Recycled household ceramic waste in eco-efficient cement: A case study

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17.1 Introduction

The current world cement production amounts near 3 billion tons/per year. Portland cement demand decreases in industrial nations and increases dramatically in developing countries. Global demand will have increased by almost 200% by 2050 from 2010 levels. The total cement output in China was about 2.48 billion tons in 2014, and this trend will continue. It is known (Ding et al., 2010) that around 1 ton of carbon dioxide is emitted for each ton of cement production (Fig. 17.1A). It is very serious for climate change caused by CO_2 emissions worldwide. Consequently, it is important to take effective measures to reduce the carbon dioxide pollution caused by the cement industry.

Meanwhile, China is the world's leading manufacturer of ceramics; as a result, more than 100 million tons of ceramic wastes are produced each year. The ceramic waste is a serious problem, as there is between 10% and 20% waste from the processing procedures. Only in Guangdong province near Hong Kong, the ceramic waste and waste sludge are about 10 million tons each year. The disposal of this waste not only occupies large areas of land but can also severely pollute the environment (Fig. 17.1B and C). Hence, the correct treatment of ceramic waste is necessary to preserve the environmental degradation. The reuse of such waste can not only protect the environment but also offers a great advantage in partial replacement of cement in concrete for example.

There have been several previous studies that have investigated the use of powdered igneous, metamorphic rocks or zeolites as pozzolanic materials (Ding et al., 2010; Kitsopoulos and Dunham, 1996; Pedersen, 2004; Mertens et al., 2009) and the use of ceramic waste as aggregate in concrete (De Brito et al., 2004; Silvestre et al., 2013). The replacement of Portland cement by powered igneous increased the compressive strength (Kitsopoulos and Dunham, 1996). The surface area only influences the short-term reactivity, and the long-term reactivity is mainly related to the Si/Al ratio of the zeolites (Mertens et al., 2009). The investigation on the ceramic roof tile wastes and clay bricks (CB) as pozzolanic admixture has also been conducted, and the calcined clay wastes from Britain, Denmark, Lithuania, and Poland are suitable for partial replacement of cement without a detrimental effect on the strength (Lavat et al., 2009;

Fig. 17.1 Pollution of the cement industry and ceramic waste on the environment: (A) cement industry in China; (B) household ceramic waste; and (C) clay bricks waste.

Wild et al., 1997). Matias G. reviewed the significant research related to heat-treated clays and ceramics (roof tiles, bricks, and pottery) incorporated in old mortars (Matias et al., 2014a, b).

The objectives of the research about ceramic waste include a number of issues such as the microstructure, chemical and physical behavior, mechanical properties and manufacturing, the durability and fire resistance, and the freeze-thaw property and cracking resistance. However, it is not intended in this study to present a complete knowledge of every aspect of the ceramic waste. Here, we focus only on the investigation of the ceramic waste from South China. The household ceramic (HC) is a large part of all the ceramic production types and the exports of HC accounted for about 65% of total ceramic output. It means that the ceramic products go to abroad and the pollution remains in the home country. But, the study on reusing of the recycled HC and CB waste was still very limited, and no literature regarding the pozzolanic activity of HC waste materials was found. The aim of this study is to evaluate the possibility of partial substitution of Portland cement with HC and CB waste powder to produce environmental-friendly cement or concrete.

In order to analyze the possible reuse of crushed ceramic waste powder as a cementitious material for replacing of Portland cement, the pozzolanic reactivity of the HC waste powder and CB waste powder have been investigated in this work. The comparison of the crystallinity degree between the CB waste and HC waste has been carried out. In addition, mortars containing fly ash (FA) as the referenced pozzolanic material were also studied to compare the properties of pastes that contain HC or CB powder.

The powdered HC, CB waste, and FA (as the referenced pozzolanic material) were used to replace cement in the ratio of 5%, l5%, and 25%. The chemical composition, the flowability, and crystal structures, especially the pozzolanic activity of the HC and CB waste powder are investigated. The evaluation of the pozzolanic activity using Frattini and strength activity index (SAI) testing method is meaningful for the possible replacement of cement. It is desirable that HC and CB wastes could be used in partial substitution of Portland cement both by their beneficial effect on the properties of cement as well as by the economic and ecologic advantage, and the market for the new pozzolanic material may be enormous: as mentioned, more than 2 billion tons of cement is produced annually in China, so 5% replacement of cement would require some 10 million tons of pozzolanic materials and reduce the similar amount of CO_2 emission.

