J Radioanal Nucl Chem (2015) 305:355–360
DOI 10.1007/s10967-015-4043-3

Improved elemental measurement accuracy by thermal neutron flux computed with their characteristic gamma-rays

Dao-wen Cheng · Li Xin · Lan Min

Received: 19 August 2014 / Published online: 17 March 2015

Abstract Neutron induced prompt gamma-ray analysis can analyze one sample of cement raw material in a few minutes. In order to improve the measurement accuracies of silicon, aluminum, iron and calcium, 50 samples were designed based on the data obtained from cement plants and simulated by MCNP. The relationship between the thermal neutron flux and elemental characteristic gamma-rays counts was found by linear regression analysis. When the counts and the flux calculated by the relationship are used to compute the element contents, all the accuracies can meet the demand of cement plants.

Keywords Measurement accuracy · Cement raw material · Thermal neutron flux · Characteristic gamma-rays

Introduction

An accurate, real time method of determining the element contents of the cement raw material (CRM) is important for cement plants to control cement quality. Although chemical method is the most commonly used in cement plants, it will take more than 1 hour to measure one sample. Therefore it cannot direct the production of cement on time. Neutron induced prompt gamma-ray analysis (NIPGA) is a fast analysis technique, which can analyze one multicomponent sample in a few minutes [1–4]. As a result, it is widely used to analyze the element contents of CRM [5].

In NIPGA, the prompt characteristic gamma-rays induced by thermal neutron capture reactions are used to compute the contents of silicon, aluminum, iron and calcium. Compared with the reactor neutron source, radioisotope neutron source and other accelerator neutron sources, D–D neutron generator is an optimal neutron source for this technique because of the advantages of low cost and no radioactivity after being turned off [6]. Therefore, D–D neutron generator is often used in NIPGA and the 2.5 MeV neutron flux can be regarded as a constant value, and the thermal neutron flux is relevant to the component of CRM. But in some papers, the thermal neutron flux is still treated as a constant value [7, 8]. It will increase the measurement error and make the measurement accuracy cannot meet the requirement of cement plants, which makes NIPGA unpromising in measuring the contents of silicon, aluminum, iron and calcium in CRM. In this paper, 50 samples of CRM were designed based on the data obtained from cement plants and simulated by MCNP. The relationship between the thermal neutron flux and element characteristic gamma-rays counts, such as silicon, aluminum, iron and calcium, was obtained by linear regression. Then, the empirical formulas of computing the contents of silicon, aluminum, iron and calcium were also found by linear regression.

Principle

In NIPGA, the energy of the characteristic gamma-ray induced by thermal neutron capture reaction can be used to identify the element type, such as silicon, aluminum, iron and calcium, and the characteristic gamma-ray count can

D. Cheng (✉) · L. Xin · L. Min (✉)
School of Basic Sciences, Changchun University of Technology, Changchun 130012, People's Republic of China
e-mail: chengdaowen@yahoo.com

L. Min
e-mail: lanmin@mail.ccut.edu.cn

be used to compute the element content. The basic formula is as follows [9]:

$$w = k(N/\varphi) + b \quad (1)$$

Take silicon for example, w is the mass content of silicon in the sample of CRM, N is the characteristic gamma-ray count of silicon, φ is the thermal neutron flux in the sample, k and b are empirical constants determined by the experimental device.

Once the D–D neutron generator has be selected, the 2.5 MeV neutron flux can be regarded as a constant value. In the sample of CRM, 2.5 MeV neutrons will be moderated by the nuclei such as silicon, aluminum, iron, calcium, oxygen and so on. If they become thermal neutrons, the nuclei of silicon, aluminum, iron and calcium may capture them and emit prompt gamma-rays. Because the abilities to moderate neutrons are different, the thermal neutron flux is relevant to the contents of all elements in the sample. In CRM, oxygen is almost in the form of SiO_2, Al_2O_3, Fe_2O_3 and CaO, accordingly the content of oxygen can be looked as the function of the contents of silicon, aluminum, iron, calcium. Furthermore, the sum content of silicon, aluminum, iron, calcium and oxygen is more than 93 %. As a result, the thermal neutron flux can be approximately looked as the function of the contents of silicon, aluminum, iron and calcium:

$$\varphi = f_{1(P_{\text{Si}})} + f_{2(P_{\text{Al}})} + f_{3(P_{\text{Fe}})} + f_{4(P_{\text{Ca}})} \quad (2)$$

where φ is the thermal neutron flux in the sample. P_{Si}, P_{Al}, P_{Fe}, P_{Ca} is the mass content of silicon, aluminum, iron and calcium respectively. Equation (2) can only calculate the thermal neutron flux in the sample whose element contents are known, but it cannot be used to compute the element contents in CRM. In order to compute the element contents in CRM, the characteristic gamma-rays are used to take the place of the element contents and the formula can be expanded by Maclaurin series as [10–12]:

$$\varphi_n = \sum_{j=1}^{n} a_j N_{\text{Si}}^j + \sum_{j=1}^{n} b_j N_{\text{Al}}^j + \sum_{j=1}^{n} c_j N_{\text{Fe}}^j + \sum_{j=1}^{n} d_j N_{\text{Ca}}^j + R_{n(N_{\text{Si}},N_{\text{Al}},N_{\text{Fe}},N_{\text{Ca}})} \quad (3)$$

