Concrete Pavement Mixture Design and Analysis (MDA):

Application of a Portable X-Ray Fluorescence Technique to Assess Concrete Mix Proportions

National Concrete Pavement Technology Center

Technical Report
March 2012

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16. Abstract

Any transportation infrastructure system is inherently concerned with durability and performance issues. The proportioning and uniformity control of concrete mixtures are critical factors that directly affect the longevity and performance of the portland cement concrete pavement systems. At present, the only means available to monitor mix proportions of any given batch are to track batch tickets created at the batch plant. However, this does not take into account potential errors in loading materials into storage silos, calibration errors, and addition of water after dispatch. Therefore, there is a need for a rapid, cost-effective, and reliable field test that estimates the proportions of as-delivered concrete mixtures. In addition, performance based specifications will be more easily implemented if there is a way to readily demonstrate whether any given batch is similar to the proportions already accepted based on laboratory performance testing.

The goal of the present research project is to investigate the potential use of a portable x-ray fluorescence (XRF) technique to assess the proportions of concrete mixtures as they are delivered. Tests were conducted on the raw materials, paste and mortar samples using a portable XRF device. There is a reasonable correlation between the actual and calculated mix proportions of the paste samples, but data on mortar samples was less reliable.

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CONCRETE PAVEMENT MIXTURE DESIGN AND ANALYSIS (MDA): APPLICATION OF A PORTABLE X-RAY FLUORESCENCE TECHNIQUE TO ASSESS CONCRETE MIX PROPORTIONS

Technical Report
March 2012

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1. INTRODUCTION

Owners of transportation infrastructure are inherently concerned about durability and performance of their system. Proportioning and uniformity of concrete mixtures are critical factors that can directly affect the longevity and performance of portland cement concrete pavements (Wang and Hu, 2005; Kropp and Hinsdorf, 1995).

At present the only means available to monitor mix proportions of any given batch are to track batch tickets created at the batch plant. However, this does not take into account potential errors in loading materials into storage silos, calibration errors, and addition of water after dispatch. Therefore, there is a need for a rapid, cost-effective, and reliable field test that estimates the proportions of as-delivered concrete mixtures. In addition, performance based specifications will be more easily implemented if there is a way to readily demonstrate whether any given batch is similar to the proportions already accepted, based on laboratory performance testing.

This report investigates the feasibility of using a portable XRF device to determine the proportions of fresh concrete.

2. BACKGROUND

2.1. Concrete Quality Assurance

Acceptance procedures for concrete delivered to a construction site are often limited to tests on slump and air content properties (Wang and Hu, 2005). Samples may be collected for later compressive strength testing. The information gained by these efforts is limited; the test methods are subject to large variability and often they do not characterize the performance characteristics sought by the owner.

There is increasing discussion regarding imposing performance based requirements in specifications. This approach has merit, but is limited in acceptability at present because there are few good tests that actually assess critical performance characteristics, or they take a long time before data are available. It is likely that a hybrid approach to performance/prescriptive will continue to be used for the near future, with steady movement toward greater emphasis on performance.

One approach is to fully characterize the acceptable concrete mixture in trials well before construction begins. All that is required during construction, then, is to prove that the mixture delivered to the site comprises the same ingredients in the same proportions to that previously tested and accepted, or at least to be close enough.

Ideally, we need a device that can report the chemical composition of the fresh concrete, from which the ingredients can be determined. Using such a device will also be cost-effective, especially given the fact that the cost of well-conducted testing and quality control is small when compared to the cost of removing and replacing failed concrete (Broton and Bhatty, p. 918).

The goal of this research is to investigate the use of a portable x-ray fluorescence (XRF) technique to assess the proportions of concrete mixtures as they are delivered.

2.2. The Fundamentals of X-Ray Fluorescence

XRF is used in some laboratories in forensic investigations of concrete to determine the elemental composition of samples (EPA, 2007 Proverbio and Carassiti, 1997 Tasong et al., 1999).

The electromagnetic radiation of wavelengths of x-rays ranges between 0.1 Å and 20 Å (Broton and Bhatty, p. 918). The necessary wavelengths are produced by an x-ray tube in which the electrons are accelerated from an emitting source toward the target material (Broton and Bhatty, p. 918). Under radiation from an x-ray source, a sample will emit characteristic X-ray intensities depending on characteristics of the beam, sample elemental concentration, powder particle size distribution, degree of compaction, and the compounds in the matrix (Proverbio and Carassiti, 1997). A detector that collects and reports the intensities of the emitted x-rays, which in turn can be used in a calibrated system to determine the relative proportions of elements in the sample, is shown in Figure 1.

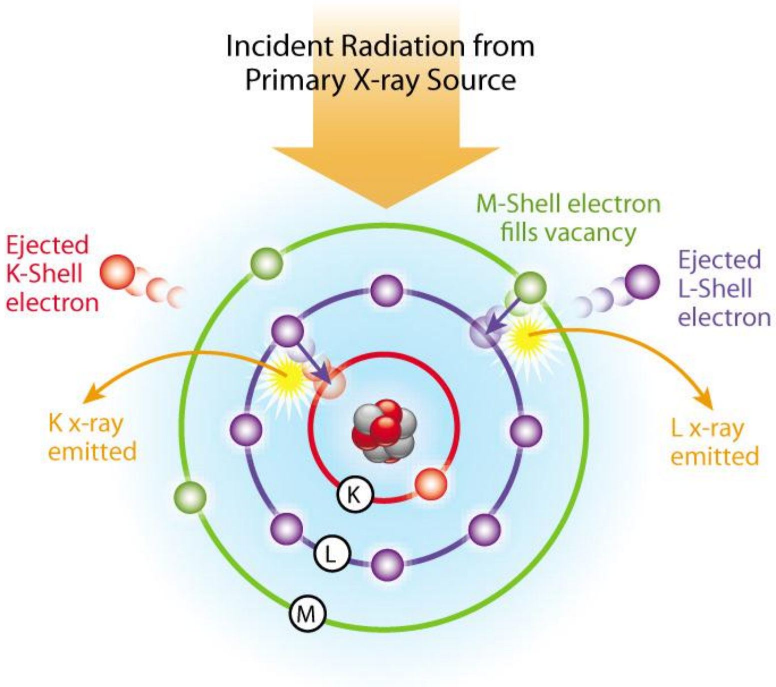

Figure 1. X-ray fluorescence principle

(Source: http://www.niton.com/portable-XRF-technology/how-xrf-works.aspx?sflang=en)

2.3. Challenges for Field Devices

Speed, accuracy, and precision are among the advantages of using the XRF technique in analyzing the chemical composition of samples; however, the specimen preparation is challenging (Broton and Bhatty, p 915). Accurate quantitative XRF analysis requires a homogeneous and flat surface (Broton and Bhatty, p 915). However, homogeneity is always a concern while detecting the elements by using an XRF device because of the relatively small aperture of the sensor. Field studies have shown that the comparability of the obtained test results with confirmatory samples is mostly affected by the heterogeneity of the sample (EPA, 2007). In central laboratories, the practice is to grind concrete samples into powders, mix them well, and then fuse them into glass pellets. In a field device, the aperture is considerably larger, leading to a reduction in precision, but doing away with the need to prepare a special sample for analysis. It should be noted that concrete is heterogeneous at almost all scales from mm down to nm, including within individual aggregate particles. Obtaining a representative sample for micro analysis is therefore always a challenge.

The lighter the element, the more difficult it is to detect emitted x-rays. Detecting the elements Si, Al, Fe, Ca, Mg, S, Na and K are satisfactory for portland cement (Broton and Bhatty, pp. 913-914). However, in the case of the device used in this work, elements lighter than magnesium could not be reliably detected. Table 1 presents the limits of detection for a SiO_2 matrix of the portable XRF device for the elements commonly found in cementitious systems. This means that moisture in a sample (including paste and mortar) may significantly affect analytical accuracy. According to the information obtained from the manufacturer, calibration of the device was based on silica being a major element; therefore the limits of detection were not provided for Si. The presented LODs are calculated as three standard deviations (99.7 % confidence interval) for each element, using 60-second analysis times per filter [Niton XL3t Goldd+ Product Specification Sheet]. LODs are dependent on the testing time, interferences, and level of statistical confidence [Niton XL3t Goldd+ Product Specification Sheet].

Table 1. Elemental limits of detection of the Niton XL3t 900 GOLDD+ Analyzer for an SiO_2 matrix

Element	Limit of Detection (ppm)
Ba	35
Sr	3
Fe	25
Mn	35
Ti	20
Ca	40
K	45
S	75
P	600
Al	2000
Mg	2.5%

Another challenge to this approach is that the predominant elements in the ingredients in concrete are from a relatively small group – namely calcium, silicon, aluminum, and iron. This can make it difficult to separate out different ingredients, particularly the cementitious materials, because they all comprise largely the same materials, albeit in different proportions and in different mineralogical combinations.

3. EXPERIMENTAL WORK

A total of 24 XRF analyses were conducted on a variety of powder, paste, and mortar samples.

3.1. Materials

The following materials were obtained for this work:

- Type I portland cement
- Class F fly ash
- Class C fly ash
- Slag cement
- Silica fume
- River sand

The fine aggregate was a No 4 (4.75 mm) river sand (Table 2).