17.2   Experiment

17.2.1   Testing materials

The HC waste and CB waste were obtained from Province Kuangdong in South China. The maximum heating temperature for household/tableware ceramics ranged between 1100°C and 1300°C. The maximum heating temperature for CB was at least 950°C and ranged between 950°C and 1100°C. The time period at maximum temperature was unavailable by the ceramic companies. In summer, the exterior weather condition in the province is very humid and sultry. The relative humidity ranged between 80% and 95%. The FA was used as referenced pozzolanic material. The mix design is listed in Table 17.1. The Portland Cement (PO) CEM I 42.5 with a specific surface area of 330 m^2/kg, FA with the specific surface area of 516 m^2/kg, the HC waste powder with a specific surface area of 530 m^2/kg and CB waste powder with a specific surface area of 690 m^2/kg were used, respectively (see Table 17.2). The ceramic wastes replace 5%, 15%, and 25% of cement. The sand used conformed to ISO 679: 2009 (ISO 679, 2009). The control sample of 100% Cem-I (PO) without waste addition was also used for comparison of SAI values. The water/binder ratio was 0.5. The specific surface area of CB powder is higher than that of HC powder. The study of Mertens G. et al. showed that the external surface area only influences the short-term reactivity, whereas the cation content has an effect on both the long- and short-term reactivity (Mertens et al., 2009).

17.2.2   Grain size analysis

Ceramic wastes were ground by a ball mill for 24 h. Based on ISO 13320-2009, the equipment GSL-101B for Laser Granulometry for Particle Size Analysis (with Measuring range between 0.15 and 400 µm) has been used. The ethanol was applied as a wetting agent for the wet dispersion of particles. The particle size distribution of cement, FA, HC, and CB waste powder is illustrated in Fig. 17.2.

Table 17.1   Mix-design of mortars.

	Cement (g)	HC/CB/FA (g)	Water (g)	ISO sand (g)	W/B
PO (CEM-I)	450	0	225	1350	0.5
HC5/CB5/FA5	427.5	22.5	225	1350	0.5
HC15/CB15/FA15	382.5	67.5	225	1350	0.5
HC25/CB25/FA25	337.5	112.5	225	1350	0.5

Table 17.2   Comparison of the specific surface area.

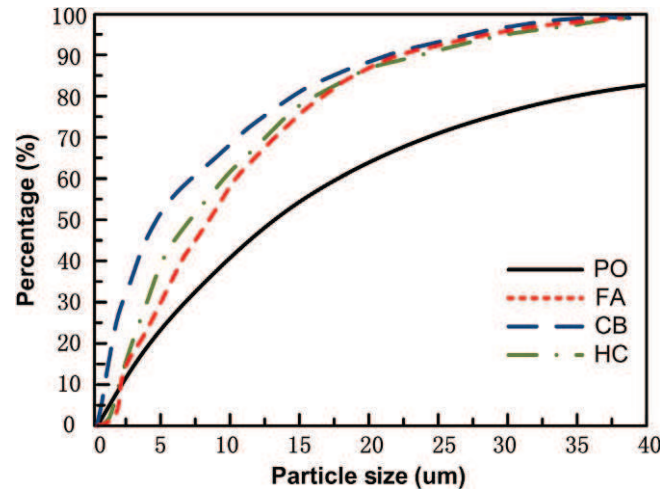|	CEM	FA	HC	CB
Specific surface area (m^2/kg)	330	516	530	690

Fig. 17.2 Particle size distribution of different powders.

From Fig. 17.2, it can be seen that for any particular size the percentage of ceramic waste powder (HC and CB) and FA was greater than that of cement. The most part (almost 100%) of the ceramic waste powder and FA was smaller than 40 μm. The FA, HC, and CB powders were ground to very fine grain size: 90% of powders were under 25 μm and 30% powders were under 5 μm. The particle size distribution may show a clear influence on the total specific pore volume of the cement or concrete matrix. The finer the powders particle size results in the denser paste and the smaller pore volume in the matrix.

17.2.3 Chemical analysis

The alkali environment of mortar or concrete matrix is an important factor for durability. The aim of the present investigation is to use the recycled ceramic waste powder as a part of the mortar or concrete. Hence, the matrix should have a similar alkali ambient to normal cement. The lower boundary of pH value of ceramic waste powder was limited, in order to avoid the reduction of the general alkali value of the concrete matrix. The evaluation of the pH-value of cement, ceramic waste powder, and FA solution was carried out (see Table 17.3). It can be seen that pH-values of HC and CB waste powder are higher than 9, and HC powder could be more suitable for use in cement or concrete matrix than that of CB powder.

The equipment XRF-1800 (X-ray fluorescence with a scanning speed of 20°/min) for analysis of the chemical compositions has been used. The chemical compositions

Table 17.3 pH-values of different materials.

	PO	CB	HC	FA
pH	12.46	9.24	10.41	11.94

Table 17.4 Comparison of the chemical composition of PO (cement), FA, and ceramic waste powder.