where φ_n is the calculated value of the thermal neutron flux when the maximum value of j is n. N_{Si}, N_{Al}, N_{Fe}, N_{Ca} is the characteristic gamma-ray count of silicon, aluminum, iron and calcium respectively, j is the exponent, a_j, b_j, c_j, d_j, is the coefficient of N_{Si}^j, N_{Al}^j, N_{Fe}^j and N_{Ca}^j, $R_{n(N_{\text{Si}},N_{\text{Al}},N_{\text{Fe}},N_{\text{Ca}})}$ is the Lagrange remainder. In order to find the coefficients and Lagrange remainder, 50 samples of CRM were designed based on the data obtained from cement plants and simulated by MCNP. The scheme of the simulation system is shown in Fig. 1.

In Fig. 1, the cylinder whose radius is R and axis is y-axis is the neutron shield. It is filled by polyethylene except the space occupied by the D–D neutron generator, the BGO detector and the sample of CRM. In order to increase the accuracy, the centers of the sample, the BGO detector and the target of the D–D neutron generator are all located on the y-axis.

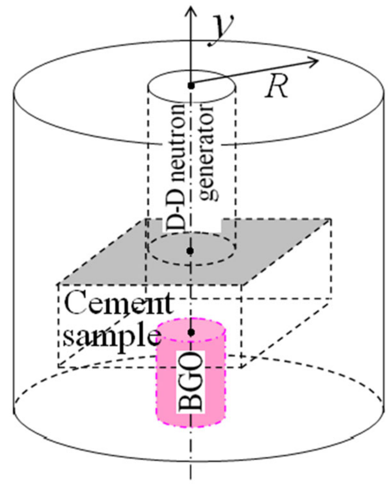

Fig. 1 Scheme of simulation system

Computing the thermal neutron flux

In this paper, 30 samples (from No. 1 to 30) of CRM were firstly simulated by MCNP. The characteristic gamma-ray energies of silicon, aluminum, iron, calcium are 4.934, 3.466, 7.631 and 6.420 MeV, respectively. The contents of silicon, aluminum, iron, calcium in each sample are given in Table 1. The characteristic gamma-rays counts and the thermal neutron flux calculated by F4 tally are also shown in Table 1.

In Table 1, P_{Si}, P_{Al}, P_{Fe} and P_{Ca} is the mass content of silicon, aluminum, iron and calcium. Because the values in MCNP code must be constants, P_{Si}, P_{Al}, P_{Fe} and P_{Ca} have no uncertainties. φ is the thermal neutron flux in the sample simulated by MCNP. N_{Si}, N_{Al}, N_{Fe}, N_{Ca} is the characteristic gamma-ray count of silicon, aluminum, iron and calcium respectively when the yield of D–D neutron generator is 10^6 n/s and the measure time is 5 min.

In this paper, the relationship between the thermal neutron flux and the characteristic gamma-rays counts of silicon, aluminum, iron and calcium was found by linear regression analysis.

When $n = 1$ in Eq. (3), the relationship is as follow:

$$\varphi_1 = 7.608 \times 10^{-3} N_{\text{Si}} + 4.248 \times 10^{-2} N_{\text{Al}} + 9.447 \times 10^{-4} N_{\text{Fe}} + 4.382 \times 10^{-3} N_{\text{Ca}} - 1.896 \times 10^{-3} \quad (4)$$

where φ_1 is the calculated value of the thermal neutron flux when $n = 1$. When $n = 2$ in Eq. (3), the relationship is as follow:

