Chemometrics and Intelligent Laboratory Systems 95 (2009) 64–73

Contents lists available at ScienceDirect

Chemometrics and Intelligent Laboratory Systems

journal homepage: www.elsevier.com/locate/chemolab

Monitoring fresh concrete by ultrasonic transmission measurements: Exploratory multi-way analysis of the spectral information

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ARTICLE INFO

Article history:
Received 15 May 2008
Received in revised form 4 July 2008
Accepted 19 August 2008
Available online 27 August 2008

Keywords:
PARAFAC
PARAFAC2
Ultrasonic measurements
Fresh Concrete
Frequency spectrum

ABSTRACT

The setting of concrete can be monitored by measuring the characteristics of ultrasonic waves sent through a fresh sample at regular intervals. So far, the development of this ultrasonic method has mainly focussed on the wave velocity for technical reasons. However, the frequency spectrum might contain even more information since it takes the entire received signal into account. Therefore, the spectra measured on 34 concrete compositions during the first 48 h after mixing were collected in a three-way array (sample × frequency × concrete age) and analysed with multi-way techniques (PARAFAC and PARAFAC2) to quantify their mutual differences.

PARAFAC2 was able to model the data better than PARAFAC and distinguish between the different concrete mixtures. Moreover, the samples could be ordered by the model in agreement with the expected setting behaviour of the mixture. This exploratory data analysis proves the utility of the frequency spectra to monitor the setting of fresh concrete.

1. Introduction

The setting of concrete is an important phenomenon in the determination of form removal times and is currently described by the penetration resistance test on the mortar fraction. However, during the last decades, the ultrasonic wave transmission technique has proven its suitability to monitor the setting, offering the advantage of continuous measurement on both mortar and concrete. During these measurements, ultrasonic waves are sent through a fresh sample at regular intervals. When the cement paste starts to set, the sand and gravel grains are bound together creating a more rigid and solid material through which the ultrasonic waves can propagate more easily. In the development of this ultrasonic method, the wave velocity has been the most studied parameter [1–3], while little research has been done on the use of the complete signal spectrum. Since current measurement systems enable the use of real broadband frequency pulses and receivers, the study of the frequency spectrum becomes more interesting. Therefore, an extensive experimental program was set up to apply the ultrasonic wave transmission technique on different concrete mixtures. The received frequency spectra were collected in a database and analysed with multi-way analysis to assess their mutual differences and classify them.

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doi:10.1016/j.chemolab.2008.08.005

2. Materials and methods

2.1. Concrete mixtures

The ultrasonic measurements were performed on three series of concrete mixtures. Besides ordinary Portland cement (OPC), these mixtures also contained cement replacing additives such as blast-furnace slag (BFS) and fly ash (FA) which are by-products of the iron manufacture and coal-fired power plants respectively [4]. The first concrete compositions were made with OPC and different types of blast-furnace cements, in which BFS is interground with OPC during the production process. According to EN 197-1, CEM III/A contains 36–65% BFS by mass, CEM III/B 66–80% and CEM III/C 81–95%. In the second and third series of concrete mixtures, respectively BFS and FA were added as a separate component to partially replace the cement. In the second series 0, 15, 30, 50, 70 and 85% of the OPC was replaced by BFS and in the third series 0, 35, 50 and 67% was replaced by FA. Table 1 summarizes the specifications of the three series of concrete compositions, while the chemical composition and the specific surface area of the different cement types and of the additives BFS and FA are given in Table 2.

Table 1

Specifications of the studied concrete mixtures: cement type (EN 197-1), water-to-binder ratio (w/b), composition (kg/m^3) and admixtures (ml/100 kg cement)

Mixture	Cement type	w/b	Composition						Admixtures	
			Cement	BFS	FA	Sand 0/4	Gravel 2/8	Gravel 8/16	Superplasticiser[a]	Air entrainer
1, 2, 3	CEM I 42.5	0.5	350	–	–	791	425	618	–	–
4, 5	CEM III/A 42.5	0.5	350	–	–	791	425	618	–	–
6, 7, 8	CEM III/B 42.5	0.5	350	–	–	791	425	618	–	–
9, 10	CEM III/A 32.5	0.5	350	–	–	791	425	618	–	–
11, 12	CEM III/C 32.5	0.5	350	–	–	791	425	618	–	–
13	CEM III/A 52.5	0.5	350	–	–	791	425	618	–	–
14, 15, 16	CEM I 52.5	0.5	350	–	–	791	425	618	–	–
17	CEM I 52.5	0.5	297	52	–	790	425	617	–	–
18	CEM I 52.5	0.5	245	105	–	789	424	617	–	–
19	CEM I 52.5	0.5	174	174	–	788	423	616	–	–
20, 21, 22	CEM I 52.5	0.5	104	244	–	787	423	615	–	–
23	CEM I 52.5	0.5	52	295	–	785	422	614	–	–
24	CEM I 52.5	0.4	400	–	–	686	451	694	65	–
25	CEM I 52.5	0.4	400	–	–	686	451	694	270	68
26, 27	CEM I 52.5	0.4	260	–	140	668	437	678	100	–
28	CEM I 52.5	0.4	260	–	140	668	437	678	187	135
29, 30	CEM I 52.5	0.4	200	–	200	660	432	668	100	–
31	CEM I 52.5	0.4	200	–	200	660	432	668	237	200
32, 33	CEM I 52.5	0.4	132	–	268	652	427	660	110	–
34	CEM I 52.5	0.4	132	–	268	652	427	660	328	303

[a] Carboxylic ether polymer with long side chains (con. 35%).