Table 2. Sieve Analysis of Fine Aggregates

Sieve Size		Retained weight,g	Percentage of individual fractionretained, %	Cumulative percentage passing, %	Cumulative percentage retained, %
3/8"	9.5mm		0.00	100.00	0.00
No. 4	4.75mm	23.9	1.73	98.27	1.73
No. 8	2.36mm	144.3	10.46	87.81	12.19
No. 16	1.18mm	214	15.51	72.30	27.70
No. 30	0.6mm	400.2	29.00	43.30	56.70
No. 50	0.3mm	403.3	29.22	14.08	85.92
No. 100	0.15mm	185.6	13.45	0.63	99.37
No. 200	0.075mm	1.5	0.11	0.52	--
Pan		4.7	0.34	0.18	--
Fineness modulus					2.84

3.2. Samples

The powder samples were tested in open topped containers that were sealed using 6-micron polypropylene (Figure 2).

The paste and mortar samples were mixed in accordance with the ASTM C305. After mixing 1500 grams per mixture, samples were molded in accordance with the ASTM C109. Three cubes (2*2*2-in.) were prepared per mixture.

3.2.1. Cementitious Materials

The five different cementitious materials (Type I portland cement, Class C fly ash, Class F fly ash, silica fume, slag cement) were tested to determine their individual chemical compositions.

Figure 2. Cementitious materials in sample holders

3.2.2. Fine Aggregates

In order to reduce the effect of moisture, the fine aggregate was tested in an oven-dried state. The aggregates were not ground prior to testing.

3.2.3. Paste

Nine paste mixes were prepared and tested with a w/b ratio of 0.45 using the 5 cementitious materials as shown in Table 3. The supplementary cementitious materials (SCM) replacement levels were fixed at 0, 20, and 40% by mass.

Table 3. Paste mixture combinations

Mixture	Portland Cement, %	Class C Fly Ash, %	Class F Fly Ash, %	Slag Cement, %
OPC	100	-	-	-
20C	80	20	-	-
20F	80	-	20	-
20SL	80	-	-	20
40C	60	40	-	-
40F	60	-	40	-
40SL	60	-	-	40
10F20SL	70	-	10	20
20F20SL	60	-	20	20

3.2.4. Mortar

Nine mortar mixes were prepared using the same binder proportions as used in the paste tests. The cementitious to sand ratio was fixed at 1:3 by mass.

3.3. Equipment

A handheld XRF device (Niton XL3t 900 GOLDD+ analyzer) was obtained from Thermo Scientific (Figure 3).

Figure 3. Handheld XRF device

The weight of the device is less than 3 lbs (1.3 kg). The dimensions are 9.60*9.05*3.75 in. (244*230*95.5 mm). The device was equipped with a 50 kV x-ray tube. The aperture of the device was 8 mm in diameter. The measurement time was user-selectable. Up to 30 seconds of testing time is known to be adequate for initial screening, whereas longer measurement times (up to 300 seconds) are needed to meet higher precision and accuracy requirements (EPA,2007). Since the testing period affects the limit of detection, the testing was conducted for 15 minutes per sample to provide sufficient time for a reasonably repeatable analysis.

3.4. Sample Placement

X-ray signal decreases as the distance from the source is increased. In order to maintain the same distance between sample and detector for each sample, the XRF device was attached to a portable test stand for all tests (Figure 4). Note: the device is below the table; samples were placed inverted on the stand. The stand included a cover to protect operators when in use.

Tests were conducted on three samples for each mixture and the results were averaged. Hardened paste and mortar samples were analyzed one day after mixing. The samples were not crushed or powdered in order to mimic field conditions.

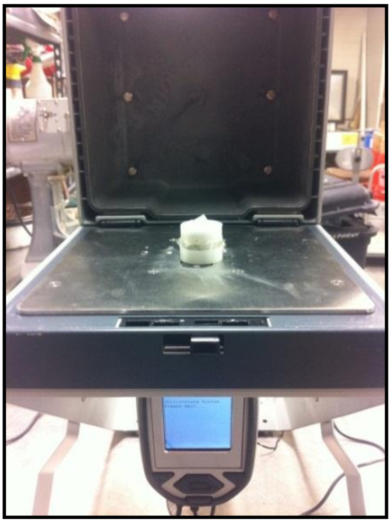

Figure 4. Portable test stand

4. RESULTS AND DISCUSSION

4.1. Cementitious Materials

The device reported the test results as elemental mass percentages. These data were converted into oxides using their atomic weights. This is normal practice even though compounds in the cementitious systems are rarely in oxide form (Kosmatka et al., 2002).

Table 4. Test Results of cementitious materials expressed as percent by mass

Oxide	Cement	C Ash	F Ash	Slag
CaO	62.95	26.35	15.03	40.86
SiO_2	18.21	30.88	49.51	34.37
Al_2O_3	3.67	15.23	12.08	9.93
Fe_2O_3	4.63	9.40	11.17	0.79
MgO	3.12	2.64	1.29	8.47
K_2O	0.77	0.42	2.11	0.41
SO_3	8.55	5.14	2.52	4.69
TiO_2	0.16	1.57	0.80	0.41
BaO	0.03	0.57	0.47	0.05
SrO	0.03	0.28	0.21	0.03
Mn_2O_3	0.48	0.06	0.11	0.38
Total	102.61	92.53	95.30	100.40

The analytical results of the portland cement obtained from the portable XRF were compared with the typical range of Type I portland cement obtained from the PCA (Kosmatka et al. 2002) as shown in Table 5.

Table 5. Comparison of test data with typical range of Type I portland cement adapted from Kosmatka et al. 2002

Oxide	Mass percent	
	Typical range (min-max)	Test data
SiO_2	18.7-22.0	18.21
Al_2O_3	4.7-6.3	3.67
Fe_2O_3	1.6-4.4	4.63
CaO	60.6-66.3	62.95
MgO	0.7-4.2	3.12
SO_3	1.8-4.6	8.55

Comparison of the results of the portable device and the typical range shows that the obtained test results are mostly within the expected range. However, the observed SO_3 content reported by the portable device at 8.55% is well above expected levels. In addition, the reported Al_2O_3 and Fe_2O_3 contents are slightly higher than expected levels.

4.2. Fine Aggregate

For comparison, a sample of the fine aggregate was ground to less than 50 micron and tested using a laboratory XRF. The results are presented in Table 6.

Table 6. Fine aggregate composition reported from laboratory and portable devices

Oxide	Mass percent	
	Laboratory	**Portable**
CaO	8.91	10.96
SiO_2	65.24	56.75
Al_2O_3	7.26	3.00
Fe_2O_3	1.77	1.42
MgO	3.04	3.34
K_2O	1.47	0.61
Na_2O	1.95	-
SO_3	0.21	0.35
TiO_2	0.11	0.06
BaO	0.02	0.04
SrO	0.03	0.02
Mn_2O_3	0.06	0.16
P_2O_5	0.07	0.00
LOI	9.30	-
Balance	0.55	23.30
Total	99.45	76.70

There was a large difference between the Balance values (the percentage of undetected elements) from the handheld device and laboratory instruments. This difference is unlikely to be a result of the moisture content, as both samples were oven-dried.

It should be noted that the fine aggregate sample was crushed to 50 micron before lab testing while the sample tested using the portable device was not ground. Sampling error or the limitations of a portable device may therefore be contributing to the differences between the two sets of data.

4.3. Paste

The test results from paste mixtures are presented in Table 7.

Table 7. Paste oxide composition

Oxide	**Mass percent**								
	OPC	**20 F**	**40 F**	**20 C**	**40 C**	**20SL**	**40 SL**	**10F 20SL**	**20F 20SL**
CaO	48.45	40.44	35.03	44.42	36.45	44.73	41.21	41.90	37.83
SiO_2	14.68	19.99	23.32	19.41	18.45	18.92	20.75	22.03	22.82
Al_2O_3	2.32	4.04	4.77	5.21	6.09	3.70	3.96	4.76	4.64
Fe_2O_3	3.29	4.19	5.21	4.14	4.60	2.73	2.17	3.26	3.69
MgO	0.00	0.00	0.00	2.71	1.71	2.46	2.21	2.46	1.79
K_2O	0.93	1.35	1.21	0.48	0.62	1.03	0.90	1.01	1.12
SO_3	6.96	5.37	5.00	4.69	6.00	4.81	4.96	4.50	4.65
TiO_2	0.12	0.21	0.30	0.36	0.55	0.16	0.19	0.21	0.25
BaO	0.03	0.09	0.15	0.11	0.17	0.03	0.03	0.06	0.09
SrO	0.02	0.05	0.07	0.06	0.09	0.02	0.02	0.03	0.05
Mn_2O_3	0.33	0.28	0.23	0.28	0.21	0.32	0.30	0.31	0.27
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Balance	22.87	24.00	24.69	18.14	25.06	21.09	23.30	19.48	22.78
Total	77.13	76.00	75.31	81.86	74.94	78.91	76.70	80.52	77.22

The percentage of detected elements was decreased in paste mixtures compared to the cementitious materials. The magnitude of the Balance is roughly equivalent to the percentage of water in the mixture.