Table 1 Data of the samples

No.	P_{Si} (%)	P_{Al} (%)	P_{Fe} (%)	P_{Ca} (%)	N_{Si}	N_{Al}	N_{Fe}	N_{Ca}	φ/ (s^{-1} cm^{-2})	D_1 (%)	D_2 (%)	D_3 (%)
1	10.05	2.76	3.31	35.88	120,301 ± 261	5441 ± 55	261,274 ± 3393	694,357 ± 2079	2537 ± 20	0.10 ± 0.66	0.15 ± 0.64	0.22 ± 0.64
2	10.08	2.77	2.21	35.41	128,693 ± 302	6123 ± 61	185,773 ± 2465	727,273 ± 2144	2701 ± 18	0.16 ± 0.61	0.09 ± 0.62	0.07 ± 0.61
3	10.93	2.79	3.48	34.85	129,880 ± 356	5709 ± 113	270,107 ± 3429	661,320 ± 1971	2495 ± 15	0.30 ± 0.78	0.13 ± 0.75	0.16 ± 0.75
4	11.10	2.81	2.35	35.00	135,405 ± 294	5981 ± 119	188,844 ± 2500	683,019 ± 2079	2560 ± 18	0.02 ± 0.73	0.12 ± 0.71	0.09 ± 0.72
5	8.86	2.83	2.10	36.84	113,088 ± 337	5943 ± 60	175,952 ± 2232	749,549 ± 2212	2673 ± 21	0.21 ± 0.63	0.02 ± 0.62	0.11 ± 0.61
6	9.55	2.84	3.72	35.45	117,724 ± 429	5911 ± 66	300,622 ± 3808	698,614 ± 2106	2600 ± 15	0.16 ± 0.73	0.16 ± 0.71	0.16 ± 0.70
7	10.67	2.90	1.98	35.72	131,290 ± 369	5942 ± 103	160,677 ± 2047	702,936 ± 2099	2584 ± 18	0.12 ± 0.71	0.12 ± 0.69	0.13 ± 0.69
8	10.98	2.98	2.51	35.25	131,504 ± 285	6112 ± 69	196,647 ± 2495	676,749 ± 2060	2515 ± 16	0.01 ± 0.65	0.02 ± 0.64	0.04 ± 0.65
9	9.53	3.03	3.11	37.00	111,700 ± 242	5998 ± 96	237,630 ± 3010	687,860 ± 2072	2445 ± 18	0.08 ± 0.73	0.14 ± 0.70	0.18 ± 0.70
10	10.81	3.09	2.20	36.28	126,580 ± 412	6010 ± 59	166,848 ± 2165	678,224 ± 1994	2454 ± 19	0.09 ± 0.67	0.19 ± 0.65	0.22 ± 0.66
11	9.42	3.10	1.73	36.50	120,098 ± 274	6628 ± 66	144,160 ± 1826	737,569 ± 2157	2659 ± 23	0.31 ± 0.60	0.22 ± 0.61	0.21 ± 0.60
12	9.03	3.14	2.22	37.09	110,322 ± 239	6510 ± 72	178,270 ± 2267	724,096 ± 2152	2555 ± 15	0.24 ± 0.64	0.30 ± 0.63	0.28 ± 0.63
13	9.28	3.16	2.24	37.07	111,856 ± 255	6244 ± 66	177,445 ± 2267	714,212 ± 2134	2524 ± 20	0.26 ± 0.64	0.26 ± 0.63	0.27 ± 0.62
14	9.83	3.22	2.30	36.26	120,861 ± 447	6552 ± 66	186,212 ± 2359	708,298 ± 2106	2573 ± 23	0.32 ± 0.69	0.07 ± 0.68	0.08 ± 0.68
15	8.97	3.28	3.14	35.39	113,739 ± 247	7031 ± 95	261,497 ± 3485	721,076 ± 2103	2682 ± 18	0.28 ± 0.69	0.34 ± 0.70	0.28 ± 0.69
16	10.00	3.31	1.68	36.36	122,948 ± 352	6690 ± 78	136,627 ± 1735	714,588 ± 2081	2588 ± 15	0.16 ± 0.65	0.34 ± 0.65	0.29 ± 0.64
17	10.18	3.35	3.09	34.53	127,113 ± 275	6879 ± 88	252,988 ± 3236	690,572 ± 2087	2625 ± 22	0.12 ± 0.69	0.09 ± 0.70	0.03 ± 0.70
18	11.01	3.37	1.63	36.09	130,248 ± 282	6496 ± 66	124,146 ± 1573	678,800 ± 2017	2463 ± 14	0.02 ± 0.62	0.04 ± 0.61	0.02 ± 0.61
19	10.11	3.40	3.37	35.76	118,927 ± 295	6503 ± 107	258,684 ± 3277	669,418 ± 1958	2464 ± 17	0.06 ± 0.75	0.21 ± 0.73	0.18 ± 0.74
20	10.26	3.43	3.90	34.88	121,207 ± 361	6946 ± 248	301,520 ± 3836	657,728 ± 2006	2480 ± 17	0.32 ± 1.04	0.31 ± 1.05	0.20 ± 1.04
21	9.06	3.44	3.24	35.29	114,258 ± 248	7276 ± 101	267,982 ± 3402	710,435 ± 2160	2648 ± 18	0.02 ± 0.71	0.05 ± 0.73	0.01 ± 0.72
22	10.71	3.47	1.64	34.49	137,017 ± 379	7336 ± 119	138,196 ± 1784	704,606 ± 2112	2682 ± 20	0.23 ± 0.70	0.01 ± 0.74	0.00 ± 0.73
23	9.57	3.52	3.75	35.55	113,425 ± 256	7157 ± 87	292,161 ± 3895	676,384 ± 2005	2503 ± 22	0.31 ± 0.72	0.34 ± 0.73	0.31 ± 0.72
24	10.72	3.55	1.96	34.69	133,760 ± 297	7494 ± 79	160,754 ± 2037	689,767 ± 2026	2616 ± 23	0.07 ± 0.63	0.01 ± 0.65	0.04 ± 0.65
25	9.20	3.59	2.07	36.82	111,395 ± 247	7129 ± 153	164,698 ± 2105	716,390 ± 2122	2546 ± 19	0.11 ± 0.77	0.13 ± 0.78	0.11 ± 0.78
26	8.95	3.69	2.60	36.80	107,043 ± 295	7382 ± 209	203,921 ± 2588	701,440 ± 2044	2506 ± 16	0.32 ± 0.90	0.10 ± 0.93	0.12 ± 0.93
27	9.61	3.72	2.96	36.07	114,575 ± 264	7303 ± 94	231,816 ± 2938	685,011 ± 2073	2500 ± 18	0.26 ± 0.71	0.15 ± 0.72	0.18 ± 0.73
28	9.37	3.74	2.02	36.43	114,675 ± 248	7534 ± 227	163,238 ± 2077	711,007 ± 2086	2568 ± 19	0.07 ± 0.88	0.12 ± 0.93	0.13 ± 0.93
29	9.38	3.77	1.71	35.89	119,334 ± 259	7820 ± 77	142,507 ± 1822	726,818 ± 2158	2661 ± 20	0.09 ± 0.62	0.11 ± 0.64	0.11 ± 0.63
30	9.31	3.84	3.71	35.01	112,699 ± 247	7642 ± 188	294,950 ± 3800	680,288 ± 2029	2553 ± 14	0.29 ± 0.88	0.16 ± 0.92	0.19 ± 0.91
31	10.51	3.89	2.44	35.83	123,048 ± 327	7518 ± 155	184,915 ± 2353	661,670 ± 2018	2438 ± 20	0.19 ± 0.83	0.27 ± 0.85	0.36 ± 0.86
32	10.91	3.91	1.82	35.53	128,986 ± 295	7754 ± 137	138,344 ± 1764	667,779 ± 1987	2464 ± 13	0.30 ± 0.75	0.40 ± 0.79	0.36 ± 0.78
33	10.66	3.99	2.86	34.55	125,557 ± 291	8192 ± 103	222,500 ± 2892	656,810 ± 1921	2494 ± 22	0.05 ± 0.71	0.23 ± 0.75	0.15 ± 0.76
34	9.91	4.00	1.74	35.48	122,941 ± 306	8422 ± 105	142,262 ± 1889	704,261 ± 2135	2613 ± 21	0.17 ± 0.69	0.35 ± 0.74	0.36 ± 0.73
35	9.33	4.03	2.31	36.58	110,222 ± 411	8073 ± 184	179,652 ± 2418	694,654 ± 2038	2492 ± 16	0.28 ± 0.89	0.55 ± 0.94	0.51 ± 0.95

