrease of the
 227 particle sizes was minor between this intervals (Figure 3). SEM images of the morphology of as-received,
 228 milled SSA and cement (Figure 4) support the findings from Figure 3. The effect of the milling on the coarse
 229 particles of as-received SSA, which were steadily crushed as the duration of the milling increased, can easily
 230 be observed in Figure 4.

231 Figure 4 SEM images of cement and milled SSA in interval 0sec- 10min



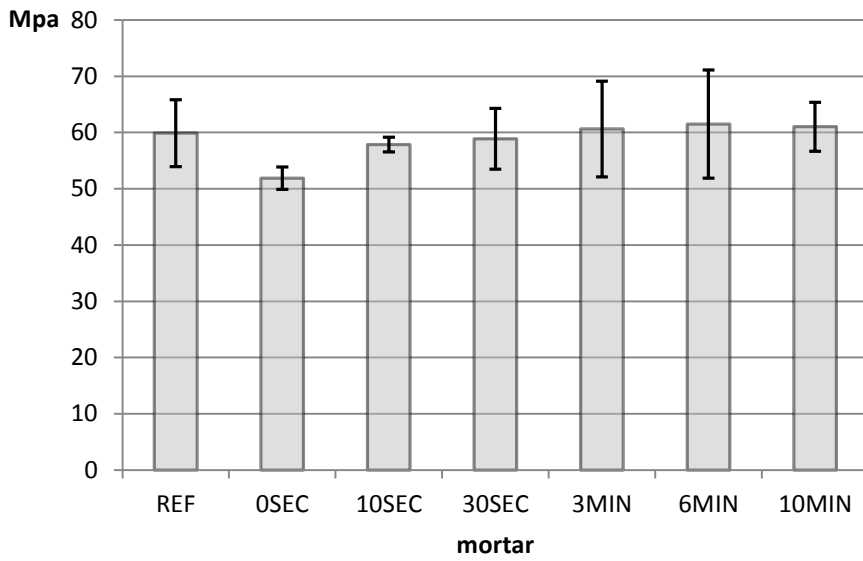
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233

234 3.2 Material properties: compressive strength, workability and colour

235 The results of the compressive strength test (Figure 5) showed a positive effect from milling the SSA. A
 236 decrease in compressive strength was found when 20 % of cement was replaced by SSA as received. The
 237 measured compressive strength of the control (REF) was around 60 MPa and decreased by 13.4% to the
 238 level of 52 MPa(0SEC) when cement was replaced by un-milled SSA. However, the compressive strength
 239 improved immediately when SSA had been milled, even for only 10 sec. The compressive strength for
 240 10SEC was approximately 58Mpa, a decrease of only 3.4% compared to the compressive strength of REF.
 241 Test mortars containing SSA milled for 3- 10 min achieved the same level as REF.

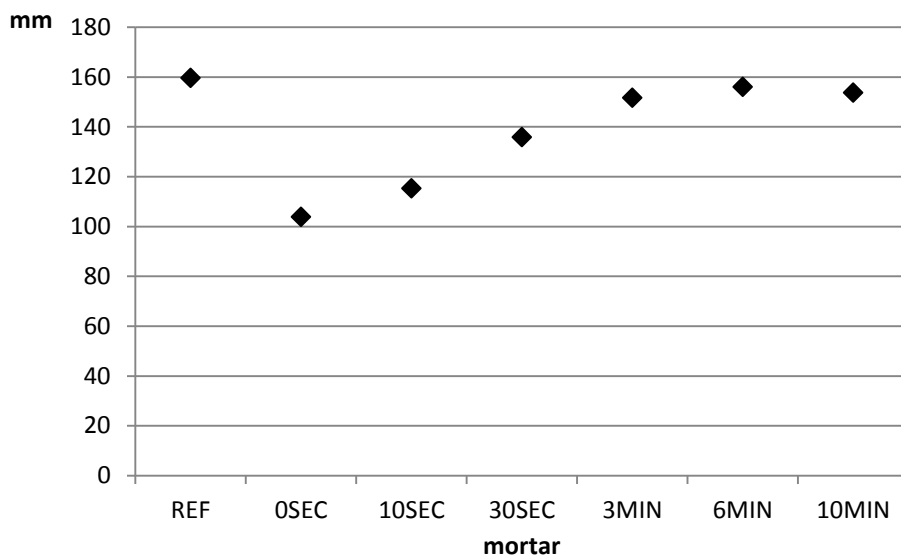
242 Figure 5 Compressive strength after 28 days



243

244 The workability, evaluated by determining the flow value of test mortars, is seen in Figure 6. The particle
245 size distribution of SSA was essential to the workability of the six test mortars. The flow value of 0SEC,
246 where 20 % cement was replaced by SSA as received, decreased by 35% in comparison to REF . As the
247 milling duration increased, the flow values increased correspondingly. For sample 6MIN the flow value was
248 close to that of REF.

249 Figure 6 Flow value -Workability of control and test mortar



250

251

252 Figure 7 shows the colour samples. It shows that the colour of mortar containing milled SSA evolved
253 simultaneously to an increased duration of the milling (Table 1). The images also display that the colour tone
254 of 0SEC, which was grey colour with a slight red tint, was comparable to the grey colour of REF. In figure 8
255 the three samples: 0SEC, 10SEC and 6MIN are displayed together with REF, and it illustrates that the colour
256 progression of the six samples containing SSA can be ordered in three step colour scale. In the colour scale
257 each of samples has a distinct colour different from the neighbouring sample. The remaining samples which
258 are not included in the colour scale in Figure 8 have tones which are similar to the samples: 0SEC, 10SEC,
259 and 6MIN.