The solver function in a spreadsheet program was used to calculate the proportions of the cementitious materials in the paste mixtures based on a least-differences approach. The solver varied the amount of SCM in each set, compared the calculated oxides with the measured, and reported the SCM dosage that yielded the lowest error.

Figure 5 presents the relationship between the cumulative error and the calculated SCM content, and is a visual representation of the sensitivity of the approach. It is promising that for each of the mixtures there was a clear minimum error. The data sets shown in Figure 5 are for the 40% SCM mixtures.

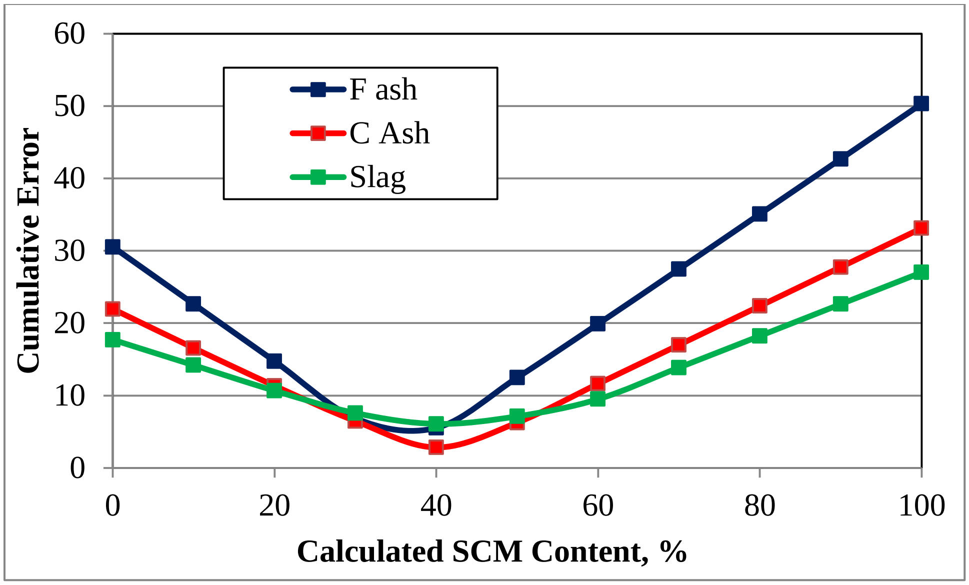

Figure 5. The relationship between cumulative error and calculated SCM content

Figure 6 presents the comparison of tested and batched SCM contents. The calculated SCM content was based on analysis using only the reported oxides. This figure shows that the portable device provides an adequate correlation between the real mix proportions for both binary and ternary paste mixtures.

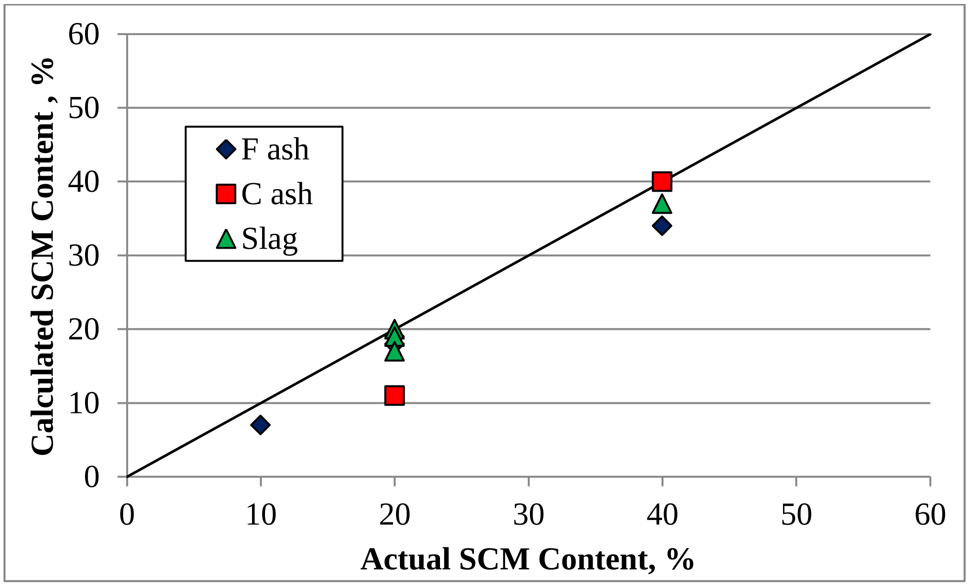

Figure 6. The relationship between tested and batched SCM contents

Figure 7 presents the relationship between the tested and actual SCM contents when the presence of the water is included in the calculation. Water in the mixture is dealt with by assuming that the “Balance” in the reported results is a measure of water content. In this case, the results are less promising. When Figure 6 and Figure 7 are compared, it can be observed that the consideration of water increases the prediction error.

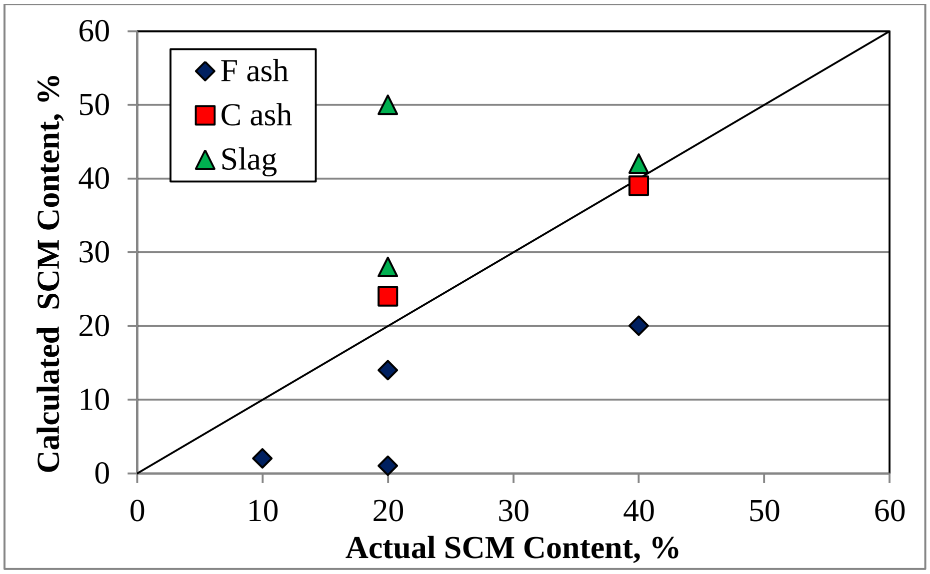

Figure 7. The relationship between tested and actual SCM content when the water presence is included

4.4. Mortar

Table 8. Test results of mortar mixtures

Oxide	Mass percent								
	OPC	**20 F**	**40 F**	**20 C**	**40 C**	**20 SL**	**40 SL**	**10F20SL**	**20F20SL**
CaO	35.57	31.40	27.75	32.94	29.33	33.68	32.55	32.25	29.72
SiO_2	13.44	17.07	20.56	15.79	17.87	16.16	17.41	17.86	19.69
Al_2O_3	1.66	2.54	3.25	3.18	4.63	2.44	2.87	2.90	3.18
Fe_2O_3	2.48	2.97	3.65	2.90	3.38	2.03	1.95	2.36	2.66
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	0.34	0.51	0.82	0.60	0.38	1.00	0.44	0.52	0.99
SO_3	4.96	4.59	3.80	4.75	4.62	4.22	3.98	3.89	3.22
TiO_2	0.09	0.16	0.22	0.24	0.41	0.11	0.14	0.15	0.18
BaO	0.04	0.07	0.08	0.07	0.09	0.04	0.04	0.05	0.06
SrO	0.02	0.03	0.04	0.03	0.05	0.02	0.02	0.02	0.03
Mn_2O_3	0.21	0.18	0.16	0.18	0.15	0.22	0.20	0.20	0.18
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Balance	41.17	40.49	39.67	39.33	39.09	40.08	40.39	39.80	40.08
Total	58.83	59.51	60.33	60.67	60.91	59.92	59.61	60.20	59.92

In the mortar tests, the undetected percentage (Balance) was significantly increased, likely due to the detection area and heterogeneity of the tested samples.

Similar to the analysis on paste mixes, the calculated SCM contents of the mortars was calculated by using a solver function, this time including the data from the sand analysis. The calculations reported the percentage of sand content to be around 30% by mass, which is close to the actual mix. Figure 8 demonstrates the relationship between the tested and actual SCM content. The inclusion of sand increased the error between the predicted and the actual percentages of SCMs, and was consistently low.

