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Adding ceramic polishing waste as filler to reduce paste volume and improve carbonation and water resistances of mortar

Leo Gu Li[1,2*], Yi Ouyang[3], Zhen-Yao Zhuo[4] and Albert Kwok Hung Kwan[2]

* Correspondence: ligu@gdut.edu.
cn
[1]Guangdong University of
Technology, Guangzhou, China
[2]The University of Hong Kong,
Hong Kong, China
Full list of author information is
available at the end of the article

Abstract

The use of ceramic waste in concrete/mortar production as aggregate replacement or cement replacement has been under consideration in the last decade to find an effective way to tackle the growing hazard of ceramic waste disposal. In this study, the authors reutilize ceramic polishing waste (CPW) as a filler to replace an equal volume of cement paste in mortar while keeping the mixture proportions of the cement paste unchanged, i.e., in a new way as paste replacement. This mixture design strategy allows a larger amount of CPW to be added to substantially reduce the paste volume, cement and carbon footprint. The mortar mixes so produced had been subjected to carbonation and water absorption tests, and the results showed that as paste replacement, the CPW can significantly enhance the carbonation and water resistances, in addition to the environmental benefits of reducing waste, cement and carbon footprint. Regression analysis of test results indicated that for carbonation resistance, the cementing efficiency factor of the CPW was around 0.5, whereas for water resistance, the cementing efficiency factor was higher than 1.0 at low CPW content and lower than 1.0 at high CPW content.
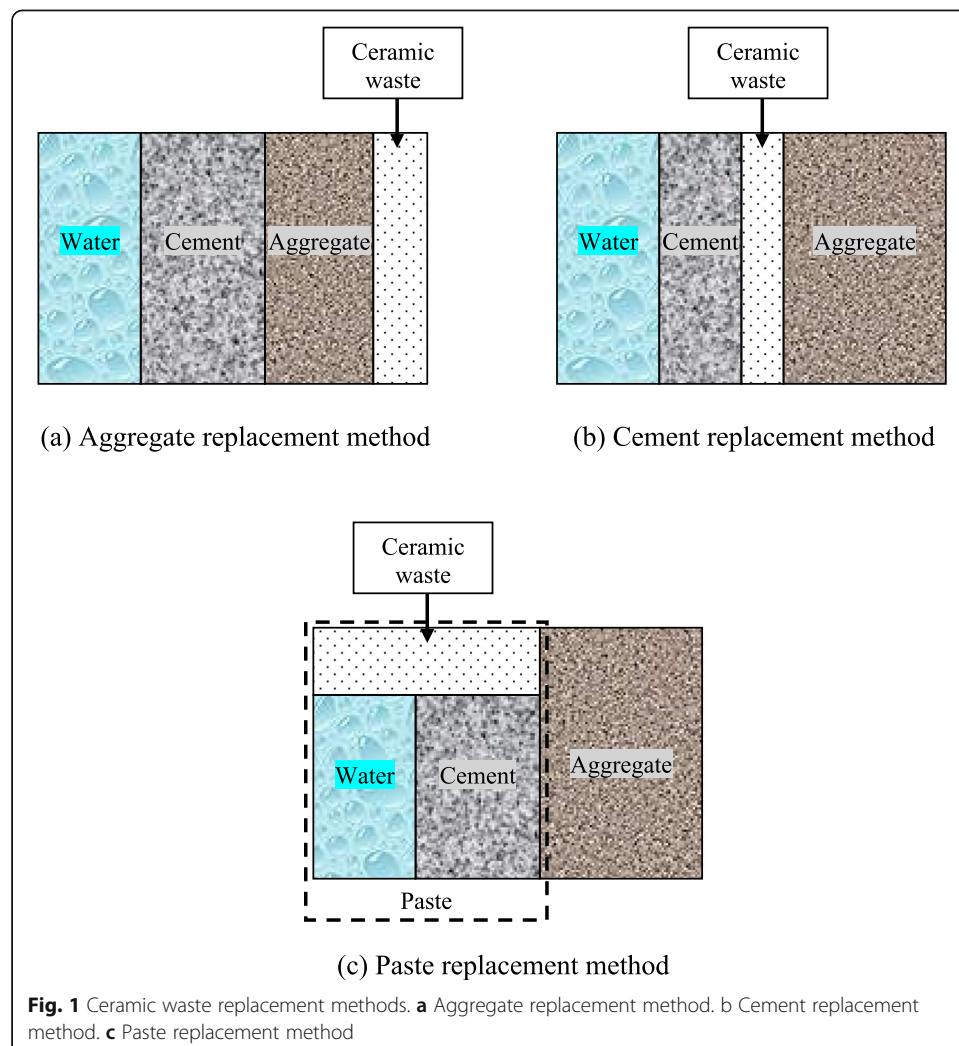
Keywords: Carbonation resistance, Cementing efficiency, Ceramic polishing waste, Durability, Water resistance

1 Introduction

In 2019, waste recycling has once again become the focus of many heated discussions among environmentalists and politicians, not because the technology in this field has achieved major advancement, but because scandals have revealed that "recycled waste" in some developed countries has, in reality, ended up in poorly managed landfills in developing countries (Wang et al. 2017; Harrabin and Edgington 2019; Wang et al. 2020; Li et al. 2021a). Therefore, people are still facing grim prospect for genuine "sustainable development" if proper actions are not taken promptly. An ideal waste recycling process should involve effective reutilization of the waste as raw materials in manufacturing or construction. In this study, a new way of reutilizing ceramic waste in

concrete/mortar production, which allows a greater consumption of the waste per volume of production, is explored.

There are two main sources of ceramic waste (de Brito et al. 2005; Pacheco-Torgal and Jalali 2010): (a) from the production of red-paste-related products like bricks and roof tiles; and (b) from the production of ceramic products like wall tiles, floor tiles and sanitary wares. In previous studies, the ceramic waste has been used either as aggregate replacement (as shown in Fig. 1a) or cement replacement (as shown in Fig. 1b). When used as aggregate replacement, it was added to replace fine aggregate (Binici 2007; Lopez et al. 2007; Guerra et al. 2009; Torkittikul and Chaipanich 2010; Siddique et al. 2018) or coarse aggregate (Senthamarai and Manoharan 2005; Suzuki et al. 2009; Medina et al. 2012; Feng et al. 2013) or both (Halicka et al. 2013; Awoyera et al. 2018). Such usage may offer certain benefits to the performance of concrete. For instance, the addition of porous ceramic waste as aggregate can provide internal water curing for high performance concrete (Suzuki et al. 2009). When used as cement replacement, it has been shown that ceramic waste powders have certain pozzolanic reactivity and thus may be added to reduce the cement content, while still attaining satisfactory strength (Pereira-de-Oliveira et al. 2012; Heidari and Tavakoli 2013; Mas et al. 2015;

Fig. 1 Ceramic waste replacement methods. **a** Aggregate replacement method. b Cement replacement method. **c** Paste replacement method

Kannan et al. 2017; Aly et al. 2019). Meanwhile, very fine ceramic waste has also been used in cement production (Ay and Ünal 2000; García-Díaz et al. 2011), but this is outside the scope of the present research, which is on the direct reutilization of ceramic waste in concrete/mortar production.

The fresh properties of the concrete/mortar produced would be affected by the addition of ceramic waste. Medina et al. (2013a) discovered that the shear yield stresses of cement mixtures under fresh state would be lowered due to the addition of fine ceramic waste powder. De Matos et al. (2018) found that porcelain polishing residues having a mean particle size of around 10 μm could be used to produce self-compacting concrete with similar rheological properties but better passing ability if added to replace cement by not more than 20%. The hardened properties would also be affected, beneficially or adversely. Correia et al. (2006) conducted a series of tests on the abrasive and water resistances of concrete made with recycled ceramic coarse aggregate and noted that the abrasive resistance was improved by the use of recycled ceramic coarse aggregate, but the water resistance was substantially afflicted. Medina et al. (2013b) showed that the use of ceramic waste as coarse aggregate would enhance the resistance against freeze-thaw cycles. Similarly, Kuan et al. (2020) pointed out that using ceramic powder could improve the freeze–thaw cycle resistance of concrete. However, Senthamarai et al. (2011) observed that the use of ceramic waste as coarse aggregate would adversely affect both the water and chloride resistances of concrete.