	PO	CB	HC	FA
SiO_2	28.43	60.6	71.03	49.1
Al_2O_3	6.95	20.35	18.22	26.2
Fe_2O_3	2.44	11.01	2.59	10.0
K_2O	1.06	4.77	4.66	1.58
TiO_2	0.36	1.37		1.88
MgO	4.3	1.02	0.33	1.23
Na_2O	0.16	0.25	1.03	0.641
CaO	52.21	0.17	0.57	8.52
MnO	0.08		0.13	
PbO			0.58	
ZrO_2	0.065		0.28	0.1
ZnO	0.043		0.2	0.036
CdO			0.18	
Rb_2O			0.11	
SO_3	3.89			0.533

of CEM, FA, HC and CB powder were analyzed and the results are presented in Table 17.4. The main chemical components of ceramic waste powder are similar to those of FA and consist mainly of SiO_2 and Al_2O_3. Combined with Fig. 17.3, it can be seen that SiO_2 of HC shows a low degree of crystallinity, it is similar to that of FA. SiO_2 with a low degree of crystallinity may be expected to contribute to the pozzolanic activity of ceramic waste powder. If the content of K_2O is high, the cement will set rapidly and the water requirement may increase. At the same time, K_2O in the cement may generate potassium gypsum ($K_2SO_3CaSO_4 2H_2O$) and reduce the strength. The higher the alkali increase, the lower the compressive strength of cement pastes (Smaoui et al., 2005; Selman and Ali, 2012).

17.2.4 Workability of different mixtures

Based on China National Guideline GB/T 2419-2005 (Test method for fluidity of cement morta) (GB/T 2419-2005, 2005), the experiment for fresh mortar has been carried out. Table 17.5 illustrates the flowability of mortars with different ratios of ceramic waste powder and FA substitutions. It can be seen that the ceramic waste powder does not exert negative influence on the workability of the mortar if the substitution ratio is lower than 25%.

17.2.5 XRD analysis

The equipment XRD-6000 (X-ray diffraction with scan range between 5° and 80°) for analysis of the crystal structures and amorphous behavior of the materials has been used. The XRD testing of cement, FA, HC, and CB waste powder is carried out. The crystallinity of the materials is a structural factor and plays an important role in the
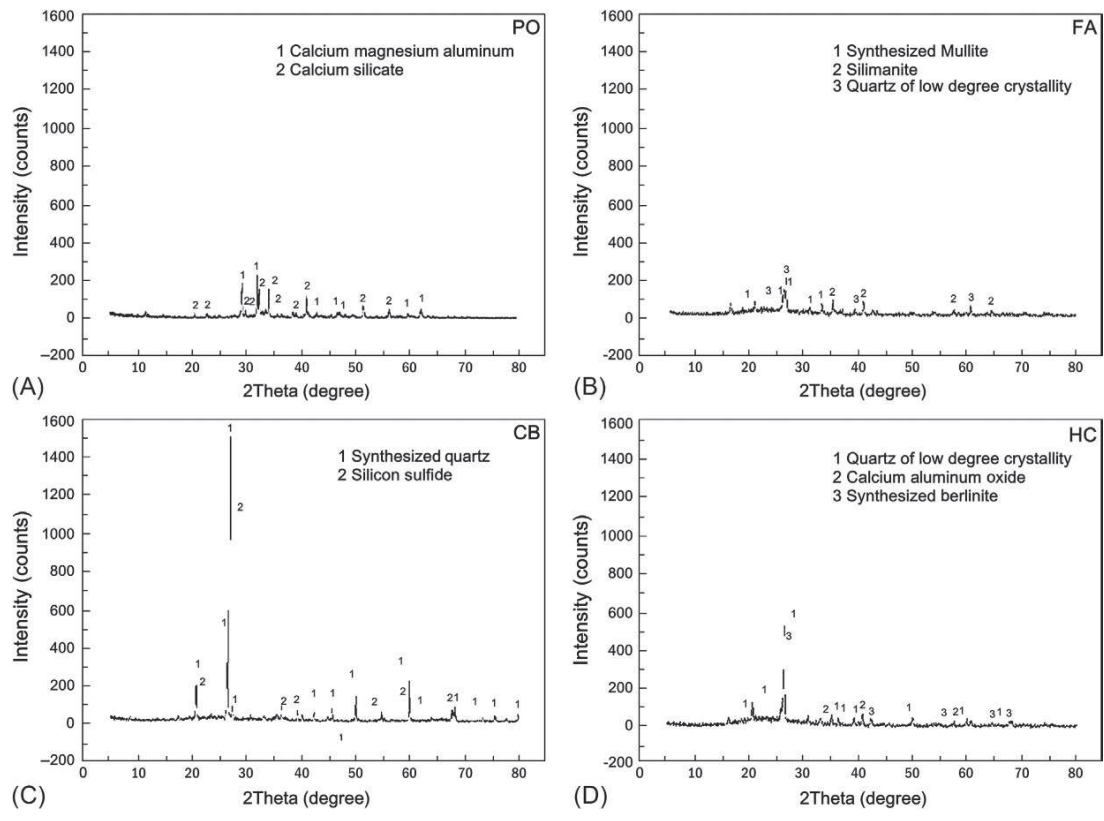
Fig. 17.3 XRD pattern of different powders: (A) PO; (B) FA; (C) CB powder; and (D) HC powder.