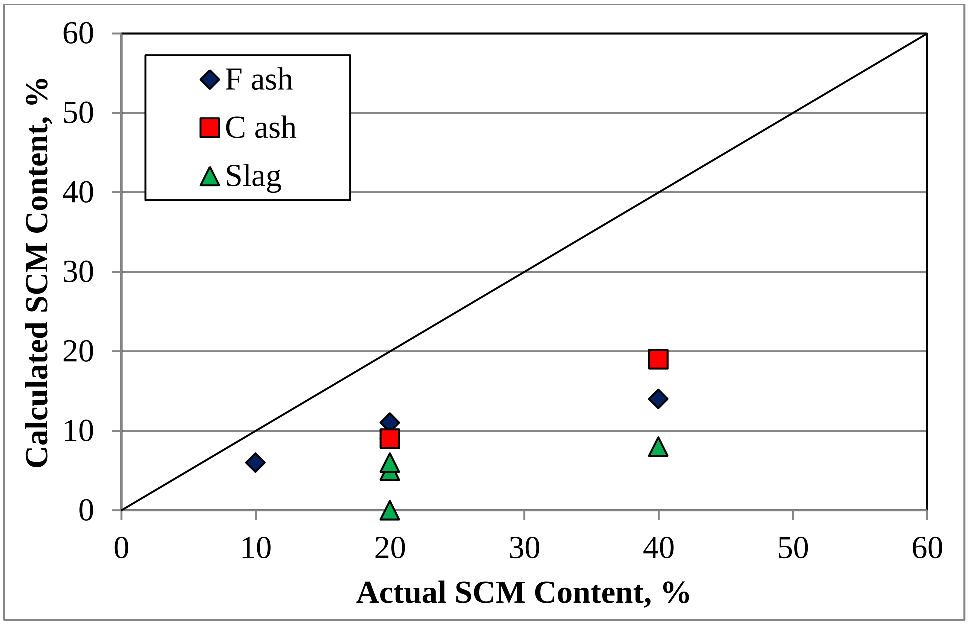

Figure 8. The relationship between tested and designed SCM content

It was considered that, depending on the depth of penetration of the beam into the sample, it was probable that the amount of sand being analyzed was not representative of the mixture. To assess this effect, the calculations were repeated with a range of fixed sand contents forced into the model for the 40% SCM mixtures. This relationship is presented in Figure 9. Based on this figure, the predicted SCM content is the closest to the actual when the assumed sand content is between 12 and 18%. This clearly illustrates that the beam was not penetrating far enough into the samples to detect all of the sand in a given volume.

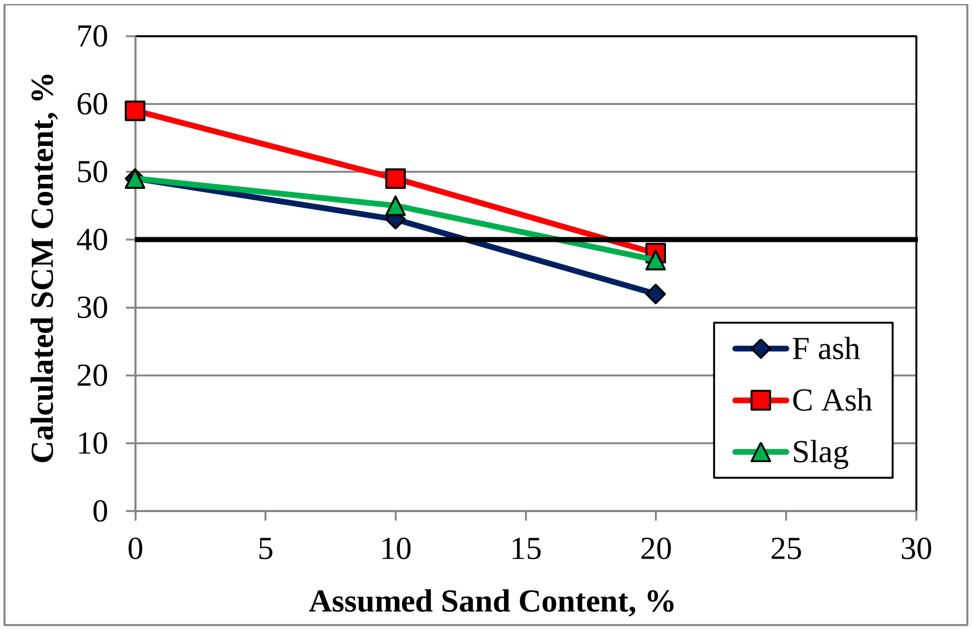

Figure 9. The calculated SCM content for varying sand contents forced into the model

Assuming a fixed sand content of 15%, the relationship between the actual and calculated SCM content was calculated and is shown in Figure 10. The error between actual and predicted SCM content is lower than the variation when the sand content was not fixed, but is still unacceptably high.

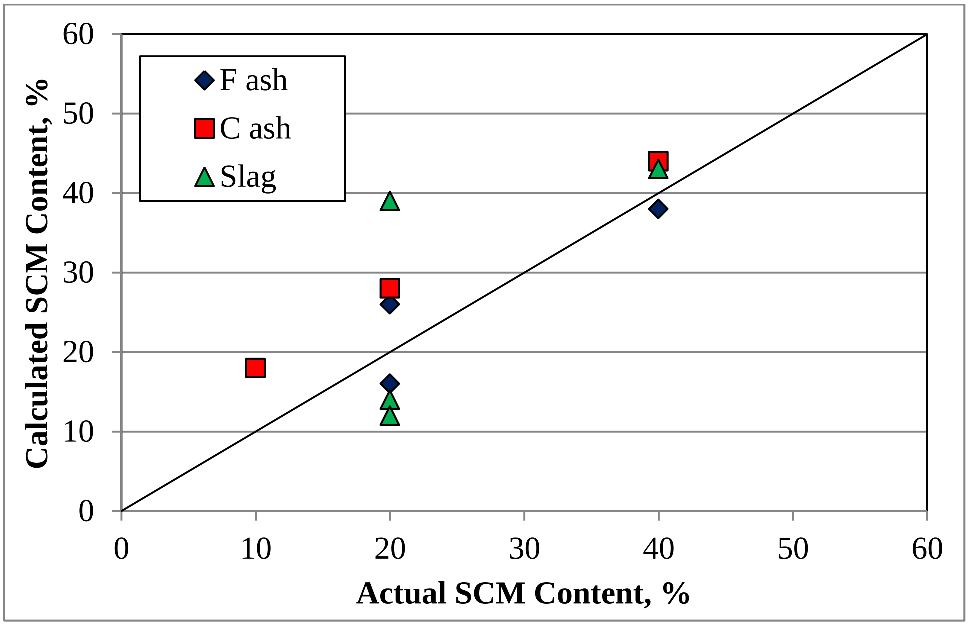

Figure 10. The relationship between tested and designed SCM content (fixed sand content at 15%)

5. CONCLUSIONS AND RECOMENDATIONS

In summary, the device appears to provide reasonable analyses of the raw materials in a mixture, except that the sulfate content of the cement was high, and the balance of undetected elements in the fine aggregate was very high. Despite these, the system appeared to be able to report the SCM dosages of paste mixtures well, and the balance appeared to be roughly equivalent to the moisture content of the samples. The analysis of the mortar samples was less promising with considerable error being introduced by inhomogeneity of the samples. Attempts to allow for this still left relatively large errors.

On a typical construction site, it may be possible to extract a mortar sample from concrete relatively easily, but extracting a paste sample is more difficult, if not impossible. Therefore it seems that continued effort is required to find ways to analyze mortars. One approach may be to develop a signature for a given mix that can then be compared with each batch as it is developed. If a significant difference is observed, this would be an indication of a problem, although the details of the problem would not be identified.

REFERENCES

Broton D. and Bhatty J. I. (2004). Chapter 8.1. Analytical Techniques in Cement Materials Characterization. In Bhatty J. I., Miller F. M. and Kosmatka S. H. (Eds.), Innovations in Portland Cement Manufacturing (pp. 913-958), Illinois: Portland Cement Association.

EPA. (2007). Field Portable X-Ray Fluorescence Spectrometry for the Determination of Elemental Concentrations in Soil and Sediment (Method 6200). Environmental Protection Agency, USA.

Franzini M., Leoni L., Lezzerini M., and Sartori F. (1999). On the binder of some ancient mortars. Mineralogy and Petrology Vol. 67, pp. 59-69.

Ho D.W.S., and Chirgwin G.J. (1996). A performance specification for durable concrete. Construction and Building Materials, Vol. 10, No. 5, pp. 375-319.

Kosmatka, S., Kerkhoff, B., and Panarese, W.C. (2002). Design and control of concrete mixtures, 14th Ed., Portland Cement Association, Skokie, IL, USA.

Kropp J., and Hinsdorf H.K. (1995). Performance criteria for concrete durability. RILEM Technical Committee TC 116-PCD, RILEM Report 12.

Niton XL3t Goldd+ Product Specification Sheet http://www.niton.com/Libraries/Document_Library/Niton_XL3t_GOLDD_Spec_Sheet.sflb.ashx (Accessed on 03/09/2012).

Proverbio E. and Carassiti F. (1997). Evaluation of chloride content in concrete by x-ray fluorescence, Cement and Concrete Research, Vol. 27, No. 8, pp. 1213-1223.

Tasong W. A., Lynsdale J. S., and Cripps J. C. (1999). Aggregate-cement paste interface Part I. Influence of aggregate geochemistry, Cement and Concrete Research, Vol. 29, pp. 1019–1025.

Wang K., and Hu J. (2005). Use of a moisture sensor for monitoring the effect of mixing procedure on uniformity of concrete mixtures. Journal of Advanced Concrete Technology, Vol. 3, No 3, pp. 371-384.