In this study, the authors focus on carbonation and water resistances of mortar containing fine ceramic polishing waste (CPW) powder. The mix design strategy adopted herein regarding the usage of CPW is neither as aggregate replacement nor as cement replacement, but as "paste replacement". The "paste replacement" method is to partially replace the cement paste volume (cement + water) in the mortar/concrete by an equal volume of solid powder (as shown in Fig. 1c). It should be noted that by using this method, whilst the cement paste volume is lowered, the mix proportions of the cement paste would not be changed (i.e. the water/cement ratio is unchanged). If the solids have some degree of pozzolanic reactivity, part of them will end up forming cementing compounds while the rest will become fillers. A series of previous studies conducted by the authors' research group have shown that this strategy of paste replacement can be applied to the addition of limestone fines (Li and Kwan 2015; Li et al. 2017a), marble dust (Li et al. 2018a; Li et al. 2019a), granite dust (Li et al. 2018b; Li et al. 2019b), clay brick waste (Li et al. 2019c) and ceramic waste (Li et al. 2019e; Li et al. 2020a; Li et al. 2020b) to mortar/concrete mixtures with satisfactory performances attained. The applicability of such strategy to the addition of CPW to mortar mixtures for reducing the paste volume and improving the carbonation and water resistances is to be investigated herein so as to extend this strategy to CPW.
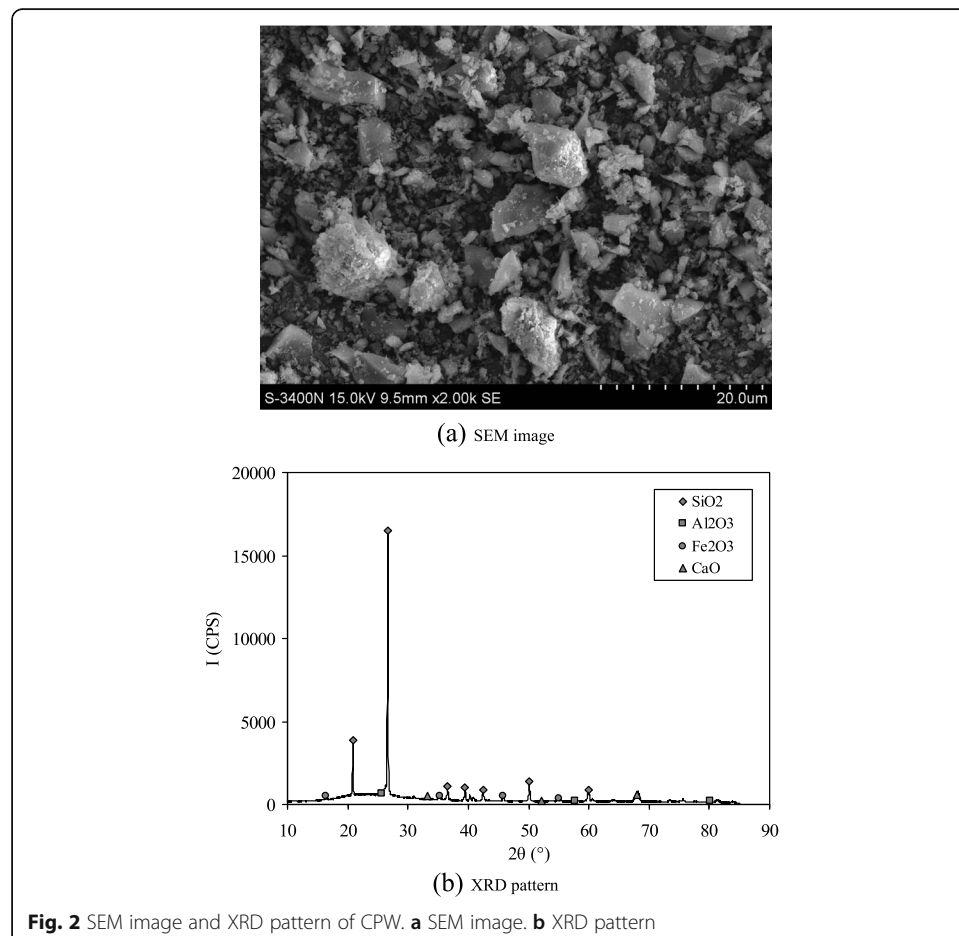
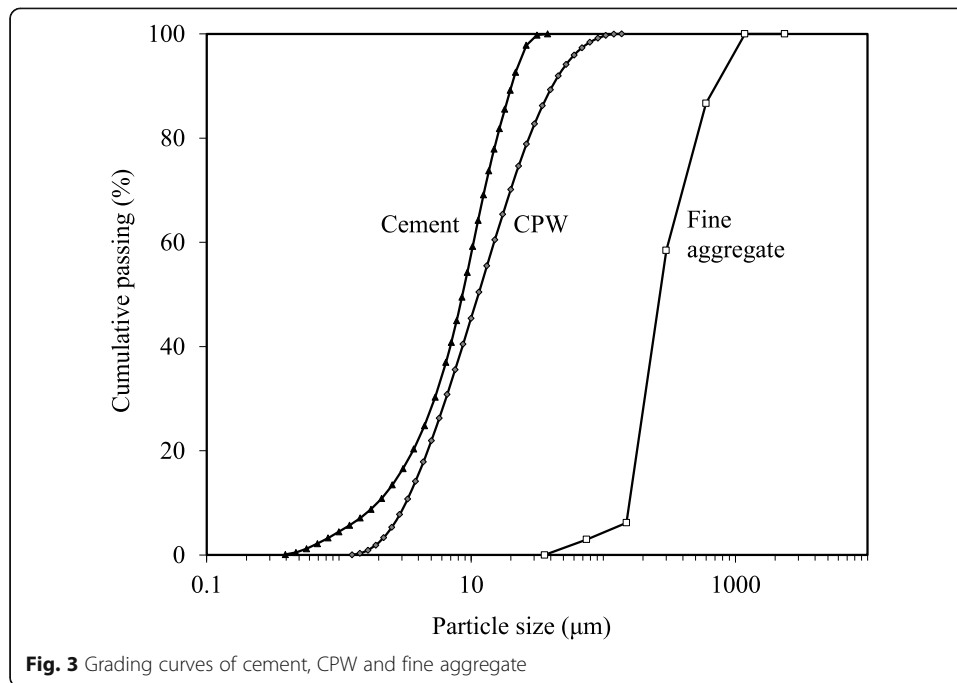## 2 Experimental studies

2.1 Raw materials

The raw materials of the mortar mixes consisted of water, cement, fine aggregate, ceramic polishing waste (CPW) and superplasticizer (SP), of which the technical details are as follows: (a) the cement was PO 42.5 ordinary Portland cement produced in compliance with the Chinese Standard GB 175–2007 (2007) and had a specific gravity of

3.10; (b) the fine aggregate was river sand having a maximum particle size of 1.18 mm, a specific gravity of 2.58, a water absorption of 1.10%, and a moisture content of 0.10%; (c) the CPW was a light-grey powder with a specific gravity of 2.43; and (d) the SP was a PC-based admixture with 20% solid by mass and a specific gravity of 1.05.