Table 17.5 Flowability of different fresh mortars.

Mixture	PO	HC5	HC15	HC25	CB5	CB15	CB25	FA5	FA15	FA25
Flowability (mm)	176	175	189	188	170	166	162	177	184	189

pozzolanic activity, causing different rates of reaction of the active phase (Tironi et al., 2013). The XRD analysis is one of the preconditions for further investigation of the pozzolanic activity. The results are presented in Fig. 17.3.

From Fig. 17.3A, it can be seen that the PO (sample of 100% cement) shows very slight crystalline behavior. The peak intensity is about 250 counts only. The calcium magnesium aluminum is the main crystalline forms detected while calcium silicate is the minor compound. Fig. 17.3B indicates that quartz of low degree crystallinity is the main compound with synthesized mullite and sillimanite as minor compounds in the FA. For the waste powder of CB, Fig. 17.3C indicates that synthesized quartz of high degree of crystallinity is the main component together with silicon sulfide. The peak intensity of CB achieves about 1600 counts. Fig. 17.3D reflects that quartz of low degree crystal is the main compound detected in the test accompanied by calcium aluminum oxide and synthesized berlinite as the minor compounds in the HC waste powder. The peak intensity of HC achieves about 500 counts, it is much lower than that of CB powder, and the average intensity of HC powder shows low crystalline degree. Compared to PO (cement), FA, and CB, it can be seen that HC waste powder shows very few high peak intensities due to the slightly crystalline structure (Fig. 17.3D). The average crystalline degree of HC powder was similar to that of the reference powder of FA, and the HC waste powder illustrates the clear amorphous structure, which indicates that the crushed HC powder could be used as both pozzolanic material and as fine filler.

17.2.6 Pozzolanic activity

For evaluation of the pozzolanic activity of the materials, it is important to consider the experimental method. Previous studies indicated that the Frattini test (as direct method) and the SAI test (as indirect method) are found to be the most accurate and reliable methods to assess the pozzolanic reaction of calcined clays in blended types of cement (Shi, 2001; He et al., 1995; Donatello et al., 2010; Tironi et al., 2013; Malquori, 2013). The evaluation of pozzolanic materials for purpose of the addition into Portland cement should be based on two factors (Malquori, 2013): (1) the strength of mortars and concretes made with a Portland pozzolan mixture, and (2) the reduction of free calcium hydroxide in the hardened pozzolanic cement. In addition, the Chapelle test may be also a selective method for testing of pozzolanic reactivity; however, the previous investigation showed that there is a low correlation between the results of Fratinni test and Chapelle test (Pontes et al., 2013) in some cases. Therefore, in this article, both the Frattini test and the SAI test are used to evaluate the pozzolanic activity of ceramic waste blended cement.

17.2.6.1 Strength activity index (SAI) of different mortars

The significant behavior for pozzolanic activity can be evaluated by the compression strength. The control sample of 100% cement without any waste addition was introduced for strength comparison. In order to evaluate the compressive strength of blended cement, the concept of SAI is used. SAI is defined as the ratio of the compressive strength of cement with additional waste powder to the compressive strength of cement without any addition (SAPRC (Standardisation Administration of the People's Republic of China), 2005; SBQTS (State Bureau of Quality and Technical Supervision), 1999; British Standard (BS) 3892, 1997; American Society for Testing and Materials (ASTM) C618, 2005). The ceramic waste powder may show pozzolanic activity, if SAI is greater than 0.65 (SAPRC (Standardisation Administration of the People's Republic of China), 2005), 0.8 (British Standard (BS) 3892, 1997), or 0.75 (American Society for Testing and Materials (ASTM) C618, 2005) with cement replacement of 10%, 20%, and 30% after 28 days based on different guidelines (SAPRC (Standardisation Administration of the People's Republic of China), 2005; SBQTS (State Bureau of Quality and Technical Supervision), 1999; British Standard (BS) 3892, 1997; American Society for Testing and Materials (ASTM) C618, 2005).

Prismatic specimens of 40 mm × 40 mm × 160 mm were cast and wet cured at 20°C (Malquori, 2013; SAPRC (Standardisation Administration of the People's Republic of China), 2005). The results of compressive strengths and SAI values (or the control sample strength: Compression strength of PO/Comparison strength of HC, CB, and FA) of various mortars at different ages (1d, 7d, 28d) are listed in Tables 17.6 and 17.7.

In comparison with the PO samples without ceramic waste powder, it can be seen that:

> The compressive strength of the samples with 15% of HC showed the highest value of all the ceramic powders and increased 11% compared to the value of the PO at 1 day.
> At 1 day, the compressive strengths of the samples with CB powders were lower than those with HC powder and decreased with the increasing of the CB powder content.