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APPENDIX

Table A.1. Raw data – powder

Sample No	Balance (%)	Ca (%)	Al (%)	Si (%)	Fe (%)	Ba (%)	Nb (%)	Zr (%)	Sr (%)	Bi (%)	Pb (%)	Zn (%)	Cu (%)	Ni (%)	Mn (%)	Cr (%)	V (%)	Ti (%)	K (%)	P (%)	Cl (%)	S (%)	Mg (%)	Sum	Elements Detected
OPC 1	37.630	45.369	1.759	8.207	2.053	0.026	0.003	0.010	0.026			0.009	0.005	0.007	0.332	0.008	0.010	0.104	0.639		0.011	3.245		99.453	61.823
OPC 2	35.383	45.199	2.129	8.819	2.062	0.027	0.003	0.011	0.027			0.008	0.004	0.007	0.339	0.006	0.009	0.099	0.629		0.026	3.322	1.879	99.988	64.605
OPC 3	38.898	44.116	1.769	8.039	2.070	0.023	0.003	0.010	0.026			0.008	0.004	0.005	0.339	0.005	0.008	0.094	0.666		0.011	3.675		99.769	60.871
OPC 4	36.270	45.303	2.125	8.998	2.009	0.026	0.003	0.010	0.026			0.008	0.005	0.008	0.327	0.006	0.010	0.098	0.624		0.019	3.453		99.328	63.058
Average	37.045	44.997	1.946	8.516	2.049	0.026	0.003	0.010	0.026			0.008	0.005	0.007	0.334	0.006	0.009	0.099	0.640		0.017	3.424	1.879	99.635	62.589
C Fly Ash 1	49.778	19.257	7.502	13.862	4.078	0.503	0.004	0.027	0.232	0.003	0.005	0.013	0.022	0.012	0.041	0.013	0.149	0.945	0.345	0.557	0.018	2.061		99.427	49.649
C Fly Ash 2	48.773	19.131	7.770	14.187	4.067	0.505	0.004	0.026	0.232	0.004	0.005	0.013	0.022	0.012	0.043	0.014	0.148	0.938	0.344	0.591	0.019	2.076	1.065	99.989	51.216
C Fly Ash 3	53.760	17.625	6.467	12.816	4.301	0.482	0.004	0.028	0.241	0.004	0.006	0.014	0.023	0.007	0.038	0.013	0.139	0.882	0.329	0.510	0.029	1.808		99.526	45.766
C Fly Ash 4	44.371	19.125	9.439	15.740	4.212	0.539	0.004	0.029	0.240	0.004	0.005	0.013	0.023	0.014	0.043	0.014	0.154	0.973	0.357	0.628	0.012	2.182	1.863	99.984	55.613
C Fly Ash 5	45.044	19.048	9.127	15.597	4.113	0.531	0.004	0.029	0.237	0.004	0.005	0.013	0.023	0.014	0.044	0.015	0.153	0.957	0.349	0.647	0.014	2.164	1.850	99.982	54.938
Average	48.345	18.837	8.061	14.440	4.154	0.512	0.004	0.028	0.236	0.004	0.005	0.013	0.023	0.012	0.042	0.014	0.149	0.939	0.345	0.587	0.018	2.058	1.593	99.782	51.436
Silica Fume 1	49.826	0.317	0.056	47.588	1.711						0.017	0.009				0.003	0.004	0.005	0.226	0.023		0.203		99.988	50.162
Silica Fume 2	53.848	0.395	0.062	45.053	0.086																			99.444	45.596
Silica Fume 3	53.973	0.390	0.062	44.910	0.089				0.004			0.036						0.003	0.308	0.054	0.132	0.035		99.996	46.023
Average	52.549	0.367	0.060	45.850	0.629				0.004		0.017	0.023				0.003	0.004	0.004	0.267	0.039	0.132	0.119		99.809	47.260
Class F Fly Ash	49.813	10.744	6.394	23.150	4.939	0.421		0.016	0.174		0.004	0.010	0.008	0.009	0.074	0.016	0.120	0.481	1.747	0.067	0.006	1.009	0.776	99.978	50.165
Slag	41.055	29.207	5.259	16.069	0.350	0.047		0.017	0.027						0.262	0.004	0.016	0.244	0.343		0.103	1.879	5.110	99.992	58.937
Fine Aggregate 1	60.224	2.923	2.110	32.271	1.085	0.036		0.004	0.015						0.241	0.003	0.010	0.062	0.771		0.028	0.211		99.994	39.770
Fine Aggregate 2	59.079	3.893	2.515	33.319	0.435	0.036		0.003	0.035								0.009	0.033	0.532		0.016	0.092		99.997	40.918
Fine Aggregate 3	60.161	6.007	1.477	30.939	0.615	0.033		0.003	0.012						0.012		0.007	0.042	0.528		0.036	0.123		99.995	39.834
Average	59.821	4.274	2.034	32.176	0.712	0.035		0.003	0.021						0.127	0.003	0.009	0.046	0.610		0.027	0.142		99.995	40.174