The CPW was obtained from a ceramics factory in Foshan city, a famous powerhouse of ceramics production in China. The CPW was generated during polishing of ceramic tiles. The original CPW collected was wet with some debris inside. In order to dry and minimize variation in quality, the CPW was treated as follows: first, the CPW was heated with an oven at 105 °C for 8 h to remove the water and then mechanically sieved using a 1.18 mm sieve to remove the debris. After the treatment, the CPW was turned to a light-grey dry powder. The SEM image and XRD pattern of the CPW are shown in Fig. 2a and b, respectively. From the SEM image, it is clear that the CPW particles are angular in shape. From the XRD pattern, it is evident that the CPW is a typical ceramic material composed mainly of SiO_2, Al_2O_3, Fe_2O_3 and CaO, indicating that the CPW should have certain pozzolanic properties.

The grading curves of the main ingredients are presented in Fig. 3. It is noted that compared to the cement, the CPW has a similar pattern of particle size distribution but a marginally larger mean particle size. In other words, the CPW was almost as fine as the cement.

(a) SEM image

(b) XRD pattern

Fig. 2 SEM image and XRD pattern of CPW. **a** SEM image. **b** XRD pattern

Fig. 3 Grading curves of cement, CPW and fine aggregate

2.2 Mix proportion

A total of 20 mortar mixes in four groups, with each group having a different water/cement (W/C) ratio among the values of 0.40, 0.45, 0.50 and 0.55, were designed and tested. The information on the mix proportions is comprehensively depicted in Table 1. For each of the mortar mixes, the volume of the fine aggregate accounted for, nominally, 40% of the total mortar volume, with the remaining 60% being the cement paste (cement + water) only or the cement paste and CPW. In each group of the mixes, which had the same W/C ratio, the combinations of the "cement paste + CPW" in terms of nominal percentages of the total mortar volume are (60% + 0%), (55% + 5%), (50% + 10%), (45% + 15%) and (40% + 20%), as illustrated in the second and the third columns of Table 1. The identifications of the mixes follow the format of "X-Y" where the W/C ratio of the mix is placed at the position of X and the "CPW volume" (defined as the ratio of the CPW's volume to the total volume of mortar) at the position of Y.

The addition of SP was to control the mortar mixes to have similar workability, and let them all meet a certain workability requirement, which in the current study, was set as having a flow spread measured by the mini slump cone test (Okamura and Ouchi (2003) of 250 ± 50 mm, or in other words, 200 to 300 mm. Therefore, the SP dosages (mass of liquid SP as a percentage of combined mass of cement + CPW) of the mortar mixes varied from one another and were determined through the process of trial mortar mixing, in which the SP was dosed into the mortar mixture bit by bit until the measured value of flow spread was within the required range. The results in SP dosage obtained from the trials for all the mortar mixes were then applied during the final production of mortar samples for subsequent testing.

Table 1 Mixture proportions of mortar mixes

Mix no.	Paste volume (%)	CPW volume (%)	Water (kg/m^3)	Cement (kg/m^3)	CPW (kg/m^3)	Fine aggregate (kg/m^3)	SP dosage (%)
0.40–0	60	0	331	828	0	1032	0.40
0.40–5	55	5	304	759	121	1032	1.10
0.40–10	50	10	276	690	243	1032	1.65
0.40–15	45	15	248	621	364	1032	2.45
0.40–20	40	20	221	552	485	1032	3.35
0.45–0	60	0	349	775	0	1032	0.37
0.45–5	55	5	319	710	121	1032	0.90
0.45–10	50	10	290	645	243	1032	1.40
0.45–15	45	15	261	581	364	1032	2.24
0.45–20	40	20	232	516	485	1032	2.80
0.50–0	60	0	364	728	0	1032	0.23
0.50–5	55	5	333	667	121	1032	0.65
0.50–10	50	10	303	606	243	1032	1.20
0.50–15	45	15	273	546	364	1032	1.90
0.50–20	40	20	243	485	485	1032	2.50
0.55–0	60	0	377	686	0	1032	0.14
0.55–5	55	5	346	629	121	1032	0.58
0.55–10	50	10	314	572	243	1032	1.05
0.55–15	45	15	283	514	364	1032	1.53
0.55–20	40	20	252	457	485	1032	2.30

Notes

(1) The moisture content and water absorption of the aggregate and the water in the SP are taken into account in the calculation of the water content

(2) The air void content, which is dependent on the compaction applied, has not been taken into account in the calculation of the above mix proportions
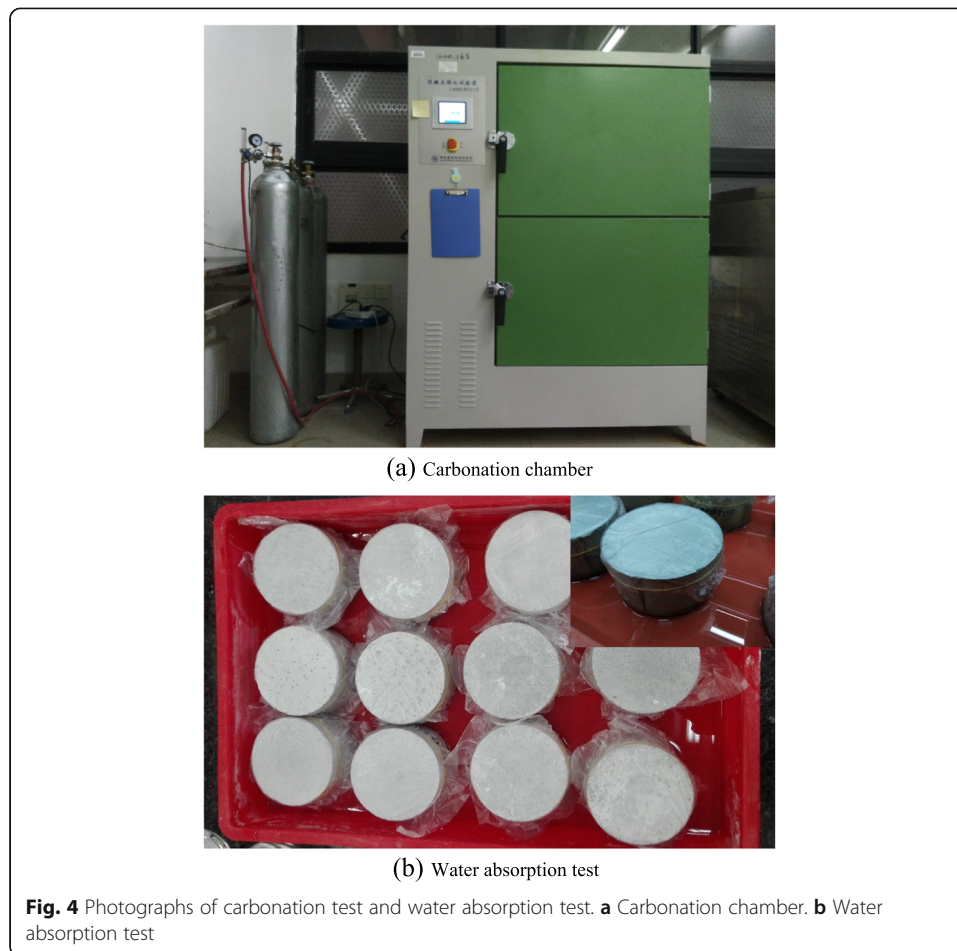
2.3 Mixing procedure and testing methods

A 10 Litre horizontal single-shaft mixer was used to mix each batch of mortar and the mixing procedure was presented as follows: (1) the cement, CPW, water and one half of SP were added and mixed for 60 s; (2) the fine aggregate and the remaining half of SP were added, and the mixing continued for 60 s.

The details of the mini slump cone test introduced by Okamura and Ouchi can be found in Ref. (Okamura and Ouchi 2003).