Table 17.6 Comparison of compressive strengths of various mortars at different ages.

N/mm^2	PO	HC5	HC15	HC25	CB5	CB15	CB25	FA5	FA15	FA25
1d	9.0	6.3	9.9	9.6	6.1	5.6	4.9	12.1	9.7	8.5
7d	37.8	36.1	32.8	30.7	37.6	33.5	28.4	37.0	35.1	34.1
28d	45.6	46.5	49.6	44.1	46	43	40	49.6	45.6	42.4

Table 17.7 Comparison of SAI values of various mortars at different ages.

	PO	HC5	HC15	HC25	CB5	CB15	CB25	FA5	FA15	FA25
1d	1	0.71	1.11	1.08	0.68	0.63	0.55	1.35	1.09	0.95
7d	1	0.95	0.87	0.81	0.99	0.89	0.75	0.98	0.93	0.90
28d	1	1.02	1.09	0.97	1.01	0.94	0.88	1.09	1	0.93

The compressive strengths of all HC, CB, and FA samples decreased with the increasing of powder content at 7 days, and all the SAI values of HC, CB, and FA were higher than 0.8 except CB25. It means that the HC and CB powder could show pozzolanic activity. However, both the pozzolanic activity and fine filler effect of waste powder may affect the compressive strength, and it is difficult to distinguish the two effects.

At 28 days, the compressive strength of HC5 and CB5 samples increased slightly, whereas HC25, CB15, and CB25 decreased. This may imply that 15% of HC powder could be a possible upper bound for an effective substitution.

At 28 days, all the SAI values of HC5, HCl5, and HC25 samples without further heating treatment are higher than 0.9 and the corresponding values of FA, indicating that HC waste powders may show well pozzolanic activity, which could be very cost-efficient for industrial use. The SAI values of CB5 and CB15 samples without further heating treatment are also higher than 0.9, but lower than the corresponding values of FA.

17.2.6.2 Frattini test

The previous study of Pontes J. suggested that Frattini results should only be applied up to 8 days (Pontes et al., 2013). Our Frattini test was conducted after 8 days curing at 40°C according to the EN 196-5, 2011 (British Standard Euronorm (BS EN) 196, 2011). The results are presented as a hyperbolic curve related to the calcium ion [CaO] concentration vs hydroxyl ion [OH$^-$] concentration (Fig. 17.4).

The interaction relationship of [CaO] and [OH$^-$] concentrations expresses the lime solubility curve and divides the [CaO] − [OH$^-$] domain into an upper pozzolanic inactive region and a lower pozzolanic active region. Between 35 and 90 mmol/L [OH$^-$], the theoretical maximum [CaO] concentration can be calculated according to Eq. (17.1) (Donatello et al., 2010):

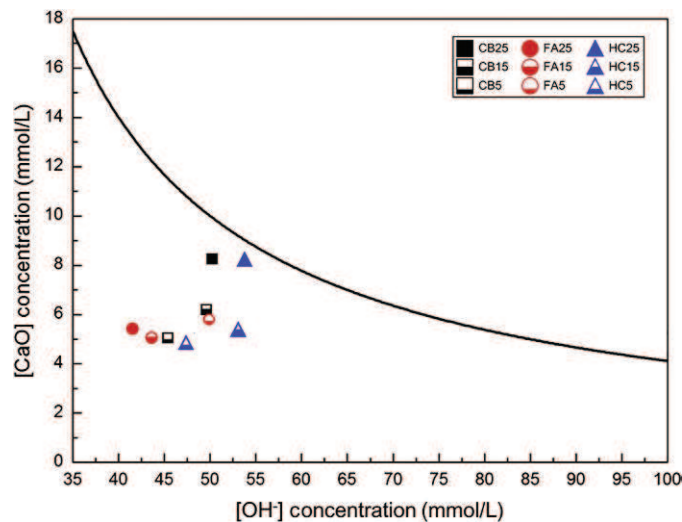$$\max[CaO] = 350 \big/ \big([OH^-] - 15\big) \tag{17.1}$$

Fig. 17.4 Frattini test results for blended cement containing FA, HC, and CB powder.

Table 17.8 Frattini test results for nine different materials quantified using Eq. (17.1).

Number	[OH⁻]	[CaO]	Theoretical max [CaO]	[CaO] reduction
	mmol/L	mmol/L	mmol/L	%
HC5	53.93	4.47	8.99	50.3
HC15	53.07	4.39	9.19	52.3
HC25	47.29	5.83	10.84	46.2
CB5	50.29	6.28	9.92	36.7
CB15	49.64	6.17	10.1	38.9
CB25	49.2	5.92	10.23	42.1
FA5	49.86	4.82	10.04	52
FA15	43.66	5.94	12.21	51.34
FA25	41.52	7.7	13.2	42

The sample calcium concentration [CaO] measured can be compared to the theoretical maximum [CaO] and the result quantified as the difference between the two values. Finally, this is expressed as a percentage of the theoretical maximum removed in Table 17.8.