Table 1 continued

No.	P_{Si} (%)	P_{Al} (%)	P_{Fe} (%)	P_{Ca} (%)	N_{Si}	N_{Al}	N_{Fe}	N_{Ca}	φ/ (s^{-1} cm^{-2})	D_1 (%)	D_2 (%)	D_3 (%)
36	10.33	4.09	2.55	34.50	126,879 ± 275	8209 ± 86	204,975 ± 2605	674,769 ± 2041	2574 ± 17	0.22 ± 0.67	0.12 ± 0.70	0.16 ± 0.71
37	10.31	4.10	3.35	34.84	120,727 ± 262	7933 ± 89	256,188 ± 3255	649,641 ± 1924	2452 ± 15	0.16 ± 0.70	0.01 ± 0.73	0.09 ± 0.73
38	9.60	4.11	1.90	36.94	112,094 ± 263	7953 ± 97	142,563 ± 1835	684,438 ± 1993	2436 ± 13	0.32 ± 0.68	0.10 ± 0.70	0.11 ± 0.70
39	9.70	4.12	2.81	34.87	119,276 ± 314	8422 ± 86	226,426 ± 2952	684,367 ± 2047	2581 ± 16	0.03 ± 0.69	0.19 ± 0.73	0.20 ± 0.73
40	9.11	4.14	2.97	34.80	115,003 ± 250	8729 ± 106	245,594 ± 3111	698,858 ± 2115	2641 ± 19	0.11 ± 0.70	0.50 ± 0.76	0.54 ± 0.76
41	9.05	4.28	2.25	36.24	109,409 ± 237	8499 ± 87	177,953 ± 2254	700,540 ± 2052	2541 ± 17	0.23 ± 0.65	0.26 ± 0.69	0.21 ± 0.69
42	9.40	4.30	2.15	35.26	117,116 ± 255	8983 ± 105	176,324 ± 2237	702,129 ± 2095	2617 ± 16	0.10 ± 0.68	0.61 ± 0.74	0.58 ± 0.74
43	9.22	4.31	2.03	35.12	118,124 ± 400	8863 ± 196	169,819 ± 2152	713,961 ± 2072	2669 ± 23	0.04 ± 0.84	0.38 ± 0.96	0.36 ± 0.96
44	8.91	4.37	1.65	36.17	110,286 ± 247	9281 ± 104	134,722 ± 1720	717,824 ± 2149	2611 ± 15	0.04 ± 0.66	0.98 ± 0.73	0.97 ± 0.73
45	9.41	4.40	2.92	35.15	113,072 ± 245	8677 ± 85	230,603 ± 3011	680,785 ± 2065	2536 ± 13	0.09 ± 0.69	0.36 ± 0.72	0.35 ± 0.73
46	9.88	4.52	1.66	35.38	120,448 ± 264	9270 ± 95	133,806 ± 1695	691,224 ± 2045	2560 ± 16	0.36 ± 0.65	1.11 ± 0.71	1.13 ± 0.71
47	9.08	4.53	1.78	36.30	110,108 ± 290	9005 ± 156	141,717 ± 1796	705,502 ± 2069	2543 ± 23	0.25 ± 0.77	1.07 ± 0.87	1.06 ± 0.86
48	9.48	4.61	2.37	35.10	115,424 ± 273	9395 ± 96	189,568 ± 2404	684,974 ± 2001	2556 ± 18	0.22 ± 0.67	1.08 ± 0.74	1.03 ± 0.74
49	9.23	4.69	1.87	36.40	109,423 ± 237	9351 ± 163	144,490 ± 1915	688,184 ± 2036	2480 ± 22	0.23 ± 0.78	1.36 ± 0.90	1.32 ± 0.90
50	10.60	4.73	2.13	34.52	126,173 ± 284	9208 ± 110	164,077 ± 2238	654,325 ± 1909	2483 ± 19	0.24 ± 0.70	0.61 ± 0.77	0.46 ± 0.77