The carbonation resistance, which is an important aspect of durability, of the mortar was evaluated through the carbonation test implemented in compliance with Chinese Standard GB/T 50082–2009 (2009). During the carbonation tests, the mortar specimens were placed in a carbonation chamber, as shown in Fig. 4a, to allow intrusion of carbon dioxide through the exposed surfaces. The depths of the intrusion were then measured as the carbonation depths to reflect the carbonation resistances of the specimens. For details of the carbonation test, the following reference is referred to (Li et al. 2017b).

The water resistance, which is another important aspect of durability, of the mortar can be reflected by the water absorption rates. In the current study, the tests to measure the initial/secondary water absorption rates of the mortar were carried out in compliance with American Standard ASTM C1585–04 (2004) (as shown in Fig. 4b). Since it is a common test, the testing procedures are not repeated herein.

(a) Carbonation chamber

(b) Water absorption test

Fig. 4 Photographs of carbonation test and water absorption test. **a** Carbonation chamber. **b** Water absorption test

Lastly, in order to study the effect of CPW on the microstructure, micrographs of the hardened mortar samples were captured by using the Hitachi S-3400 N-II scanning electron microscope (SEM).

3 Test results

3.1 SP dosage and flow spread

The SP dosages added to achieve the target flow spread of within 200 to 300 mm are listed in the last column of Table 1, while the actual flow spread achieved, which were all within the target range, are tabulated in the second column of Table 2. From these results, it can be seen that as expected, the SP dosage was generally higher at a lower W/C ratio and lower at a higher W/C ratio. More importantly, at a fixed W/C ratio, the SP dosage increased significantly as the CPW volume increased. This was because of the decrease in water content of the mortar mix.

3.2 Carbonation depth

Table 2 depicts the carbonation depths for all the mortar mixes. When the carbonation depths of all the mortar mixes are plotted against the CPW volume in Fig. 5, it is found that when the value of CPW volume was unchanged, a lower W/C ratio would result

Table 2 Test results of mortar mixes

Mix no.	Flow spread (mm)	Carbonation depth (mm)	Initial water absorption rate ($\times 10^{-4}$ mm/s$^{1/2}$)	Secondary water absorption rate ($\times 10^{-4}$ mm/s$^{1/2}$)
0.40–0	228	3.27	6.42	3.70
0.40–5	288	2.75	3.26	1.63
0.40–10	271	1.64	2.50	1.42
0.40–15	282	0.91	1.58	1.05
0.40–20	230	0.19	1.35	0.36
0.45–0	227	4.03	8.15	5.54
0.45–5	279	3.26	4.32	1.83
0.45–10	228	2.39	3.41	1.56
0.45–15	231	1.08	2.66	1.33
0.45–20	260	0.72	1.73	0.72
0.50–0	240	6.53	10.89	8.03
0.50–5	252	5.43	5.59	3.07
0.50–10	278	3.00	3.95	2.17
0.50–15	256	2.12	3.78	1.36
0.50–20	229	1.43	2.95	1.05
0.55–0	226	7.70	14.07	13.02
0.55–5	248	6.52	7.92	4.54
0.55–10	287	4.72	5.55	2.79
0.55–15	241	3.58	4.84	2.10
0.55–20	236	2.13	3.71	1.50
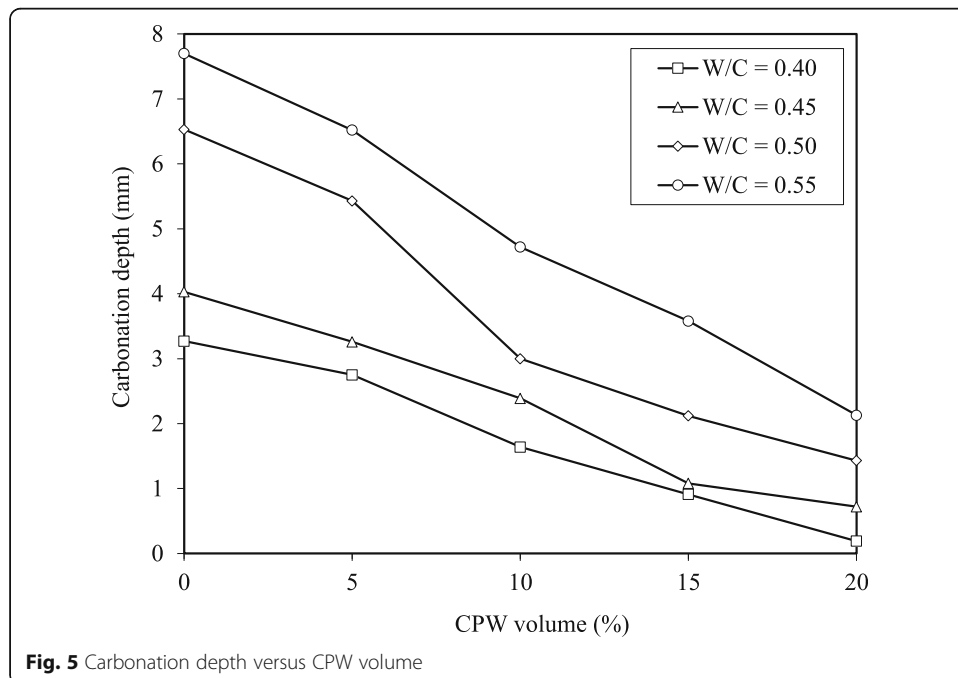
Fig. 5 Carbonation depth versus CPW volume

in a smaller carbonation depth of the mortar. For example, when the W/C ratio decreased from 0.55 to 0.40 while the CPW volume was kept as 0%, the carbonation depth would be reduced from 7.70 mm to 3.27 mm. Such variation of carbonation depth with the W/C ratio is expected, since the W/C ratio is well known to be the main factor affecting the carbonation resistance of mortar (Li et al. 2017b; Leemann et al. 2015).

More significantly, when the W/C ratio was fixed, the carbonation depth of the mortar would become smaller in the presence of higher CPW volume. For instance, when the CPW volume increased from 0% to 20% while the W/C ratio was maintained at 0.55, the carbonation depth would drop from 7.70 mm to 2.13 mm. Consequently, the presence of CPW as paste replacement has enhanced the carbonation resistance of the mortar. The probable reason is the densification of the microstructure after the addition of the CPW, as will be seen from the SEM images later.

3.3 Water absorption rates

As mentioned previously, the initial and the secondary water absorption rates of each mortar mix were measured through water absorption tests, with the values of presented in Table 2.