From Table 17.8, it can be observed that:

The [OH⁻] concentration of the HC waste is in the range between 47 and 54 mmol/L, and the [OH⁻] concentration of the CB waste is lower than the corresponding value of HC waste powder. Compared to HC5, the [OH⁻] and [CaO] concentrations of HC15 changed very slightly, only 2% and 1%, respectively. However, compared to HC15, the [OH⁻] and [CaO] concentrations of HC25 changed about 11% and 32.8%, respectively.

The pozzolanic activity of HC5, HC15, FA5, and FA15 is relatively high with more than 50% CaO consumed; whereas CB5, CB15, CB25, HC25, and FA25 may show relative low pozzolanic activity, with 37% and 46% CaO consumed.

Similar to SAI test, the results above imply that 15% of HC waste powder could be a possible threshold for an effective substitution.

The values of [CaO] reduction of CB5/CB15/CB25 are clear less than the values of HC5/HC15/HC25, so the CB waste powder may show lower pozzolanic activity than that of HC waste powder.

As mentioned, for materials like HC, CB, and FA, the [OH⁻] and [CaO] concentrations are interrelated, and the correlation is represented by a [OH⁻] − [CaO] curve (solubility line) in Fig. 17.4. It can be seen that the results of pastes containing HC5, HC15, HC25, CB5, CB15, CB25, FA5, FA15, and FA25 are lying below the solubility line. It indicates that the [Ca²⁺] released by cement hydration to the solution was consumed due to the progress of the pozzolanic reaction and represents some pozzolanic active properties.

17.2.6.3 Relationship between the results of SAI test and Frattini test

The previous investigations (Lavat et al., 2009; Wild et al., 1997; ISO 679, 2009; Shi, 2001; He et al., 1995; Donatello et al., 2010; Tironi et al., 2013) showed that the Frattini test and the SAI test may be suitable for analyzing of the pozzolanic activity of various materials in blended cement. The Frattini test results provide an insight into

the likely Ca(OH)$_2$ concentration in the pore solution of SAI samples. For both methods, HC15 showed the highest activity, and the removal of Ca(OH)$_2$ from solution in the Frattini test indicates that in the SAI test sufficient reaction between HC15 and pore solution Ca(OH)$_2$ occurs to form strength providing C–S–H gel-type phases after 28 days. However, for cement with CB addition, the two results between Frattini test and the SAI test are not very consistent. Based on the SAI values in Table 17.6, CB indicates lower activity than those of FA and HC after 7 days, especially for CB25.

As mentioned in the introduction, FA as the referenced pozzolanic material was introduced to compare the properties with pastes that contain HC or CB powder. Fig. 17.5 illustrates the relationship of pozzolanic activity results of FA between the Frattini test and SAI test at 28 days. The unit of X is dimensionless and equal to the control sample strength (comparison strength of FA, HC, and CB samples/Compression strength of the cement sample).

For samples with FA powder, there is a positive linear correlation between results from Frattini (CaO removed in %) test and SAI test (Donatello et al., 2010), in other words, the compression strength of samples with different ratios of FA powder increases linearly with the increasing of the consumed CaO. The relationship between Frattini (denoted by Y) and SAI (denoted by X) can be expressed in the following equation:

$$Y = aX + b \tag{17.2}$$

where a denotes the slope of fitting line and b denotes the intercept. The slope is an important factor and illustrates the amount of CaO removed% divided by per unit of SAI; for substitution ratios with FA powder between 5%, 15%, and 25%, $a = 59.93$. The Frattini results and SAI results are strong correlated ($R = 0.86$).
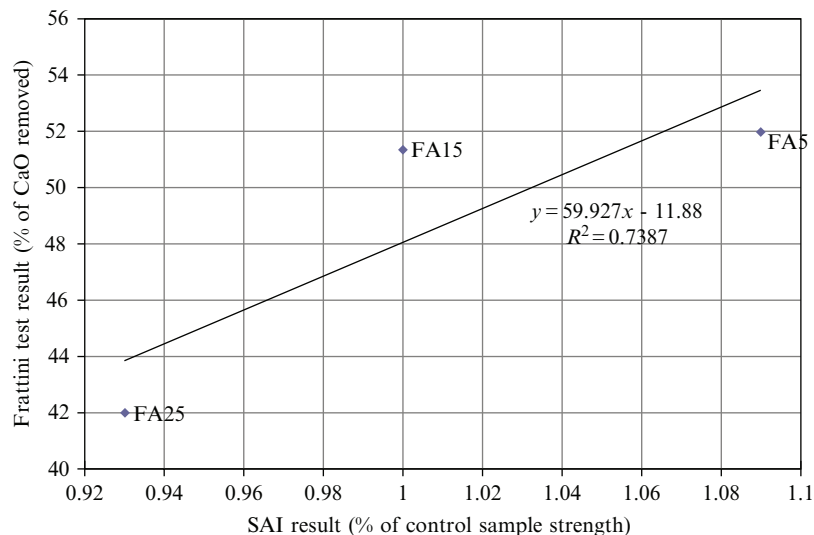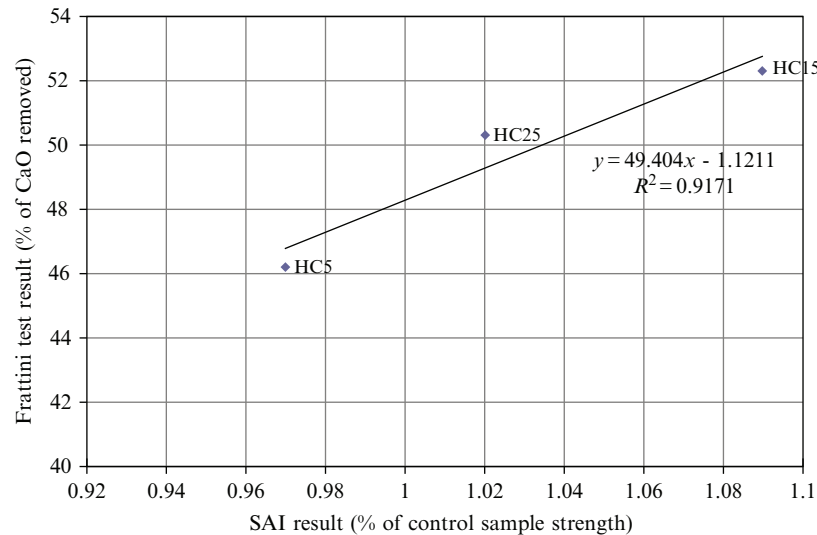

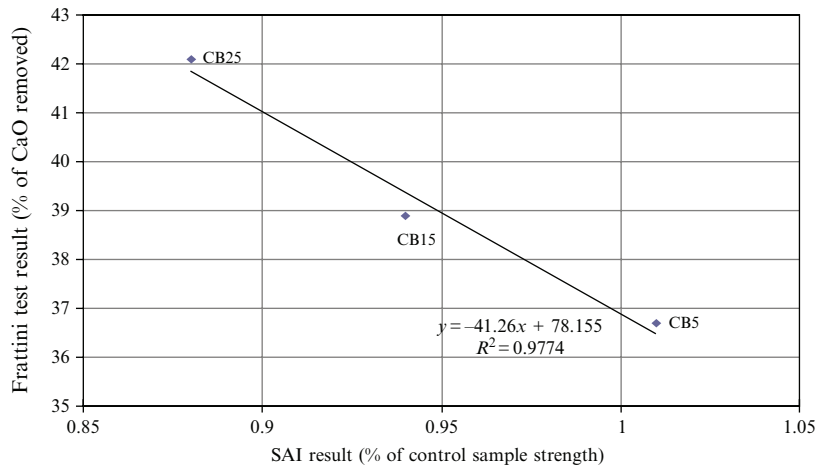**Fig. 17.5** Correlation between Frattini test and SAI results of FA.

Fig. 17.6 Correlation between Frattini test and SAI results of HC.

Fig. 17.6 illustrates the relationship between Frattini test and SAI results of samples with HC waste powder. Similar to FA powder, for samples with HC waste, there is also a clear positive linear correlation between results of CaO removed in % and SAI.

From Fig. 17.6, it can be seen that for substitution ratios with HC powder between 5%, 15%, and 25%, the slope $a = 49.4$. The Frattini and SAI results are also strongly correlated ($R = 0.958$). The slope for HC powder is lower than that for FA powder ($49.4 < 59.93$). It may imply that the amount of CaO removed% of HC samples is less than that of FA samples for per unit of SAI, and the pozzolanic activity of FA is higher than that of HC.

Fig. 17.7 illustrates the relationship between Frattini test and SAI results for CB powder. Opposed to the discussions in Figs. 17.5 and 17.6, there is a negative linear correlation between the two tests with the replacement of 5%, 15%, and 25% of CB waste powder, the slope $a = -41.26$, and opposed to Figs. 17.5 and 17.6, the CaO consumed declines with the increasing of SAI. It may reflect the low magnitude of the pozzolanic activity of CB powder; the reason could be traced back to the following points:

- Based on the XRD analysis in Section 17.2.5, CB waster powder shows quartz of high degree crystallinity accompanied by silicon sulfide.
- The SAI values of blended cement can be affected by two factors: the pozzolanic activity and the fine filler effect of CB powder; however, the effect between the two factors of waste powder on the compressive strength cannot be separated quantitatively.
- Qualitatively, the fine filler effect of CB powder may show higher influence on the SAI values than that of pozzolanic activity; and a large part of fine-milled CB powder may be still unreacted and plays a role as fine filler due to the large specific surface area.