2.2. Ultrasonic wave transmission measurements

The ultrasonic p-wave transmission measurements on the hardening concrete samples were performed with the FreshCon system developed at the University of Stuttgart. Details about this system are described in previous publications [1,5]. During the setting process, the sample container was sealed with plastic film to limit the shrinkage of the concrete resulting in decoupling of the sample and the container walls. All the tests were conducted in a climate chamber at 20 °C and 60% relative humidity.

Every 5 min a pulse signal with a width of 5 µs was transmitted through the fresh concrete sample with the aid of a piezoelectric broadband transmitter. After traveling through the hardening sample, the ultrasonic wave was detected by the ultrasonic receiver. The sample rate of the received signal amounted to 10 MHz. To eliminate the DC component and low- and high-frequency noise from this signal, a band-pass filter (100 Hz–1 MHz) was applied. The fast Fourier transform (FFT) of each received signal was then calculated with a spectral resolution of 610 Hz. These spectra were smoothed using a 3-point moving average algorithm and the logarithm was taken to be considerate of both large and small spectral changes. An example of the change of the measured frequency spectrum in time and of a raw spectrum measured at 24 h is shown in Fig. 1.

Table 2

Chemical composition (%), mineralogical composition according to the Bogue calculation (%) and Blaine specific surface area (m^2/kg) of the cement and the additives

Cement type	CEM I 52.5	BFS	FA[a]	CEM III/A 52.5	CEM I 42.5	CEM III/A 42.5	CEM III/B 42.5	CEM III/A 32.5	CEM III/C 32.5
CaO	62.21	40.38	3.21	48.77	63.13	51.88	45.17	49.85	43.66
SiO_2	18.84	34.35	53.58	27.58	21.22	25.15	28.78	26.88	31.55
Al_2O_3	5.39	11.36	26.49	6.58	3.90	7.39	8.89	8.30	9.42
Fe_2O_3	3.79	0.48	7.01	1.88	5.05	2.32	1.55	2.01	0.83
MgO	0.86	7.57	2.08	6.73	0.89	4	5.80	4.22	4.22
SO_3	3.06	1.65	–	2.76	1.70	3.29	3.33	2.97	2.07
CO_2	0.72	0.25	–	0.95	0.39	1.17	1.83	1.16	0.97
Cl^-	0.04	0.013	–	–	0.01	0.04	0.04	0.04	0.22
C_3S	59.6	–	–	–	57.4	–	–	–	–
C_2S	9.1	–	–	–	17.6	–	–	–	–
C_3A	7.9	–	–	–	1.8	–	–	–	–
C_4AF	11.5	–	–	–	15.4	–	–	–	–
Blaine SSA	370	400	275	515	315	485	450	345	317

[a] Mean chemical composition of 2 batches.

2.3. Exploratory multi-way data analysis

2.3.1. Three-way component models

The change of the frequency spectrum in time for the different concrete compositions was investigated by multi-way analysis. The dataset consists indeed of a 3-way array: the frequency content was measured in function of concrete sample (first mode), frequency (second mode) and concrete age (third mode). Two multi-way models were tried out. The most simple and restricted one is PARAFAC (parallel factor analysis) which decomposes a three-dimensional array $\boldsymbol{X}$ ($I \times J \times K$) into a summation of R trilinear components (Fig. 2a). Each component is a triple product of vectors, called score vector (first mode) and loadings (second and third mode) [6]. A slab $\mathbf{X}_k$ ($I \times J$) of $\boldsymbol{X}$ can be described by Eq. (1).

$$\mathbf{X}_k = \mathbf{B} \cdot \mathbf{D} \cdot \mathbf{A}^T + \mathbf{E}_k \tag{1}$$

where $\mathbf{B}$ is the $I \times R$ matrix of loadings, $\mathbf{A}$ the $J \times R$ matrix of loadings, $\mathbf{D}_k$ the $R \times R$ diagonal matrix containing the scores for slab $\mathbf{X}_k$ and $\mathbf{E}_k$ the $I \times J$ matrix of residuals [7]. The main advantage of PARAFAC is the uniqueness of the solution: if the data is indeed trilinear and the correct number of components is selected, the true underlying spectra will be found in the frequency mode [8]. On the other hand, if the trilinearity condition is not fulfilled, degenerate solutions with unstable and unreliable parameters can be encountered. In the case of ultrasonic measurements on concrete, the trilinearity can be destroyed if the spectral peaks shift from sample to sample. A modified version of PARAFAC known as PARAFAC2 can model data with such shifts in one mode [9]. Unlike PARAFAC, the latter model does not assume parallel