When the two types of water absorption rates for the mortar mixes with various W/C ratios are plotted against the corresponding CPW values in Figs. 6 and 7, respectively, it is found that: at a fixed CPW value, a lower W/C ratio would lead to a lower initial/secondary water absorption rate. For instance, when the W/C ratio decreased from 0.55 to 0.40 while the CPW volume was kept at 0%, the initial water absorption rate would go down from 14.07×10^{-4} mm/s$^{1/2}$ to 6.42×10^{-4} mm/s$^{1/2}$, and the secondary water absorption rate would go down from 13.02×10^{-4} mm/s$^{1/2}$ to 3.70×10^{-4} mm/s$^{1/2}$. Such change of water absorption rate with the W/C ratio is reasonable, because similar results have been found in other studies (Li and Kwan 2015; Du et al. 2016).
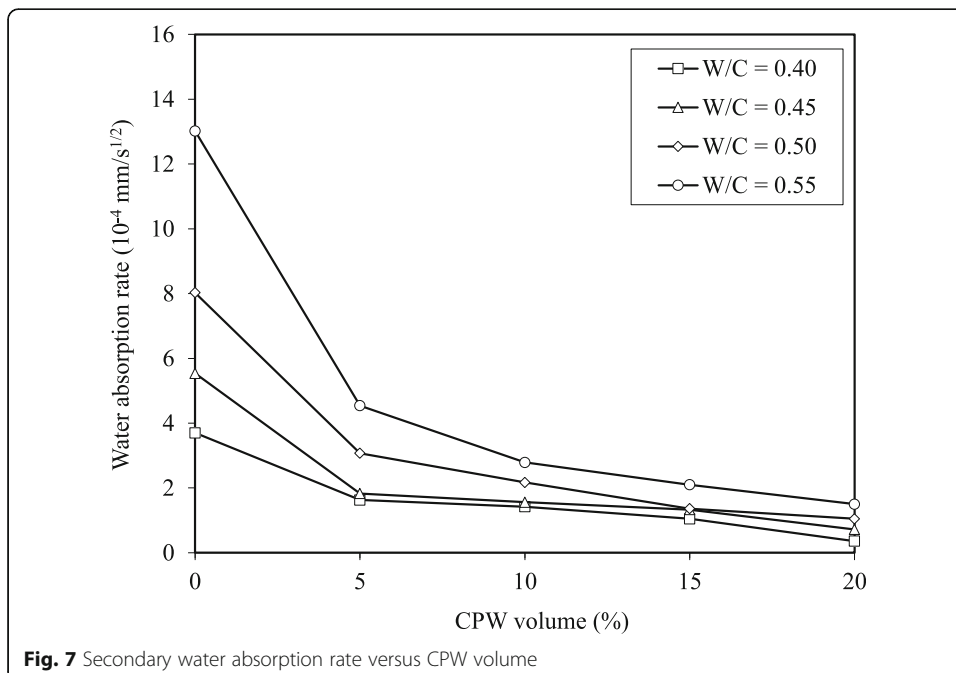
More importantly, when the W/C ratio was kept unchanged, increasing the CPW amount would result in a lower water absorption rate. For example, when the CPW volume was raised from 0% to 20% while the W/C ratio was maintained as 0.55, the initial water absorption rate would go down from 14.07×10^{-4} mm/s$^{1/2}$ to 3.71×10^{-4} mm/s$^{1/2}$, and the secondary water absorption rate would go down from 13.02×10^{-4} mm/s$^{1/2}$ to 1.50×10^{-4} mm/s$^{1/2}$. Therefore, it is evident that the paste replacement method is a very effective way of adding the CPW to enhance the water resistance of mortar.
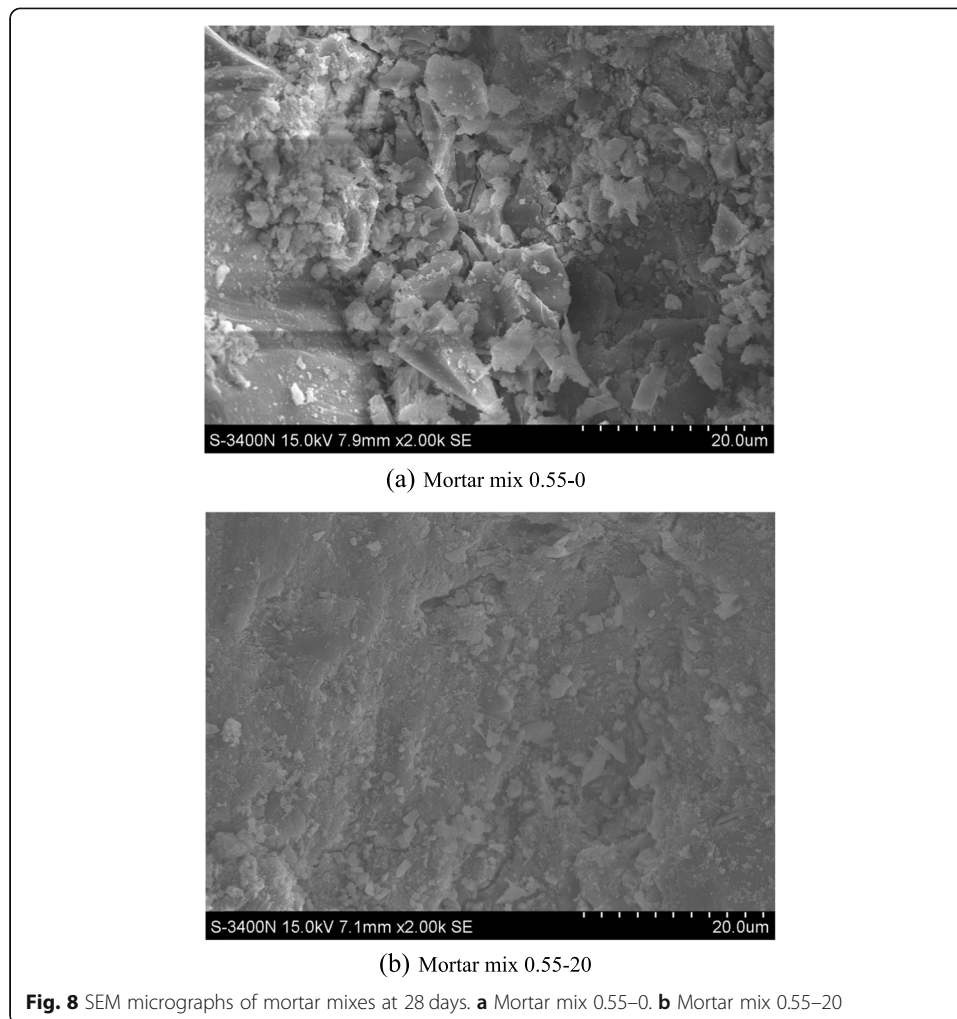
3.4 Microstructure from SEM images

The SEM images of the mortar specimens 0.55–0 and 0.55–20 are presented in Figs. 8a and 7b, respectively. Through comparison, it is found that the microstructure was rather loose in the specimen 0.55–0, which has no CPW content, but significantly more compact in the specimen 0.55–20, which has 20% CPW volume. Therefore, the addition of CPW as paste replacement would densify the microstructure and reduce the voids inside, and thus should improve the impermeability to increase the carbonation and water resistances of mortar.

Fig. 6 Initial water absorption rate versus CPW volume
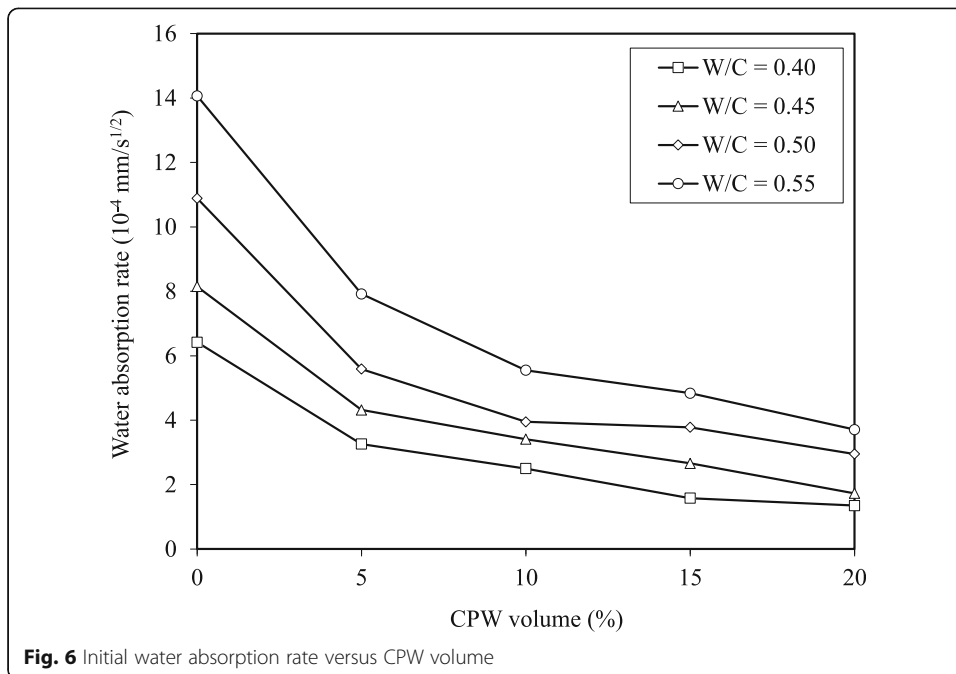
The explanations on the densification of microstructure by adding CPW may be given as follows: (1) adding CPW can fill into the voids between aggregate particles so as to reduce the volume of voids to be filled with cement paste, so as to improve the packing density of the particle system; (2) the CPW has certain pozzolanic reactivity and thus could participate in hydration reaction to produce more C-S-H gel to fill the voids; (3) the addition of more SP to achieve the required workability would help to better disperse the cement grains and CPW particles to allow more uniform mixing and better compaction during casting.