$$\begin{aligned}\varphi_2 = & -3.965\times10^{-3}N_{Si} - 1.041\times10^{-2}N_{Al} \\ & + 7.780\times10^{-4}N_{Fe} + 1.532\times10^{-3}N_{Ca} \\ & + 4.721\times10^{-8}N_{Si}^2 + 3.892\times10^{-6}N_{Al}^2 \\ & + 3.947\times10^{-10}N_{Fe}^2 + 2.036\times10^{-9}N_{Ca}^2 + 0\end{aligned} \quad (5)$$

where φ_2 is the calculated value of the thermal neutron flux when $n = 2$. When $n = 3$ in Eq. (3), the relationship is as follow:

$$\begin{aligned}\varphi_3 = & 0\times N_{Si} + 0\times N_{Al} + 0\times N_{Fe} + 0\times N_{Ca} \\ & + 1.898\times10^{-8}N_{Si}^2 + 2.509\times10^{-6}N_{Al}^2 \\ & + 4.174\times10^{-9}N_{Fe}^2 + 5.445\times10^{-9}N_{Ca}^2 \\ & + 6.530\times10^{-14}N_{Si}^3 + 5.836\times10^{-11}N_{Al}^3 \\ & - 5.881\times10^{-15}N_{Fe}^3 - 2.195\times10^{-15}N_{Ca}^3 + 0\end{aligned} \quad (6)$$

where φ_3 is the calculated value of the thermal neutron flux when $n = 3$.

In Table 1,

$$D_i = \frac{|\varphi - \varphi_i|}{\varphi_i}\times 100 \quad (7)$$

In order to select a more accurate relationship, Eqs. (4), (5) and (6) were used to calculate the thermal neutron flux in the samples from No. 31 to 50. The results are also shown in Table 1. From Table 1 six average values can be computed: $A_{D1} = (\sum_{i=1}^{30} D_{1i})/30 = 0.17$, $A_{D2} = (\sum_{i=1}^{30} D_{2i})/30 = 0.15$, $A_{D3} = (\sum_{i=1}^{30} D_{3i})/30 = 0.15$, $A'_{D1} = (\sum_{i=31}^{50} D_{1i})/20 = 0.18$, $A'_{D2} = (\sum_{i=31}^{50} D_{2i})/20 = 0.53$ and $A'_{D3} = (\sum_{i=31}^{50} D_{3i})/20 = 0.51$.

From Eqs. (4), (5) and (6) and the six average values, we can find that Eq. (4) has greater physical significance and higher accuracy.

Improving the element measurement accuracy

In practical application, it is difficult to measure the thermal neutron flux with high-precision, so φ_1 has to be used in Eq. (1). The equations for calculating the element contents were found by linear regression analysis with the data from No. 1 to No. 50 in Table 1:

$$w_{Si} = 0.2079\ N_{Si}/\varphi_1 + 0.0943 \quad (8)$$

$$w_{Al} = 1.3253\ N_{Al}/\varphi_1 - 0.1771 \quad (9)$$

$$w_{Fe} = 0.0323\ N_{Fe}/\varphi_1 - 0.0222 \quad (10)$$

$$w_{Ca} = 0.1278\ N_{Ca}/\varphi_1 + 0.9840 \quad (11)$$

where w_{Si}, w_{Al}, w_{Fe}, w_{Ca} are mass contents (computed by their characteristic gamma-ray counts and the thermal neutron flux) of silicon, aluminum, iron and calcium in the sample, N_{Si}, N_{Al}, N_{Fe}, N_{Ca} are their characteristic gamma-