Table A.2. Raw data - paste

Sample No	Composition	Balance (%)	Ca (%)	Al (%)	Si (%)	Fe (%)	Ba (%)	Zr (%)	Sr (%)	Pb (%)	Zn (%)	Cu (%)	Ni (%)	Mn (%)	Cr (%)	V (%)	Ti (%)	K (%)	P (%)	Cl (%)	S (%)	Mg (%)	Sum	Elements Detected
OPC 1	Plain Paste	51.605	34.687	1.168	6.635	1.461	0.024	0.007	0.018		0.008	0.008		0.231	0.005	0.007	0.075	0.328		0.027	2.921		99.215	47.610
OPC 2	Plain Paste	52.577	34.386	1.092	6.613	1.438	0.023	0.007	0.018		0.014	0.029		0.223	0.004	0.005	0.074	0.738		0.025	2.727		99.993	47.416
OPC 3	Plain Paste	50.304	35.101	1.415	7.152	1.476	0.023	0.007	0.019		0.008	0.007	0.003	0.237	0.007	0.008	0.074	0.876		0.020	2.915		99.652	49.348
OPC 4	Plain Paste	51.546	34.609	1.167	6.923	1.442	0.024	0.007	0.018		0.007	0.005	0.003	0.234	0.005	0.006	0.069	0.815		0.028	2.838		99.746	48.200
OPC 5	Plain Paste	51.570	34.378	1.298	6.998	1.455	0.022	0.007	0.018		0.011	0.013	0.003	0.231	0.005	0.006	0.072	1.085		0.019	2.539		99.730	48.160
Average		51.520	34.632	1.228	6.864	1.454	0.023	0.007	0.018		0.010	0.012	0.003	0.231	0.005	0.006	0.073	0.768		0.024	2.788		99.667	48.147
F Fly Ash 1	F ash 20%	53.736	28.993	2.154	9.486	1.876	0.080	0.008	0.039		0.008	0.009	0.003	0.197	0.006	0.024	0.135	0.842		0.019	2.377		99.992	46.256
F Fly Ash 2	F ash 20%	53.407	28.975	2.181	9.686	1.875	0.082	0.008	0.039		0.008	0.008	0.003	0.193	0.008	0.025	0.135	0.751		0.024	2.396		99.804	46.397
F Fly Ash 3	F ash 20%	54.179	28.980	2.106	9.164	1.840	0.078	0.008	0.038		0.010	0.013	0.003	0.191	0.005	0.023	0.124	1.139		0.016	2.046		99.963	45.784
F Fly Ash 4	F ash 20%	53.493	29.137	2.139	9.186	1.846	0.076	0.008	0.038		0.010	0.013	0.003	0.195	0.006	0.023	0.125	0.933		0.019	2.048		99.298	45.805
F Fly Ash 5	F ash 20%	53.894	28.435	2.118	9.224	1.813	0.081	0.008	0.039		0.009	0.012		0.187	0.006	0.022	0.123	1.919		0.006	1.882		99.778	45.884
Average		53.742	28.904	2.140	9.349	1.850	0.079	0.008	0.039		0.009	0.011	0.003	0.193	0.006	0.023	0.128	1.117		0.017	2.150		99.767	46.025
F Fly Ash 1	F ash 40%	55.545	25.527	2.443	10.549	2.292	0.139	0.009	0.061		0.013	0.021	0.003	0.159	0.009	0.038	0.176	0.694		0.029	2.066		99.773	44.228
F Fly Ash 2	F ash 40%	56.054	25.715	2.291	10.319	2.287	0.137	0.009	0.061		0.013	0.021	0.003	0.160	0.008	0.038	0.177	0.682		0.026	1.984		99.985	43.931
F Fly Ash 3	F ash 40%	54.961	24.674	2.745	11.570	2.335	0.138	0.009	0.060		0.011	0.018	0.003	0.163	0.008	0.041	0.190	0.720		0.027	2.317		99.990	45.029
F Fly Ash 4	F ash 40%	54.991	24.249	2.628	11.179	2.298	0.140	0.009	0.062		0.013	0.021	0.003	0.163	0.008	0.040	0.182	1.913			1.651		99.550	44.559
Average		55.388	25.041	2.527	10.904	2.303	0.139	0.009	0.061		0.013	0.020	0.003	0.161	0.008	0.039	0.181	1.002		0.027	2.005		99.825	44.437
F Fly Ash 1	100% Class F, paste	63.881	10.158	3.572	15.023	3.621	0.300	0.012	0.128	0.003	0.017	0.033	0.004	0.056	0.014	0.087	0.341	1.192	0.019	0.014	1.506		99.981	36.100
F Fly Ash 2	100% Class F, paste	60.772	9.835	4.247	17.180	3.744	0.304	0.012	0.131	0.003	0.012	0.020	0.005	0.053	0.012	0.092	0.356	1.287	0.050	0.008	1.291		99.414	38.642
F Fly Ash 3	100% Class F, paste	62.913	9.632	3.884	16.131	3.671	0.306	0.011	0.129	0.003	0.014	0.023	0.004	0.051	0.013	0.089	0.348	1.230	0.057	0.011	1.391		99.911	36.998
Average		62.522	9.875	3.901	16.111	3.679	0.303	0.012	0.129	0.003	0.014	0.025	0.004	0.053	0.013	0.089	0.348	1.236	0.042	0.011	1.396		99.769	37.247
C Fly Ash 1	C ash 20%	49.903	32.117	2.900	9.508	1.848	0.094	0.009	0.047	0.005	0.124	0.094	0.004	0.198	0.006	0.029	0.219	0.183	0.047	0.009	1.718		99.062	49.159
C Fly Ash 2	C ash 20%	52.848	30.990	2.298	8.067	1.782	0.093	0.010	0.047		0.023	0.027	0.004	0.195	0.007	0.028	0.202	0.723	0.060	0.020	2.295		99.719	46.871
C Fly Ash 3	C ash 20%	48.816	32.146	3.079	9.647	1.866	0.097	0.009	0.048	0.006	0.124	0.092	0.006	0.201	0.005	0.029	0.219	0.276	0.061	0.010	1.621	1.637	99.995	51.179
Average		50.522	31.751	2.759	9.074	1.832	0.095	0.009	0.047	0.006	0.090	0.071	0.005	0.198	0.006	0.029	0.213	0.394	0.056	0.013	1.878	1.637	99.592	49.070
C Fly Ash 1	C ash 40%	54.780	25.920	3.345	8.671	2.026	0.148	0.011	0.073		0.019	0.031	0.004	0.146	0.008	0.051	0.332	0.434	0.205	0.025	2.527	1.236	99.992	45.212
C Fly Ash 2	C ash 40%	55.732	26.179	3.115	8.778	1.991	0.151	0.011	0.072		0.012	0.020	0.005	0.147	0.006	0.047	0.317	0.521	0.168	0.020	2.304		99.596	43.864
C Fly Ash 3	C ash 40%	55.850	26.007	3.239	8.496	2.047	0.156	0.012	0.076		0.011	0.014	0.006	0.148	0.007	0.048	0.334	0.650	0.192	0.022	2.399		99.714	43.864
C Fly Ash 4	C ash 40%	55.943	26.007	3.163	8.527	2.038	0.155	0.012	0.076	0.002	0.011	0.015	0.004	0.144	0.008	0.049	0.329	0.500	0.183	0.022	2.388		99.576	43.633
C Fly Ash 5	C ash 40%	55.129	26.153	3.259	8.673	2.055	0.156	0.012	0.076		0.011	0.015	0.004	0.146	0.009	0.050	0.330	0.460	0.200	0.025	2.404	0.827	99.994	44.865
Average		55.487	26.053	3.224	8.629	2.031	0.153	0.012	0.075	0.002	0.013	0.019	0.005	0.146	0.008	0.049	0.328	0.513	0.190	0.023	2.404	1.032	99.774	44.288
C Fly Ash 1	100% Class C, paste	61.602	13.891	5.514	11.845	2.960	0.330	0.018	0.161	0.003	0.010	0.017	0.005	0.020	0.010	0.103	0.659	0.271	0.433	0.015	1.561		99.428	37.826
C Fly Ash 2	100% Class C, paste	58.884	14.424	6.034	12.578	2.897	0.331	0.019	0.162	0.003	0.013	0.026	0.006	0.019	0.009	0.103	0.657	0.274	0.442	0.011	2.489		99.381	40.497
C Fly Ash 3	100% Class C, paste	57.185	14.963	6.569	13.195	2.998	0.340	0.019	0.165	0.003	0.012	0.022	0.006	0.023	0.009	0.111	0.684	0.283	0.492	0.011	2.061	0.841	99.992	42.807
Average		59.224	14.426	6.039	12.539	2.952	0.334	0.019	0.163	0.003	0.012	0.022	0.006	0.021	0.009	0.106	0.667	0.276	0.456	0.012	2.037	0.841	99.600	40.377

Table A.3. Raw data – paste continued

Sample No	Composition	Balance (%)	Ca (%)	Al (%)	Si (%)	Fe (%)	Ba (%)	Zr (%)	Sr (%)	Pb (%)	Zn (%)	Cu (%)	Ni (%)	Mn (%)	Cr (%)	V (%)	Ti (%)	K (%)	P (%)	Cl (%)	S (%)	Mg (%)	Sum	Elements Detected
Slag 1	Slag 20%	50.123	32.608	2.094	8.948	1.237	0.027	0.008	0.018		0.061	0.078	0.002	0.226	0.004	0.008	0.099	0.491		0.033	2.412	1.515	99.992	49.869
Slag 2	Slag 20%	50.993	32.039	2.088	9.115	1.204	0.027	0.008	0.018	0.004	0.183	0.215	0.003	0.226	0.004	0.008	0.094	0.840		0.020	1.450	1.455	99.994	49.001
Slag 3	Slag 20%	52.988	31.270	1.696	8.473	1.182	0.026	0.008	0.018	0.002	0.094	0.118	0.003	0.218	0.004	0.007	0.092	1.233		0.026	1.917		99.375	46.387
Average		51.368	31.972	1.959	8.845	1.208	0.027	0.008	0.018	0.003	0.113	0.137	0.003	0.223	0.004	0.008	0.095	0.855		0.026	1.926	1.485	99.787	48.419
Slag 1	Slag 40%	53.472	29.192	2.100	9.745	0.954	0.030	0.009	0.018		0.026	0.027		0.215	0.004	0.008	0.113	0.906		0.027	1.791	1.358	99.995	46.523
Slag 2	Slag 40%	52.915	29.846	2.116	9.477	0.971	0.029	0.009	0.018		0.007	0.011		0.209	0.005	0.008	0.111	0.471		0.042	2.227	1.522	99.994	47.079
Slag 3	Slag 40%	53.398	29.339	2.067	9.879	0.953	0.028	0.009	0.018		0.006	0.006		0.211	0.005	0.008	0.114	0.855		0.037	1.947	1.115	99.995	46.597
Average		53.262	29.459	2.094	9.700	0.959	0.029	0.009	0.018		0.013	0.015		0.212	0.005	0.008	0.113	0.744		0.035	1.988	1.332	99.995	46.733
Slag 1	100% slag, paste	56.541	21.814	3.383	12.810	0.269	0.035	0.011	0.018		0.003	0.012		0.176	0.003	0.012	0.171	0.420		0.054	1.526	2.739	99.997	43.456
Slag 2	100% slag, paste	58.236	21.433	2.956	11.674	0.274	0.035	0.011	0.018		0.004	0.044		0.180	0.004	0.012	0.165	0.326		0.054	2.043	2.527	99.996	41.760
Slag 3	100% slag, paste	58.037	21.659	3.091	12.155	0.277	0.036	0.011	0.018		0.005	0.027		0.175	0.004	0.012	0.168	0.315		0.051	1.859	2.096	99.996	41.959
Average		57.605	21.635	3.143	12.213	0.273	0.035	0.011	0.018		0.004	0.028		0.177	0.004	0.012	0.168	0.354		0.053	1.809	2.454	99.996	42.392
Silica Fume 1	Silica fume 20%	53.877	29.818	1.281	10.384	1.413	0.020	0.006	0.014	0.005	0.155	0.212		0.196	0.003	0.006	0.062	0.205		0.013	1.653		99.323	45.446
Silica Fume 2	Silica fume 20%	52.707	30.353	1.418	11.274	1.439	0.020	0.006	0.015	0.005	0.153	0.166		0.197	0.007	0.006	0.061	0.181		0.012	1.410		99.430	46.723
Silica Fume 3	Silica fume 20%	53.760	29.896	1.300	10.452	1.407	0.020	0.006	0.014	0.005	0.152	0.221		0.195	0.003	0.006	0.061	0.194		0.013	1.611		99.316	45.556
Average		53.448	30.022	1.333	10.703	1.420	0.020	0.006	0.014	0.005	0.153	0.200		0.196	0.004	0.006	0.061	0.193		0.013	1.558		99.356	45.908
Silica Fume 1	Silica fume 40%	57.014	22.563	0.953	15.753	1.327	0.016	0.004	0.011	0.006	0.132	0.213		0.151	0.005	0.005	0.048	0.185		0.020	1.589		99.995	42.981
Silica Fume 2	Silica fume 40%	55.434	23.513	1.061	16.013	1.343	0.017	0.004	0.011	0.006	0.141	0.224		0.148	0.003	0.004	0.048	0.150		0.005	1.402		99.527	44.093
Silica Fume 3	Silica fume 40%	55.837	23.000	1.077	16.375	1.321	0.015	0.004	0.011	0.006	0.135	0.216		0.147	0.004	0.006	0.048	0.157		0.007	1.461		99.827	43.990
Average		56.095	23.025	1.030	16.047	1.330	0.016	0.004	0.011	0.006	0.136	0.218		0.149	0.004	0.005	0.048	0.164		0.011	1.484		99.783	43.688
Silica Fume 1	100% silica fume, paste	70.991	0.293	0.035	28.318	0.044			0.003		0.023						0.003	0.184	0.024	0.062	0.017		99.997	29.006
Silica Fume 2	100% silica fume, paste	68.980	0.301	0.034	30.249	0.071			0.003		0.025						0.003	0.206	0.031	0.065	0.028		99.996	31.016
Silica Fume 3	100% silica fume, paste	69.493	0.301	0.000	29.779	0.051			0.003		0.025						0.003	0.203	0.030	0.063	0.020		99.971	30.478
Average		69.821	0.298	0.023	29.449	0.055			0.003		0.024						0.003	0.198	0.028	0.063	0.022		99.988	30.167
Ternary 1 sample 1	20% F fly ash, 20% slag	53.658	27.274	2.475	10.680	1.675	0.085	0.009	0.039	0.003	0.088	0.112		0.187	0.006	0.025	0.151	0.463		0.034	2.045	0.982	99.991	46.333
Ternary 1 sample 2	20% F fly ash, 20% slag	54.170	27.188	2.252	10.243	1.615	0.084	0.009	0.039	0.003	0.127	0.160	0.003	0.193	0.006	0.023	0.145	1.025		0.026	1.727	0.955	99.993	45.823
Ternary 1 sample 3	20% F fly ash, 20% slag	52.977	26.671	2.648	11.086	1.604	0.083	0.009	0.039		0.027	0.031	0.003	0.192	0.005	0.024	0.155	1.294		0.021	1.816	1.309	99.994	47.017
Average		53.602	27.044	2.458	10.670	1.631	0.084	0.009	0.039	0.003	0.081	0.101	0.003	0.191	0.006	0.024	0.150	0.927		0.027	1.863	1.082	99.993	46.391
Ternary 2 sample 1	10% F fly ash, 20% slag	51.342	30.251	2.455	10.365	1.488	0.058	0.009	0.029	0.005	0.127	0.093	0.003	0.215	0.005	0.014	0.122	0.581		0.025	1.631	1.178	99.996	48.654
Ternary 2 sample 2	10% F fly ash, 20% slag	49.817	30.604	2.614	10.614	1.461	0.058	0.009	0.029	0.005	0.103	0.069	0.003	0.220	0.004	0.015	0.124	0.463		0.024	1.592	2.166	99.994	50.177
Ternary 2 sample 3	10% F fly ash, 20% slag	51.975	28.993	2.485	9.924	1.372	0.057	0.009	0.028		0.008	0.011	0.002	0.204	0.006	0.016	0.125	1.461		0.025	2.181	1.114	99.996	48.021
Average		51.045	29.949	2.518	10.301	1.440	0.058	0.009	0.029	0.005	0.079	0.058	0.003	0.213	0.005	0.015	0.124	0.835		0.025	1.801	1.486	99.995	48.951