Fig. 7 Secondary water absorption rate versus CPW volume

(a) Mortar mix 0.55-0

(b) Mortar mix 0.55-20

Fig. 8 SEM micrographs of mortar mixes at 28 days. **a** Mortar mix 0.55–0. **b** Mortar mix 0.55–20

4 Detailed analysis of test results

4.1 Concurrent changes in cement content and durability performance

From Table 1, it can be seen that the addition of CPW to replace an equal volume of cement paste would allow the consumption of waste up to 20% of the mortar volume and whittle down the cement content by up to 33%, while achieving higher carbonation and water resistances for improving the durability performance. To illustrate the concurrent reduction in cement content and improvement in durability, the carbonation depth, initial water absorption rate and secondary water absorption rate are plotted against the cement content for different CPW volumes and W/C ratios in Figs. 9, 10 and 11, respectively. It is evident that the conventional method of decreasing the W/C ratio to improve the durability would increase the cement content, whereas the proposed method of adding CPW as paste replacement to improve the durability would decrease the cement content for reducing carbon footprint and increase the waste consumption for reducing waste disposal.

Compared to the addition of solid waste as aggregate replacement, which does not reduce the cement content and might not improve the mortar performance, and the addition of solid waste as cement replacement, which often adversely affects the mortar

Fig. 9 Carbonation depth versus cement content
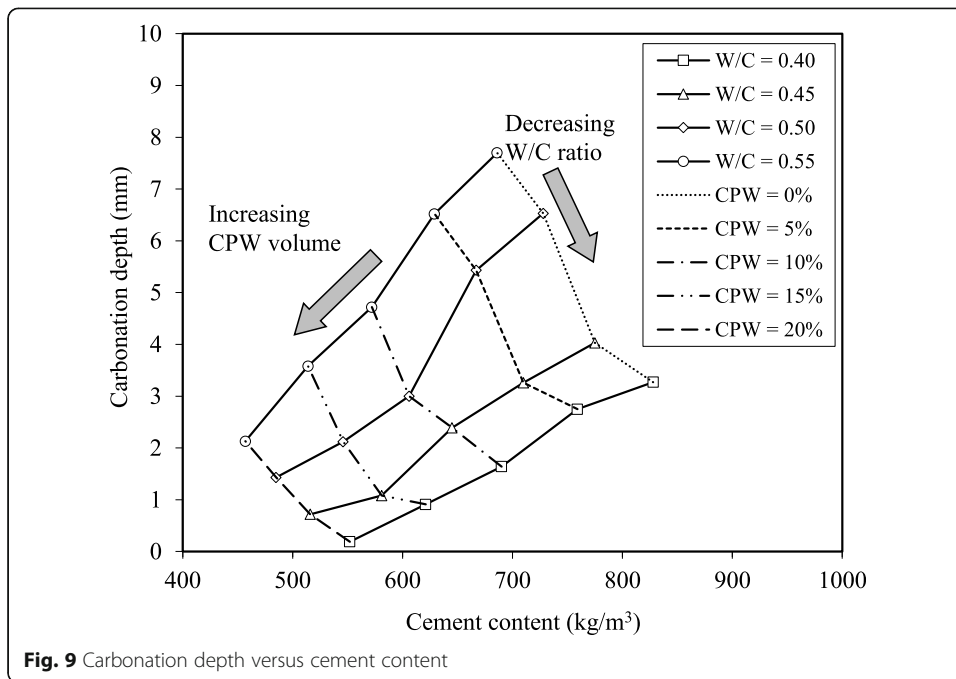
performance and therefore imposes a severe limit on the amount of solid waste to be added, this paste replacement method offers the advantages in consuming a larger amount of waste, reducing a larger amount of cement and improving the mortar perform-ance, all at the same time. However, this paste replacement method is applicable only if the solid waste to be added is almost as fine as the cementitious materials so that the solid waste would intermix with the cement paste to form a powder paste having the same vol-ume as the original cement paste for filling up the voids between aggregate particles. In fact, such addition of the solid waste as paste replacement may also be viewed as an

Fig. 10 Initial water absorption rate versus cement content
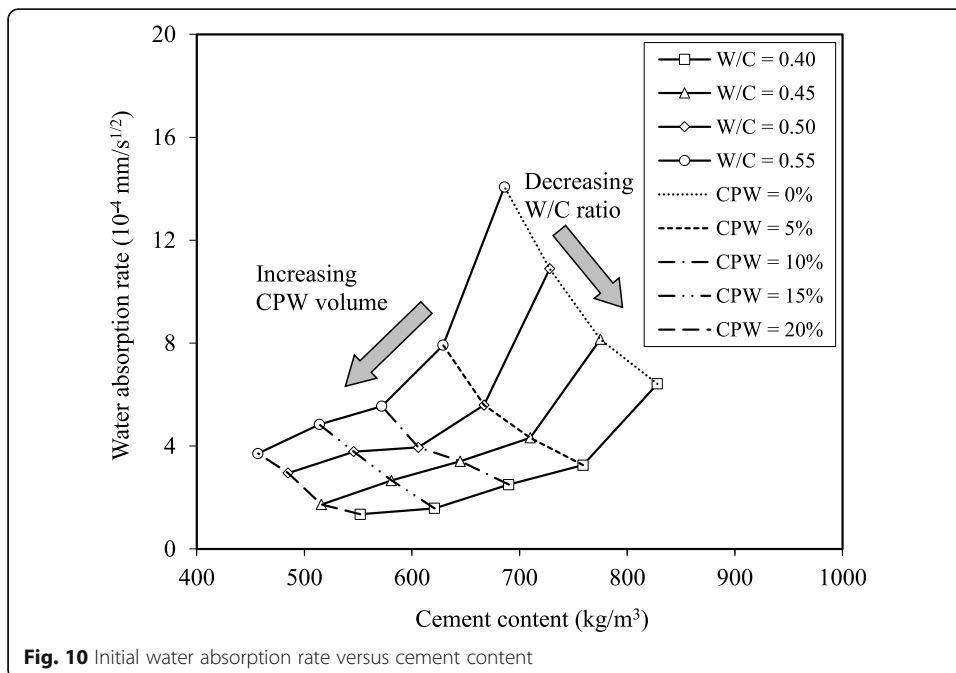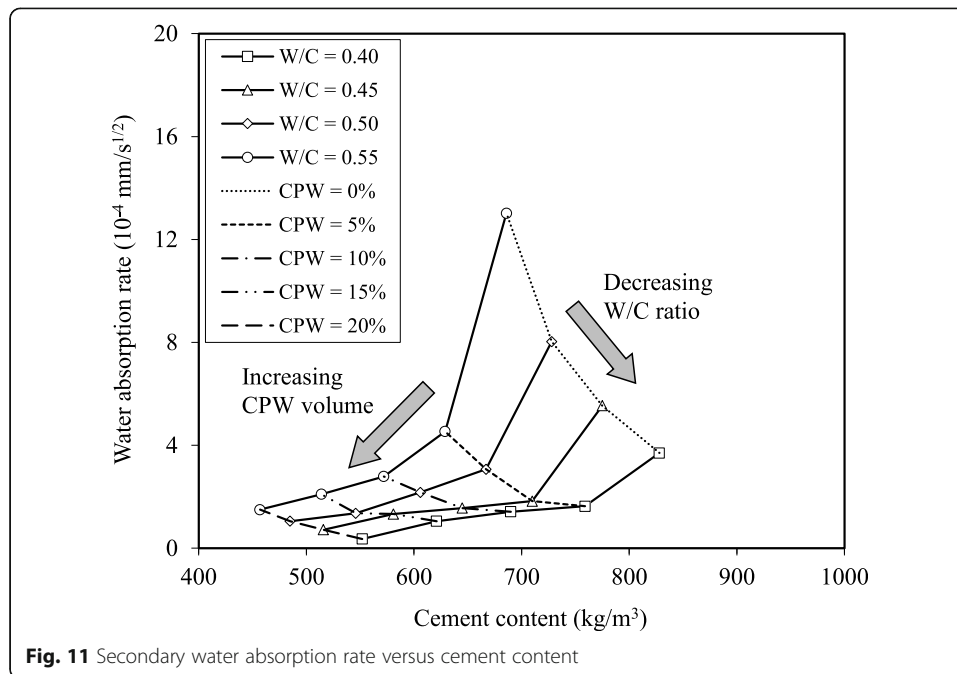
Fig. 11 Secondary water absorption rate versus cement content