Table 2 Deviations between element contents and their calculated values

No.	Δw_{Si} (%)	Δw_{Al} (%)	Δw_{Fe} (%)	Δw_{Ca} (%)	$\Delta w_{Si}'$ (%)	$\Delta w_{A\ l}'$ (%)	$\Delta w_{Fe}'$ (%)	$\Delta w_{Ca}'$ (%)
1	0.11 ± 0.09	0.10 ± 0.05	0.01 ± 0.07	0.04 ± 0.10	0.20 ± 0.02	0.08 ± 0.03	0.02 ± 0.04	0.14 ± 0.03
2	0.10 ± 0.08	0.05 ± 0.05	0.01 ± 0.04	0.07 ± 0.10	0.42 ± 0.02	0.24 ± 0.03	0.11 ± 0.03	0.88 ± 0.04
3	0.02 ± 0.12	0.07 ± 0.08	0.00 ± 0.07	0.11 ± 0.10	0.34 ± 0.03	0.02 ± 0.05	0.07 ± 0.04	0.34 ± 0.03
4	0.01 ± 0.11	0.11 ± 0.09	0.01 ± 0.05	0.08 ± 0.10	0.09 ± 0.02	0.13 ± 0.06	0.01 ± 0.03	0.55 ± 0.03
5	0.05 ± 0.08	0.05 ± 0.05	0.01 ± 0.04	0.05 ± 0.11	0.44 ± 0.03	0.09 ± 0.03	0.09 ± 0.03	0.18 ± 0.04
6	0.03 ± 0.10	0.00 ± 0.06	0.00 ± 0.08	0.08 ± 0.10	0.10 ± 0.03	0.06 ± 0.03	0.08 ± 0.05	0.36 ± 0.04
7	0.02 ± 0.11	0.03 ± 0.07	0.00 ± 0.04	0.02 ± 0.10	0.03 ± 0.03	0.02 ± 0.05	0.01 ± 0.03	0.16 ± 0.04
8	0.01 ± 0.10	0.06 ± 0.06	0.01 ± 0.05	0.12 ± 0.10	0.27 ± 0.02	0.02 ± 0.03	0.05 ± 0.03	0.19 ± 0.03
9	0.06 ± 0.09	0.04 ± 0.08	0.00 ± 0.06	0.10 ± 0.11	0.34 ± 0.02	0.09 ± 0.05	0.12 ± 0.04	1.37 ± 0.03
10	0.02 ± 0.11	0.02 ± 0.05	0.02 ± 0.04	0.05 ± 0.10	0.47 ± 0.03	0.14 ± 0.03	0.13 ± 0.03	0.81 ± 0.03
11	0.04 ± 0.08	0.02 ± 0.05	0.01 ± 0.03	0.18 ± 0.10	0.42 ± 0.02	0.15 ± 0.03	0.05 ± 0.02	0.04 ± 0.04
12	0.02 ± 0.08	0.05 ± 0.06	0.01 ± 0.04	0.02 ± 0.11	0.05 ± 0.02	0.05 ± 0.03	0.00 ± 0.03	0.85 ± 0.04
13	0.05 ± 0.08	0.05 ± 0.06	0.01 ± 0.04	0.17 ± 0.11	0.08 ± 0.02	0.10 ± 0.03	0.03 ± 0.03	1.00 ± 0.04
14	0.00 ± 0.10	0.03 ± 0.06	0.01 ± 0.05	0.21 ± 0.10	0.07 ± 0.03	0.01 ± 0.03	0.02 ± 0.03	0.29 ± 0.04
15	0.03 ± 0.08	0.03 ± 0.07	0.00 ± 0.06	0.04 ± 0.10	0.38 ± 0.02	0.16 ± 0.05	0.16 ± 0.05	0.80 ± 0.04
16	0.01 ± 0.09	0.06 ± 0.06	0.01 ± 0.03	0.03 ± 0.10	0.06 ± 0.03	0.03 ± 0.04	0.00 ± 0.02	0.28 ± 0.03
17	0.03 ± 0.09	0.06 ± 0.07	0.00 ± 0.06	0.03 ± 0.10	0.20 ± 0.02	0.02 ± 0.04	0.10 ± 0.04	1.15 ± 0.03
18	0.08 ± 0.09	0.05 ± 0.06	0.02 ± 0.03	0.12 ± 0.10	0.39 ± 0.02	0.18 ± 0.03	0.11 ± 0.02	0.61 ± 0.03
19	0.03 ± 0.10	0.08 ± 0.08	0.00 ± 0.07	0.04 ± 0.10	0.36 ± 0.02	0.21 ± 0.05	0.11 ± 0.04	0.44 ± 0.03
20	0.04 ± 0.14	0.09 ± 0.17	0.01 ± 0.09	0.12 ± 0.10	0.34 ± 0.03	0.03 ± 0.12	0.09 ± 0.05	0.25 ± 0.03
21	0.00 ± 0.08	0.02 ± 0.08	0.01 ± 0.07	0.03 ± 0.10	0.33 ± 0.02	0.12 ± 0.05	0.14 ± 0.04	0.72 ± 0.04
22	0.03 ± 0.11	0.01 ± 0.09	0.01 ± 0.03	0.14 ± 0.10	0.43 ± 0.03	0.12 ± 0.06	0.06 ± 0.02	1.42 ± 0.04