260 Figure 7 Colour samples of reference mortar, as received and milled SSA arranged in the following order. REF – 10MIN



261

262 Figure 8 Colour samples REF, 0SEC, 10SEC and 6MIN



263

264

265 4. Discussion

266 The findings of the present study supports the findings of Donatello et al. [11] and Pan et al. [12] as all three
267 studies showed that the compressive strength and the workability improved when SSA was milled. In the
268 present study the milling of SSA did not result in particle size distributions that exceeded the particle size
269 distribution of cement (Fig 3). On the other hand the milling of the SSA did provide a material which could
270 replace the cement by 20 wt % and at the same time gain compressive strengths and flow values which were
271 comparable and reached the level of REF (figure 5 and6). In comparison, results found in the studies by
272 Donatello et al. [11] and Pan et al. [12] showed that the compressive strength only 94 % and 77 % to the
273 level of the compressive strength of ordinary mortar respectively. The differences in the results found
274 between the studies may be due to differences in materials parameters. For instance, the cement used in
275 present study was a CEM II, whereas Donatello et al. [11] used a CEM I for mortar production.

276 Results on compressive strength found in studies by Monzó et al. [9] and Garcés et al [23] showed that the
277 strength development depended on the cement used in test mortars with SSA. These studies therefore
278 exemplify the relevance of considering the type of cement when discussing the reactivity of SSA and the use
279 of SSA as SCM. However, in order to be able to answer and understand how SSA interact with the clinker
280 phases it may require as Lothenbach et al [24] suggest more advanced assessments methods as parametric
281 modelling, based on profound knowledge on thermodynamics of the compounds, to determine the hydration
282 products formed, and thus be able to predict the long term performance of the cement based material
283 produced.

284 A direct correlation between increasing flow values and increasing compressive strength due to the milling
285 of the SSA is clearly seen in figure 5 and 6. The gradual pulverisation of the coarse and angular particles (Fig
286 4) affected simultaneously the workability and the compressive strength. The values found in each
287 experiment correspond to one another, as they follow the same trend. Since the flow value of the fresh
288 mortar increased without any addition of extra water, the reason was most likely due to changes in the
289 morphology of the SSA, and the circumstance that the availability of water in the mix was raised because, as

290 discussed by Donatello et al. [11], the imbibing porous particles of the SSA is crushed down without gaining
291 larger specific surface area.

292 The colour samples produced in this study display that the colour changed gradually from the normal grey of
293 ordinary mortar to increasing tones of red when the fineness of the SSA increased due to the milling (Fig.7)
294 This finding confirms the finding of a previous study by Kappel et al. [25], which revealed that the colour
295 did not change significantly unless the SSA was milled to obtain finer particles and thus, it was found that
296 the milling of an iron rich SSA was a precondition for the red colour to evolve. This study showed that
297 increasing colours of red correspond to increasing flow values and compressive strength, which means
298 whereas the performance of mortar with milled SSA compares to performance of ordinary, it differs visually
299 from its starting point.

300 In the project Biocrete [13] the colour was used as marker for the quantities to be used without affecting the
301 colour of concrete at the same time, even though concrete with a reddish colour containing a higher amount
302 of SSA met the technical requirements set for the concrete [14]. If the motivation for utilizing SSA is to
303 reduce the amount of the CO₂ intensive clinker by substitution of SSA, the colour of the concrete seems less
304 important as a measure to control the substitution rate. In general, the colour has not been included as an
305 experimental parameter into studies on SSA containing mortar or concrete and no previous studies to the
306 author knowledge have reported on the colour of mortar with SSA. This could be due disengagement with
307 the importance of the subject, and the circumstance that the colour of the cement based material is not
308 relevant for its application. However, exemplified by the Biocrete project, the colour change of concrete may
309 be regarded as limiting factor for a general application, and therefore we believe that the colour of SSA
310 containing mortar and concrete is relevant to address, and to unfold the colour potential of milled SSA which
311 intentionally can be used aesthetically and/or integrated in the design solution.

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315 **5. Conclusion**

316 The results of the study showed that milling of the SSA improved the strength development and the
317 workability of mortar with SSA to the extent that the performance of mortars with 20 % cement substituted
318 by SSA_{3-10 min} were comparable to the compressive strength and the workability of a ordinary reference
319 mortar. Mortar with the iron rich SSA did not change its colour significantly unless the SSA was milled.
320 Mortar with un-milled SSA was in a grey colour with a slightly red tint. However, the colour increased to the
321 extent that mortar changed colour from grey to a reddish colour as the particle size of the SSA decreased due
322 to better distribution of smaller particles in the matrix. Overall, the results of the study showed that simple
323 pre-treatments of SSA: drying and milling have an effect on the performance of the mortar, which provide an
324 opportunity to adjust the SSA in accordance to requirements set for application. However, the question on
325 the reactivity of SSA and its long term performances may have to be settled before SSA may obtain the
326 status secondary resource suitable as SCM in blended cement.

327

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