addition of the solid waste as a filler to fill up part of the voids between aggregate particles so that the cement paste volume needed may be reduced by the volume of solid waste added. This would increase the packing density of the solid waste plus aggregate mixture (Yu et al. 1997; Zhang et al. 2011; Cepuritis et al. 2014; Li et al. 2019d) and quite possibly, this is one of the root causes for the improvement in mortar performance.

4.2 Cementing efficiency of CPW

For evaluating the effectiveness of supplementary cementitious material (SCM) in performance attributes of cement-based material, it has been proposed to employ the concept of cementing efficiency (Hobbs 1988; Wong and Abdul Razak 2005; European Committee for Standardization 2013; Li et al. 2021b). Basically, the cementing efficiency of a SCM is evaluated in terms of a cementing efficiency factor (CEF), defined as the mass of cement that is replaceable per mass of the SCM added without changing the performance. Smith (1967) first proposed this concept and suggested that a CEF of 0.25 for fly ash (FA) may be adopted for preliminary design of FA concrete. Papadakis and Tsimas (2002) tested the durability performance of low-calcium FA and high-calcium FA, and obtained their carbonation resistance CEFs as 0.5 and 0.7, respectively.

Previous studies by other researchers (Pereira-de-Oliveira et al. 2012; Heidari and Tavakoli 2013; Mas et al. 2015; Kannan et al. 2017) have indicated that ceramic waste in powder form can have certain pozzolanic reactivity and thus cementing property, but so far, such cementing property has never been quantified. Herein, it is proposed to evaluate the cementing property of the CPW in terms of the CEF, which is defined as the ratio of the equivalent mass of cement to the mass of CPW added (Hobbs 1988; Wong and Abdul Razak 2005).

To evaluate the cementing efficiency of the CPW, an effective water to cementitious materials ratio (W/CM$_{eff}$) is introduced, as given below:

$$W/CM_{eff} = \frac{m_W}{m_C + \alpha \times m_{CPW}} \qquad (1)$$

in which α is the CEF of CPW; and m_W, m_C and m_{CPW} are the water, cement and CPW contents in kg/m^3. It should be noted that the values of α for the carbonation depth, initial water absorption rate and secondary water absorption rate are not the same. For differentiation, the α for carbonation depth is denoted by α_c, the α for initial water absorption rate is denoted by $\alpha_{w,I}$ and the α for secondary water absorption rate is denoted by $\alpha_{w,II}$. To evaluate each CEF, the corresponding mortar performance is correlated to W/CM$_{eff}$ by regression analysis, and different values of α are tried until the highest R^2 value is obtained.

Fig. 12 presents the analysis results for the carbonation resistance, where the carbonation depth is correlated to W/CM$_{eff}$ using the following equation:

$$\text{Carbonation depth} = 28.57 \cdot W/CM_{eff} - 8.14 \qquad (2)$$

in which the carbonation depth is in mm. Maximization of the R^2 value yielded $\alpha_c = 0.51$ and $R^2 = 0.969$. During the analysis, it appeared that the CEF α_c is not sensitive to the CPW content. Hence, it may be said that for evaluation of the carbonation resistance, the CPW may be treated as equivalent to 0.5 times its mass of cement. The R^2 value so obtained is very high, suggesting that the correlation equation above may be used to predict the carbonation depth of mortar made with CPW added as paste replacement.
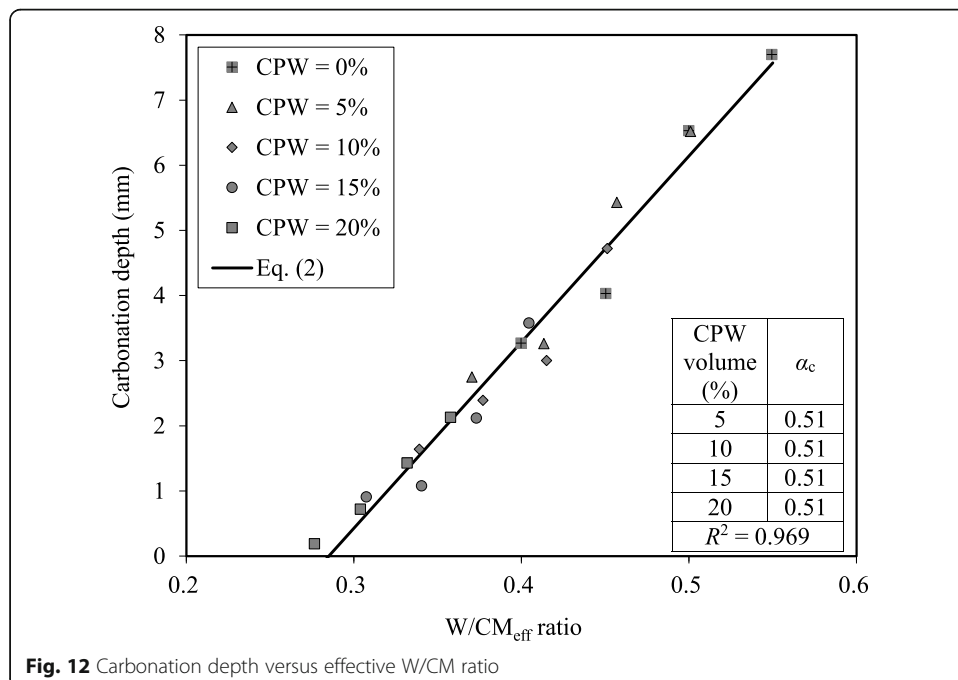

Fig. 12 Carbonation depth versus effective W/CM ratio

Figs. 13 and 14 present the analysis results for the water resistance, where the initial water absorption rate and secondary water absorption rate are correlated to W/CM_{eff} using the following equations:

$$\text{Initial water absorption rate} = 112.55 \cdot W/CM_{eff}^{3.31} \tag{3}$$

$$\text{Secondary water absorption rate} = 123.42 \cdot W/CM_{eff}^{3.89} \tag{4}$$

in which the two types of water absorption rates are both in $\times 10^{-4}\,mm/s^{1/2}$. However, the analysis revealed that the CEFs $\alpha_{w,I}$ and $\alpha_{w,II}$ are both dependent on the CPW content, The values of $\alpha_{w,I}$ and $\alpha_{w,II}$ so determined are given in the tables inserted in the two figures. For the initial water absorption rate, the value of $\alpha_{w,I}$ varies from 1.20 at a CPW volume of 5% to 0.56 at a CPW volume of 20%. For the secondary water absorption rate, the value of $\alpha_{w,II}$ varies from 1.45 at a CPW volume of 5% to 0.70 at a CPW volume of 20%. Roughly, for evaluation of the water resistance, the CPW may be treated conservatively as equivalent to 0.6 times its mass of cement. The R^2 values so obtained for Eqs. (3) and (4) are 0.979 and 0.963, respectively, which are both very high, suggesting that these two equations may be used to predict the two types of water absorption rates of mortar made with CPW added as paste replacement.