23	0.08 ± 0.09	0.08 ± 0.07	0.01 ± 0.08	0.14 ± 0.10	0.25 ± 0.02	0.02 ± 0.04	0.06 ± 0.05	0.11 ± 0.03
24	0.01 ± 0.09	0.07 ± 0.06	0.00 ± 0.04	0.01 ± 0.10	0.17 ± 0.02	0.12 ± 0.04	0.03 ± 0.03	0.97 ± 0.03
25	0.02 ± 0.09	0.06 ± 0.11	0.01 ± 0.04	0.08 ± 0.11	0.03 ± 0.02	0.10 ± 0.07	0.03 ± 0.03	0.71 ± 0.04
26	0.05 ± 0.11	0.05 ± 0.15	0.01 ± 0.06	0.06 ± 0.10	0.12 ± 0.02	0.08 ± 0.10	0.05 ± 0.03	0.94 ± 0.03
27	0.01 ± 0.09	0.04 ± 0.08	0.01 ± 0.06	0.16 ± 0.11	0.20 ± 0.02	0.15 ± 0.05	0.05 ± 0.04	0.49 ± 0.03
28	0.02 ± 0.10	0.03 ± 0.15	0.01 ± 0.04	0.04 ± 0.10	0.05 ± 0.02	0.05 ± 0.11	0.00 ± 0.03	0.41 ± 0.03
29	0.03 ± 0.08	0.06 ± 0.06	0.00 ± 0.03	0.04 ± 0.10	0.40 ± 0.02	0.05 ± 0.04	0.05 ± 0.02	0.39 ± 0.04
30	0.01 ± 0.10	0.04 ± 0.13	0.01 ± 0.08	0.12 ± 0.10	0.04 ± 0.02	0.10 ± 0.09	0.02 ± 0.05	0.49 ± 0.03
31	0.10 ± 0.12	0.03 ± 0.12	0.01 ± 0.05	0.10 ± 0.11	0.45 ± 0.03	0.21 ± 0.07	0.13 ± 0.03	0.64 ± 0.03
32	0.04 ± 0.11	0.07 ± 0.11	0.03 ± 0.04	0.02 ± 0.10	0.39 ± 0.02	0.12 ± 0.07	0.12 ± 0.02	0.24 ± 0.03
33	0.10 ± 0.10	0.18 ± 0.09	0.00 ± 0.06	0.07 ± 0.10	0.40 ± 0.02	0.01 ± 0.05	0.07 ± 0.04	0.56 ± 0.03
34	0.05 ± 0.09	0.09 ± 0.08	0.01 ± 0.04	0.11 ± 0.10	0.15 ± 0.02	0.11 ± 0.05	0.01 ± 0.02	0.43 ± 0.04
35	0.07 ± 0.12	0.07 ± 0.14	0.01 ± 0.05	0.08 ± 0.10	0.25 ± 0.03	0.08 ± 0.09	0.07 ± 0.03	0.84 ± 0.03
36	0.04 ± 0.09	0.03 ± 0.07	0.01 ± 0.05	0.06 ± 0.10	0.03 ± 0.02	0.08 ± 0.04	0.01 ± 0.03	0.91 ± 0.03
37	0.04 ± 0.10	0.02 ± 0.08	0.01 ± 0.07	0.05 ± 0.10	0.43 ± 0.02	0.22 ± 0.04	0.12 ± 0.04	0.15 ± 0.03
38	0.09 ± 0.09	0.05 ± 0.08	0.03 ± 0.04	0.06 ± 0.10	0.38 ± 0.02	0.22 ± 0.05	0.14 ± 0.02	1.37 ± 0.03
39	0.00 ± 0.09	0.03 ± 0.07	0.00 ± 0.06	0.01 ± 0.10	0.07 ± 0.02	0.01 ± 0.04	0.03 ± 0.04	0.70 ± 0.03
40	0.03 ± 0.08	0.06 ± 0.08	0.01 ± 0.06	0.04 ± 0.10	0.33 ± 0.02	0.12 ± 0.05	0.12 ± 0.04	1.01 ± 0.04
41	0.02 ± 0.08	0.01 ± 0.07	0.00 ± 0.04	0.06 ± 0.10	0.04 ± 0.02	0.13 ± 0.04	0.03 ± 0.03	0.40 ± 0.03
42	0.01 ± 0.08	0.07 ± 0.08	0.00 ± 0.04	0.03 ± 0.10	0.21 ± 0.02	0.08 ± 0.05	0.04 ± 0.03	0.61 ± 0.04
43	0.08 ± 0.11	0.08 ± 0.14	0.00 ± 0.04	0.06 ± 0.10	0.46 ± 0.03	0.02 ± 0.09	0.08 ± 0.03	0.95 ± 0.03
44	0.03 ± 0.08	0.17 ± 0.08	0.00 ± 0.03	0.04 ± 0.11	0.17 ± 0.02	0.16 ± 0.05	0.01 ± 0.02	0.04 ± 0.04
45	0.04 ± 0.08	0.04 ± 0.08	0.00 ± 0.06	0.17 ± 0.10	0.11 ± 0.02	0.16 ± 0.04	0.02 ± 0.04	0.36 ± 0.03
46	0.04 ± 0.08	0.08 ± 0.08	0.00 ± 0.03	0.02 ± 0.10	0.02 ± 0.02	0.00 ± 0.05	0.02 ± 0.02	0.31 ± 0.03
47	0.01 ± 0.09	0.03 ± 0.12	0.01 ± 0.04	0.05 ± 0.10	0.01 ± 0.02	0.13 ± 0.08	0.03 ± 0.02	0.37 ± 0.03