Table A.4. Raw data – mortar

Sample No	Composition	Balance (%)	Ca (%)	Al (%)	Si (%)	Fe (%)	Ba (%)	Zr (%)	Sr (%)	Zn (%)	Cu (%)	Mn (%)	Cr (%)	V (%)	Ti (%)	K (%)	P (%)	Cl (%)	S (%)	Sum	Elements Detected
OPC 1	Plain Mortar	64.145	25.278	0.817	6.086	1.053	0.037	0.006	0.017	0.015	0.037	0.145	0.003	0.005	0.053	0.302		0.023	1.973	99.995	35.850
OPC 2	Plain Mortar	62.864	26.066	0.930	6.295	1.222	0.046	0.007	0.025	0.033	0.068	0.152	0.004	0.005	0.060	0.258		0.015	1.806	99.856	36.992
OPC 3	Plain Mortar	63.864	24.939	0.892	6.467	1.017	0.037	0.004	0.015	0.024	0.031	0.139	0.004	0.005	0.053	0.294		0.024	2.186	99.995	36.131
Average	Plain Mortar	63.624	25.428	0.880	6.283	1.097	0.040	0.006	0.019	0.024	0.045	0.145	0.004	0.005	0.055	0.285		0.021	1.988	99.949	36.324
F Fly Ash 1	F fly ash 20%	64.001	22.450	1.382	8.153	1.270	0.062	0.005	0.024	0.019	0.039	0.124	0.005	0.015	0.095	0.448		0.018	1.883	99.993	35.992
F Fly Ash 2	F fly ash 20%	64.324	22.160	1.405	8.091	1.345	0.058	0.004	0.022	0.023	0.046	0.131	0.004	0.016	0.094	0.410		0.013	1.643	99.789	35.465
F Fly Ash 3	F fly ash 20%	64.203	22.726	1.247	7.699	1.324	0.057	0.005	0.022	0.016	0.034	0.127	0.006	0.017	0.091	0.414		0.023	1.986	99.997	35.794
Average	F fly ash 20%	64.176	22.445	1.345	7.981	1.313	0.059	0.005	0.023	0.019	0.040	0.127	0.005	0.016	0.093	0.424		0.018	1.837	99.926	35.750
F Fly Ash 1	F fly ash 40%	62.892	19.508	2.173	11.258	1.679	0.088	0.006	0.032	0.039	0.064	0.120	0.005	0.028	0.141	0.535		0.013	1.365	99.946	37.054
F Fly Ash 2	F fly ash 40%	64.473	20.429	1.536	8.902	1.640	0.061	0.004	0.033	0.019	0.038	0.115	0.005	0.028	0.134	0.736		0.023	1.629	99.805	35.332
F Fly Ash 3	F fly ash 40%	66.007	19.565	1.457	8.677	1.524	0.070	0.005	0.033	0.011	0.019	0.108	0.005	0.025	0.122	0.760		0.023	1.574	99.985	33.978
Average	F fly ash 40%	64.457	19.834	1.722	9.612	1.614	0.073	0.005	0.033	0.023	0.040	0.114	0.005	0.027	0.132	0.677		0.020	1.523	99.912	35.455
F Fly Ash 1	100% Class F	64.356	8.288	3.797	17.730	2.508	0.118	0.005	0.060	0.007	0.009	0.038	0.009	0.071	0.282	1.123	0.082	0.012	1.245	99.740	35.384
F Fly Ash 2	100% Class F	67.555	7.904	3.309	15.315	2.646	0.123	0.006	0.059	0.007	0.010	0.040	0.009	0.078	0.308	1.150	0.068	0.017	1.384	99.988	32.433
F Fly Ash 3	100% Class F	63.891	7.441	3.644	20.209	2.189	0.116	0.005	0.056	0.004	0.003	0.031	0.007	0.057	0.235	1.127	0.073	0.008	0.691	99.787	35.896
Average	100% Class F	65.267	7.878	3.583	17.751	2.448	0.119	0.005	0.058	0.006	0.007	0.036	0.008	0.069	0.275	1.133	0.074	0.012	1.107	99.838	34.571
C Fly Ash 1	C fly ash 20%	62.327	23.284	1.841	7.651	1.253	0.058	0.005	0.030	0.039	0.073	0.128	0.004	0.020	0.148	0.731	0.055	0.015	1.658	99.320	36.993
C Fly Ash 2	C fly ash 20%	63.840	23.294	1.547	7.003	1.288	0.055	0.005	0.027	0.007	0.009	0.124	0.004	0.019	0.135	0.440	0.033	0.028	2.137	99.995	36.155
C Fly Ash 3	C fly ash 20%	62.457	24.060	1.660	7.491	1.310	0.062	0.005	0.025	0.027	0.046	0.129	0.004	0.020	0.146	0.310	0.047	0.027	1.914	99.740	37.283
Average	C fly ash 20%	62.875	23.546	1.683	7.382	1.284	0.058	0.005	0.027	0.024	0.043	0.127	0.004	0.020	0.143	0.494	0.045	0.023	1.903	99.685	36.810
C Fly Ash 1	C fly ash 40%	63.996	21.210	2.331	7.908	1.480	0.088	0.006	0.044	0.014	0.028	0.103	0.005	0.038	0.243	0.384	0.148	0.018	1.924	99.968	35.972
C Fly Ash 2	C fly ash 40%	63.708	20.887	2.418	8.286	1.510	0.073	0.006	0.037	0.024	0.049	0.106	0.005	0.035	0.242	0.240	0.153	0.020	1.907	99.706	35.998
C Fly Ash 3	C fly ash 40%	63.070	20.802	2.607	8.877	1.492	0.085	0.006	0.043	0.029	0.057	0.107	0.006	0.035	0.247	0.313	0.156	0.016	1.725	99.673	36.603
Average	C fly ash 40%	63.591	20.966	2.452	8.357	1.494	0.082	0.006	0.041	0.022	0.045	0.105	0.005	0.036	0.244	0.312	0.152	0.018	1.852	99.782	36.191
C Fly Ash 1	100% Class C	71.848	12.392	2.830	5.454	2.150	0.144	0.009	0.081	0.011	0.019	0.016	0.008	0.082	0.495	0.212	0.289	0.029	3.920	99.989	28.141
C Fly Ash 2	100% Class C	71.408	12.375	2.943	5.830	2.081	0.139	0.008	0.077	0.011	0.017	0.017	0.008	0.081	0.486	0.228	0.286	0.027	3.969	99.991	28.583
C Fly Ash 3	100% Class C	70.930	12.523	2.960	6.193	2.151	0.144	0.009	0.077	0.010	0.019	0.024	0.006	0.081	0.485	0.222	0.311	0.039	3.808	99.992	29.062
Average	100% Class C	71.395	12.430	2.911	5.826	2.127	0.142	0.009	0.078	0.011	0.018	0.019	0.007	0.081	0.489	0.221	0.295	0.032	3.899	99.991	28.595