Fig. 17.7 Correlation between Frattini test and SAI results of CB.

17.2.6.4 Discussion

Figs. 17.5–17.7 show the possible trend qualitatively. The pozzolanic activity of FA powder is higher than that of HC powder, and the pozzolanic activity of HC powder is higher than that of CB powder. The negative correlation between SAI and Frattini test could be attributed to a large part of the CB powder that may unreact due to a high degree of crystallinity and plays a role as fine filler.

Some literature works mentioned that the Frattini test and the SAI could be the most accurate and reliable methods to assess pozzolanic activity (Donatello et al., 2010; Tironi et al., 2013; Malquori, 2013), and the most important quality for pozzolanic activity can be seen in the compressive strength (SAPRC (Standardisation Administration of the People's Republic of China), 2005; SBQTS (State Bureau of Quality and Technical Supervision), 1999; British Standard (BS) 3892, 1997; American Society for Testing and Materials (ASTM) C618, 2005). However, based on the investigations in Sections 17.2.6.1–17.2.6.3, both Frattini test and the SAI method may not be the only sufficient condition to judge the pozzolanic activity accurately and reliably due mainly to the following reasons:

- Both the pozzolanic activity and the fine filler effect may affect the SAI values of blended cement, but the effect of these two factors cannot be separated strictly.
- Generally speaking, the Frattini test and SAI method should be the necessary conditions to assess the pozzolanic activity. For instance, Fig. 17.4 indicates that the CB waste powder shows some pozzolanic activity, and SAI values of all the CB samples in Table 17.6 are greater than 0.75 or 0.8 (American Society for Testing and Materials (ASTM) C618, 2005), even though CB powder indicates a high degree of crystalline phases (quartz, silicon sulfide, etc.) in Fig. 17.3C. Actually, the pozzolanic active material should show the amorphous structure or low crystalline degree, similar to Fig. 17.3A for PO, Fig. 17.3B for FA and Fig. 17.3D for HC.
- Compared to the SAI and Frattini results, the combination of XRD analysis, the SAI test, and Frattini test could be more suitable to form a sufficient condition for an accurate and reliable assessment of the pozzolanic activity.

In addition, it is worth noting the following differences between the HC and CB ceramic waste powders:

· Low degree crystalline quartz is the main compound of HC powder, and the HC waste shows some amorphous structure. CB powder shows relatively high degree of crystallinity.
· Except CB25, all the SAI values of HC and CB samples are higher than 0.8 at 7 days. At 28 days, the SAI values of CB declined with the increasing of waste content.

According to the Frattini results and SAI test, both the HC and CB ceramic waste powder show pozzolanic activity. However, on the basis of a comprehensive analysis of the high pH-value and low crystalline degree, and other aspects like the grain size analysis as well as XRF analysis of the above investigations, HC powder could be more suitable for use in cement or concrete matrix than that of CB powder.

17.3   Conclusions

Samples with Portland cement, FA blended cement, the HC waste and CB waste powder with cement substitution ratios of 5%, 15%, and 25% were experimentally investigated. The pozzolanic activity is an important precondition for reusing of the ceramic waste. The present study of ceramic waste powder led to the following conclusions:

The main chemical components of HC and CB waste powder are similar to those of FA and consist mainly of SiO_2 and Al_2O_3.

Based on the Frattini results and SAI test, both the HC and CB ceramic waste powder show pozzolanic activity. However, the pozzolanic activity of HC powder was higher than that of CB waste powder.

The SAI values and Frattini results of HC15 are higher than those of HC 5 and HC 25. This may imply that 15% of HC could be a possible upper bound for an effective substitution ratio of cement.

For a waste powder with good pozzolanic activity like HC or FA, there should be a positive linear correlation between the Frattini and SAI results with a significant correlation coefficient.

The negative correlation between SAI and Frattini results of CB could be attributed to a large part of fine-milled CB waste powder that may unreact and plays a role as fine filler in the blended cement matrix.

The combination of XRD, SAI, and Frattini test could be a sufficient condition for an accurate and reliable assessment of the pozzolanic activity of the ceramic waste powder.

The possible substitution of cement by ceramic waste powder without further heating treatment will show major ecological benefits in terms of saving cement and reducing CO_2 emission.

Notation

PO   cement mortars/samples without ceramic waste additives.
HC/CB X   cement mortars/samples with the ceramic waste replacement of X%; for instance, HC/CB 10: samples with ceramic waste powder replacement of 10%.

FA Y   cement mortars/samples with FA replacement of Y%; for instance, FA5: samples with FA replacement of 5%.

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