Table 2 continued

No.	Δw_{Si} (%)	Δw_{Al} (%)	Δw_{Fe} (%)	Δw_{Ca} (%)	$\Delta w_{Si}'$ (%)	$\Delta w_{A\ l}'$ (%)	$\Delta w_{Fe}'$ (%)	$\Delta w_{Ca}'$ (%)
48	0.02 ± 0.09	0.07 ± 0.08	0.00 ± 0.05	0.05 ± 0.10	0.00 ± 0.02	0.03 ± 0.05	0.00 ± 0.03	0.48 ± 0.03
49	0.02 ± 0.09	0.12 ± 0.13	0.01 ± 0.04	0.04 ± 0.10	0.22 ± 0.02	0.13 ± 0.08	0.09 ± 0.02	0.76 ± 0.03
50	0.08 ± 0.10	0.02 ± 0.09	0.01 ± 0.04	0.22 ± 0.10	0.30 ± 0.02	0.24 ± 0.05	0.09 ± 0.03	0.55 ± 0.03

ray counts, and φ_1 is the calculated value of the thermal neutron flux in the corresponding sample computed by the Eq. (4). The deviations between element contents and their calculated values (w_{Si}, w_{Al}, w_{Fe}, w_{Ca}) are shown in Table 2.

In some papers, the thermal neutron flux is regarded as a constant value. In order to compare the elemental measurement accuracies, the element contents are also computed when the thermal neutron flux is regarded as a constant value. The deviations between element contents and their calculated values (w_{Si}', w_{Al}', w_{Fe}', w_{Ca}') are also shown in Table 2.

In Table 2, $\Delta w_{Si} = |w_{Si} - P_{Si}|$, $\Delta w_{Al} = |w_{Al} - P_{Al}|$, $\Delta w_{Fe} = |w_{Fe} - P_{Fe}|$, $\Delta w_{Ca} = |w_{Ca} - P_{Ca}|$, $\Delta w_{Si}' = |w_{Si}' - P_{Si}|$, $\Delta w_{Al}' = |w_{Al}' - P_{Al}|$, $\Delta w_{Fe}' = |w_{Fe}' - P_{Fe}|$ and $\Delta w_{Ca}' = |w_{Ca}' - P_{Ca}|$.

In GB/T 176-2008 (Method for Chemical Analysis of Cement), the absolute value of deviations of silicon, aluminum, iron and calcium are 0.20, 0.30, 0.20 and 0.40 %, respectively. From Table 2 we can find: the deviations in columns 2–5, determined by the present method, are all lower than the requirements of GB/T 176-2008; however, many ones in columns 6–9, determined by assuming constant flux, do not meet the requirement.

Results and discussion

In NIPGA, because the thermal neutron flux in the sample, which should be used to compute the element contents, cannot be determined accurately or computed from the known conditions, the measurement accuracy is very low. In this paper, the thermal neutron flux has been computed by the characteristic gamma-ray counts which are simulated by MCNP and the element contents have been calculated with high-precision by the flux and the characteristic gamma-ray counts. But until now, the errors of the experimental data (N_{Si}, N_{Al}, N_{Fe} and N_{Ca}) determined by our equipment are too big to find the relationship between the thermal neutron flux and the elemental characteristic gamma-rays counts. Now we are improving the equipment to increase measurement accuracy of N_{Si}, N_{Al}, N_{Fe}, N_{Ca} and φ.

Acknowledgments We thank Li Xiang-long for his help in sample preparation and operation and maintenance of the elemental analyzer. We also thank Ding Jian-sheng for his help in writing the acquisition for the analyzer. The help of other colleagues with the chemical analysis is appreciated. Research supported by National Natural Science Foundation of China (11305019 and 11205069).

References

1. Salagean MN, Pantelica AI, Georgescu II, Muntean MI (1999) Czech J Phys 49:355
2. Lim CS (2004) J Radioanal Nucl Chem 262:525
3. Lim CS, Sowerby BD (2005) J Radioanal Nucl Chem 264:15
4. El-Taher A, Anwar M, Abdelhalim K (2014) J Radioanal Nucl Chem 299:1949
5. Oliveira C, Salgado J, Carvalho FG (1997) J Radioanal Nucl Chem 216:191
6. Cheng DW, Lu JB, Yang D, Wang HD, Ma KY (2012) J Radioanal Nucl Chem 292:1085
7. Jia FuQ, Gu DS, Cheng DW, Liu LM, Zhu QB, Wang JS (2010) Nucl Sci Tech 21:63
8. Wang HD, Lu JB, Lu YP, Yang D, Ma KY, Yang K, Liu YM, Cheng DW (2012) Sci China 55:2062
9. Liu YR, Lu YX, Xie YL, Wang YH, Tan J, Meng BN (1991) J Radioanal Nucl Chem 151:83
10. Hajra JP (1991) Metall Trans B 22:583
11. Lim TC (2004) J Math Chem 36:147
12. Alexandre A, Alberto S (2006) Set Valued Anal 14:381