Table A.5. Raw data – mortar continued

Sample No	Composition	Balance (%)	Ca (%)	Al (%)	Si (%)	Fe (%)	Ba (%)	Zr (%)	Sr (%)	Zn (%)	Cu (%)	Mn (%)	Cr (%)	V (%)	Ti (%)	K (%)	P (%)	Cl (%)	S (%)	Sum	Elements Detected
Slag 1	Slag 20%	62.244	23.425	1.405	8.034	0.926	0.037	0.005	0.018	0.049	0.058	0.146	0.003	0.006	0.068	1.750		0.010	1.319	99.503	37.259
Slag 2	Slag 20%	63.096	24.629	1.249	7.404	0.926	0.037	0.005	0.015	0.026	0.046	0.174	0.003	0.006	0.067	0.244		0.036	1.897	99.860	36.764
Slag 3	Slag 20%	63.823	24.175	1.216	7.235	0.843	0.035	0.004	0.015	0.023	0.039	0.141	0.003	0.005	0.068	0.478		0.039	1.855	99.997	36.174
Average	Slag 20%	63.054	24.076	1.290	7.558	0.898	0.036	0.005	0.016	0.033	0.048	0.154	0.003	0.006	0.068	0.824		0.028	1.690	99.787	36.732
Slag 1	Slag 40%	63.918	23.086	1.465	7.992	0.841	0.036	0.005	0.016	0.012	0.023	0.139	0.004	0.007	0.085	0.251		0.046	1.674	99.600	35.682
Slag 2	Slag 40%	63.087	23.209	1.619	8.519	0.837	0.028	0.005	0.017	0.016	0.028	0.137	0.004	0.008	0.090	0.404		0.038	1.609	99.655	36.568
Slag 3	Slag 40%	63.404	23.501	1.479	7.917	0.913	0.037	0.006	0.016	0.018	0.029	0.144	0.003	0.007	0.084	0.427		0.036	1.499	99.520	36.116
Average	Slag 40%	63.470	23.265	1.521	8.143	0.864	0.034	0.005	0.016	0.015	0.027	0.140	0.004	0.007	0.086	0.361		0.040	1.594	99.592	36.122
Silica Fume 1	Silica fume 20%	65.478	18.717	0.978	11.772	0.769	0.035	0.010	0.016	0.016	0.023	0.092		0.004	0.043	0.570		0.029	1.444	99.996	34.518
Silica Fume 2	Silica fume 20%	65.868	18.441	0.915	11.661	0.743	0.032	0.004	0.013	0.008	0.012	0.089		0.006	0.045	0.529		0.034	1.597	99.997	34.129
Silica Fume 3	Silica fume 20%	65.537	18.846	1.014	11.323	0.796	0.034	0.004	0.015	0.010	0.012	0.099	0.003	0.006	0.049	0.832		0.033	1.384	99.997	34.460
Average	Silica fume 20%	65.628	18.668	0.969	11.585	0.769	0.034	0.006	0.015	0.011	0.016	0.093	0.003	0.005	0.046	0.644		0.032	1.475	99.997	34.369
Silica Fume 1	Silica fume 40%	66.367	13.397	0.966	16.548	0.825	0.037	0.005	0.019	0.007	0.007	0.063		0.005	0.041	0.427		0.046	1.235	99.995	33.628
Silica Fume 2	Silica fume 40%	65.230	14.443	0.963	16.867	0.589	0.029	0.004	0.012	0.008	0.007	0.066	0.003	0.005	0.037	0.609		0.043	1.081	99.996	34.766
Silica Fume 3	Silica fume 40%	66.308	13.229	0.945	17.008	0.603	0.030	0.003	0.015	0.006	0.005	0.056		0.005	0.036	0.485		0.043	1.222	99.999	33.691
Average	Silica fume 40%	65.968	13.690	0.958	16.808	0.672	0.032	0.004	0.015	0.007	0.006	0.062	0.003	0.005	0.038	0.507		0.044	1.179	99.997	34.028
Silica Fume 1	100% silica fume	60.437	3.458	0.600	34.484	0.358	0.022		0.010	0.015	0.004	0.005		0.007	0.025	0.466	0.028	0.030	0.049	99.998	39.561
Silica Fume 2	100% silica fume	60.850	1.510	0.708	35.848	0.499	0.019	0.002	0.013	0.015	0.002	0.013		0.007	0.052	0.423		0.023		99.984	39.134
Silica Fume 3	100% silica fume	60.755	2.233	0.637	34.464	0.277	0.016		0.011	0.015	0.002			0.005	0.020	0.604	0.034	0.105	0.817	99.995	39.240
Average	100% silica fume	60.681	2.400	0.648	34.932	0.378	0.019	0.002	0.011	0.015	0.003	0.009		0.006	0.032	0.498	0.031	0.053	0.433	99.992	39.312
Ternary 1 sample 1	20% F fly ash, 20% slag	63.651	21.538	1.723	9.007	1.131	0.060	0.005	0.023	0.031	0.056	0.131	0.004	0.017	0.109	0.537		0.028	1.429	99.480	35.829
Ternary 1 sample 2	20% F fly ash, 20% slag	62.987	21.969	1.697	9.021	1.163	0.062	0.005	0.024	0.029	0.053	0.130	0.005	0.016	0.109	0.949		0.017	1.281	99.517	36.530
Ternary 1 sample 3	20% F fly ash, 20% slag	63.992	21.065	1.692	9.230	1.171	0.064	0.005	0.023	0.028	0.048	0.128	0.004	0.016	0.114	0.481		0.030	1.526	99.617	35.625
Ternary 1 sample 4	20% F fly ash, 20% slag	63.731	21.686	1.662	8.486	1.143	0.060	0.006	0.025	0.025	0.045	0.132	0.004	0.016	0.110	1.258		0.017	1.264	99.670	35.939
Ternary 1 sample 5	20% F fly ash, 20% slag	61.843	19.649	2.060	12.705	1.167	0.048	0.007	0.021	0.028	0.024	0.114	0.004	0.016	0.100	0.568		0.018	1.090	99.462	37.619
Ternary 1 sample 6	20% F fly ash, 20% slag	66.040	21.594	1.226	7.171	1.162	0.055	0.006	0.022	0.028	0.046	0.126	0.004	0.015	0.104	0.781		0.028	1.284	99.692	33.652
Ternary 1 sample 7	20% F fly ash, 20% slag	63.560	21.227	1.708	8.839	1.307	0.053	0.006	0.026	0.029	0.051	0.133	0.005	0.016	0.110	1.129		0.012	1.168	99.379	35.819
Average	20% F fly ash, 20% slag	63.686	21.247	1.681	9.208	1.178	0.057	0.006	0.023	0.028	0.046	0.128	0.004	0.016	0.108	0.815		0.021	1.292	99.545	35.859
Ternary 2 sample 1	10% F fly ash, 20% slag	62.485	22.970	1.697	8.684	1.070	0.054	0.007	0.020	0.019	0.037	0.135	0.004	0.011	0.090	0.358		0.036	1.729	99.406	36.921
Ternary 2 sample 2	10% F fly ash, 20% slag	62.666	23.282	1.629	8.536	1.008	0.042	0.005	0.018	0.030	0.052	0.142	0.003	0.011	0.087	0.454		0.028	1.444	99.437	36.771
Ternary 2 sample 3	10% F fly ash, 20% slag	62.907	22.706	1.610	8.705	1.024	0.049	0.005	0.025	0.031	0.057	0.133	0.005	0.012	0.091	0.473		0.028	1.573	99.434	36.527
Ternary 2 sample 4	10% F fly ash, 20% slag	64.659	23.254	1.202	7.486	1.067	0.041	0.005	0.021	0.025	0.049	0.144	0.004	0.011	0.089	0.422		0.030	1.485	99.994	35.335
Average	10% F fly ash, 20% slag	63.179	23.053	1.535	8.353	1.042	0.047	0.006	0.021	0.026	0.049	0.139	0.004	0.011	0.089	0.427		0.031	1.558	99.568	36.389