5 Conclusions

The feasibility of adding ceramic polishing waste (CPW) as paste replacement in mortar to reduce waste disposal and cement consumption, and also to improve durability has been studied by making a series of mortar mixes with different CPW
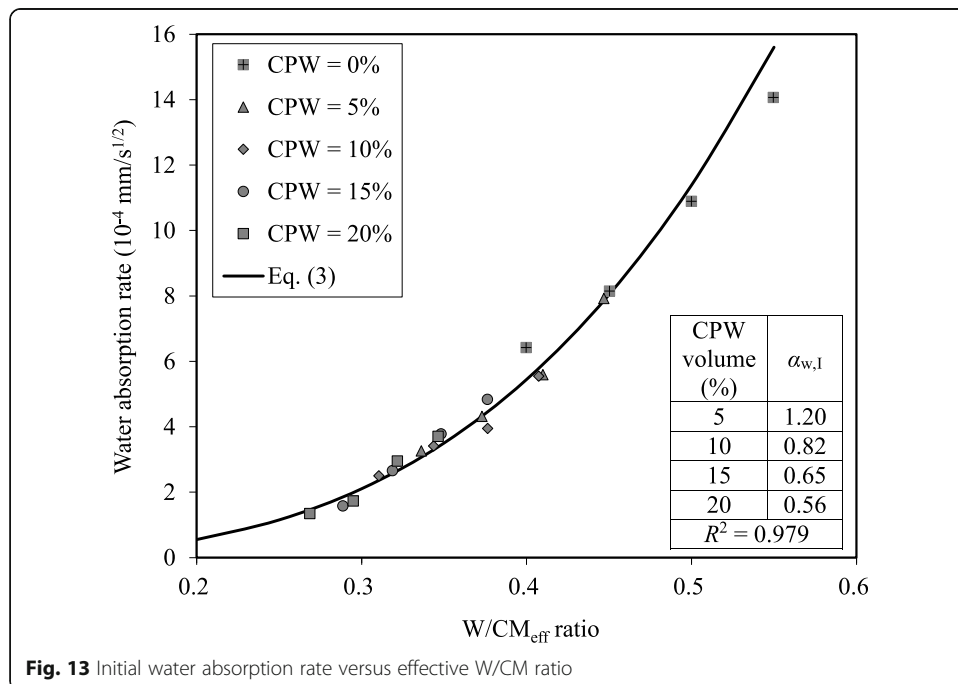

CPW volume (%)	$\alpha_{w,I}$
5	1.20
10	0.82
15	0.65
20	0.56
$R^2 = 0.979$	

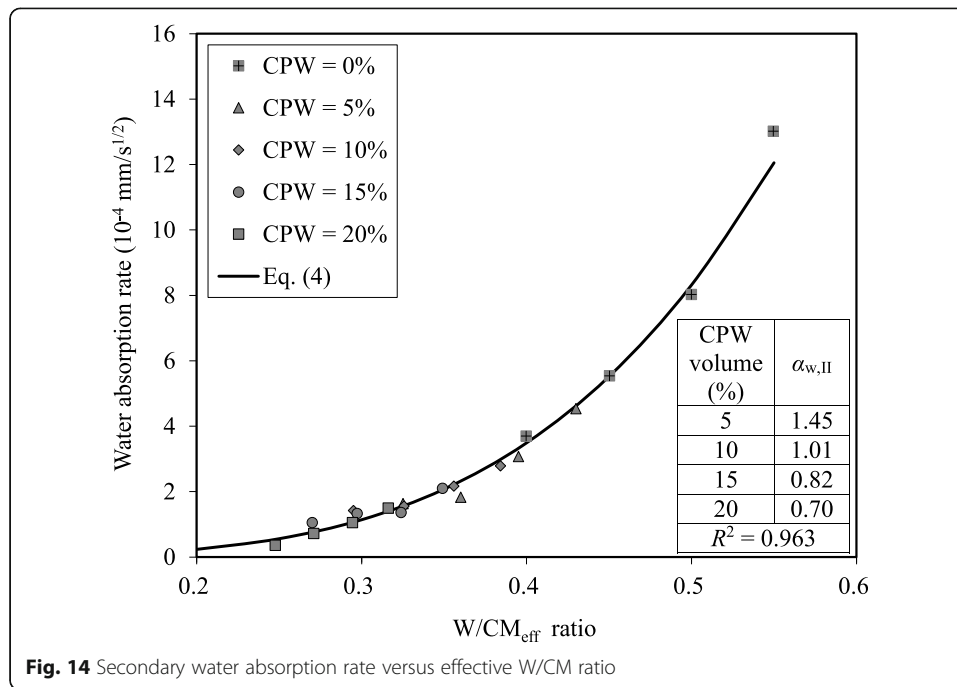**Fig. 13** Initial water absorption rate versus effective W/CM ratio

Fig. 14 Secondary water absorption rate versus effective W/CM ratio

volumes (as % of mortar volume) and W/C ratios for testing of their carbonation and water resistances. Up to 20% CPW by volume of mortar had been added and very promising results were obtained, from which the following conclusions are made.

(1) The addition of up to 20% CPW to replace an equal volume of cement paste in mortar would reduce the paste volume and cement content by 33% without adversely affecting the performance of the mortar.

(2) The addition of CPW up to 20% by volume of mortar as paste replacement would dramatically reduce the carbonation depth by more than 70% and the initial/secondary water absorption rates by also more than 70%. Densification of the microstructure, as revealed by SEM images, is the most probable cause of such dramatic improvements in durability.

(3) Compared to the conventional method of decreasing the W/C ratio to improve durability, which is less effective in increasing the carbonation and water resistances and would increase the cement content, this method of adding CPW as paste replacement to improve durability is more effective and would at the same time reduce the cement content.

(4) Compared to the method of adding CPW as aggregate replacement, which does not reduce the cement content, and the method of adding CPW as cement replacement, which may not improve the durability performance, this method of adding CPW as paste replacement is a much better method in terms of waste reutilization, carbon reduction and durability performance.

(5) The pozzolanic reactivity of the CPW used has been quantified in terms of cementing efficiency factors. For the carbonation depth, the cementing efficiency factor has been found to be insensitive to the CPW volume and is generally around 0.5. For the initial and secondary water absorption rates, the cementing efficiency factors have been found to decrease with increasing CPW volume, but nevertheless remain at around 0.6 or higher even at a CPW volume of 20%.

Abbreviations

CPW: Ceramic polishing waste; SP: Superplasticizer; W/C ratio: Water/cement ratio; SEM: Scanning electron microscope; W/CM$_{eff}$: Effective water to cementitious materials ratio; α: Cementing efficiency factor of CPW; α$_c$: Cementing efficiency factor of CPW for carbonation depth; α$_{w,I}$: Cementing efficiency factor of CPW for initial water absorption rate; α$_{w,II}$: Cementing efficiency factor of CPW for secondary water absorption rate; m$_W$: Water content; m$_C$: Cement content; m$_{CPW}$: CPW content

Author details
[1]Guangdong University of Technology, Guangzhou, China. [2]The University of Hong Kong, Hong Kong, China. [3]Mott Macdonald (Hong Kong) Ltd., Hong Kong, China. [4]Agile Property Holdings Ltd., Guangzhou, China.

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