

Efficient reuse of the recycled construction waste cementitious materials

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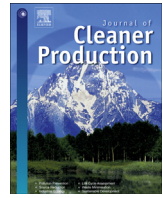
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Efficient reuse of the recycled construction waste cementitious materials



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ABSTRACT

This paper addresses the efficiently reuse of the recycled construction waste cementitious materials (RCWCM). The RCWCM is firstly collected, and then subjected to crushing, grinding and thermal treatments, respectively. After that, the obtained powder material is named dehydrated cement paste (DCP) in this study. Due to the fact that the DCP has relatively high pH value and high activity, two specific attempts are tried to efficiently reuse the obtained DCP. The results show that it is possible to produce a prefabricated building material with an industry by-product (fly ash) and a recycled waste material (DCP). The compressive strength of the produced prefabricated building material can be higher than 60 MPa. Additionally, after being further dispersed, the DCP could be utilized as a high performance cement additive, which can significantly promote the hydration and microstructure development of cement.

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1. Introduction

As sustainable development is currently a pressing global subject, the issues regarding to less energy consumption and CO₂ emission are the key factors for the development of construction industry. As commonly known, recycled construction wastes have great potential to be utilized as a type of environmentally friendly building materials. Especially for the concrete made structure, when they are demolished or renovated, concrete recycling is an increasingly common method of using the rubble (Marinković et al., 2010). For the recycled coarse aggregates, their influence on the properties of reproduced concrete has been investigated a lot. Many researches are focus on the fatigue behaviour (Thomas et al., 2014), durability (André et al., 2014), mechanical properties (Belén et al., 2011), leaching properties (Medina et al., 2014; Zong et al., 2014) of the recycled aggregate concrete. However, due to the variation of the basic properties of the recycled coarse aggregates, the performance of the recycled aggregates concrete can be significantly different. Additionally, the recycled fine aggregates also attract a lot of attentions in recent years. For instance, the

characterization of the recycled fine aggregates (Rodrigues et al., 2013), fresh and hardened behaviour of concrete with recycled fine aggregate (Evangelista and Brito, 2007; Khatib, 2005) can be easily found in the open literature. Nevertheless, it can be noticed that a large amount of the studies about recycled construction waste are focused on the recycled aggregates, the investigation regarding to the application of the recycled construction waste cementitious materials (RCWCM) is insufficient.

In the RCWCM, the hardened cement paste is the main component, which can regain the hydration capacity after subjecting to the high temperature (300–1000 °C) environment (Castellote et al., 2004; Shui et al., 2009). In addition, the rehydration of a heated cement paste shows that the process is reversible and new formation of a C–S–H gel from the new nesosilicate is confirmed with a CaO/SiO₂ ratio close to the initial C–S–H gel and recovering its initial stoichiometry (Alonso and Fernandez, 2004). Nevertheless, all the related investigations are only focus on the properties evaluation of the hardened cement paste subjected to high temperature. The attempt of reasonable application of the dehydrated cement paste (DCP) in practice can seldom be found, which should be attributed to the obvious difference of the cementitious properties between DCP and Portland cement. According to the previous investigation (Shui et al., 2009), the authors found that the DCP has high pH value and high reactive activity. Actually, these fundamental properties of DCP could be

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reasonably reutilized. For example, the high pH value of DCP is suitable to be utilized to activate the acidic oxide and produce the prefabricated material, while that the high activity of the DCP can be used to stimulate the hydration of cement and promote the microstructure development of cement.

Consequently, in this study, the focus is directed towards to efficiently reuse of the RCWCM. The dehydrated cement paste (DCP) is firstly recycled from RCWCM, and then used to produce prefabricated building material and high performance cement additive. Techniques such as isothermal calorimetry and scanning electron microscopy are employed to investigate detailed mechanisms during the reactions.

2. Materials and experimental methodologies

2.1. Materials

In this study, the Ordinary Portland Cement (OPC) CEM I 42.5 N and a low calcium fly-ash with average particle sizes of less than 0.075 mm are used. The physical and chemical information of the utilized cement and fly ash are shown in Tables 1 and 2. (Based on standards ASTM C150/C150 M and ASTM C618) Moreover, a polycarboxylic ether based superplasticizer is used to adjust the workability of the cementitious materials.

Additionally, the RCWCM is collected from the waste hardened cement samples (cubes or prisms) that were subjected to mechanical experiments in material testing laboratories. The reasons to choose the waste hardened cement in material testing laboratories are based on the sustainable development aspects, which can be summarized as follows: 1) the cement-like materials testing laboratories produce large amount of waste cement based materials every year; 2) The waste hardened cement paste obtained from materials testing laboratories was broken during testing, which means that less energy may be consumed in crushing these materials; 3) It is very convenient to collect the waste hardened cement paste in laboratory and no extra labour is needed for long distance transportation.

2.2. Experimental methodologies

2.2.1. Treatments on the RCWCM

The treatments of RCWCM follow the procedures shown in Yu and Shui (2013). After considering the activity of the DCP after different thermal treatment temperatures and the energy consumption during the experiments, the DCP treated at 650 °C is produced and named original DCP (O-DCP) in this study, which is then used to produce the prefabricated material. The chemical analysis of the O-DCP is shown in Table 2. Additionally, to further improve the activity of O-DCP, an ultrasonic device (SB-3200D, temperature: 20 °C, frequency: 20 HZ) is utilized to disperse the O-DCP for 2 h. The dispersed DCP is named D-DCP, which is used as high performance cement additive afterwards.

Table 1

Physical information of the used cement and fly ash.

Properties	Cement	Fly ash
Blaine surface area (m ² /kg)	355	340
Specific gravity (kg/m ³)	3160	2293
Requiring water for normal consistency	0.258	–
Initial setting time (mins)	190	–
Final setting time (mins)	240	–
Water requirement ratio	–	94%
Loss on ignition	–	1.15%
Moisture content	–	0.32%

Table 2

Chemical composition of the used cement, fly ash and O-DCP.

	Cement	Fly ash	O-DCP
SiO ₂	22.51	50.20	23.77
Al ₂ O ₃	6.21	38.93	5.82
Fe ₂ O ₃	3.65	3.82	3.67
CaO	60.40	3.51	59.64
MgO	3.30	0.35	0.24
SO ₃	1.81	0.75	2.71
Na ₂ O	0.33	0.34	0.26
K ₂ O	0.70	0.85	0.47
L.O.I	1.09	1.25	3.42

2.2.2. Consistence and setting time measurements

The required water for a normal consistency and setting times of the cementitious composites are assessed in accordance with ASTM C187 (1991) and ACTM C191 (1999), respectively. The mix recipes for consistence and setting time measurement are listed in Table 3.

2.2.3. Compressive strength measurement

Based on the consistence and setting times measurements, the new designed mix recipes for the measurement of compressive strength are shown in Table 4. During the experiments, the cementitious pastes are cast in steel moulds with the size of 40 × 40 × 40 mm and compacted on a vibrating table. After 24 h, those cube specimens are demolded and subjected to the fog-spraying curing regime at 20 °C and a relative humidity above 95% until the date for testing. For the production of prefabricated building material, the curing conditions are modified. After subjecting to the fog-spraying curing for 24 h, the specimens are then cured in a steam room at 95 °C for another 24 h. Afterwards, the samples are slowly cooled down to room temperature and tested.

2.2.4. Scanning electron microscopy analysis

Scanning electron microscopy (SEM) is employed to study the microstructure of the prefabricated building material (fly ash and O-DCP) and the hardened cement mixture with D-DCP. The hardened specimens are cut into small fragments and soaked in ethanol for more than 7 days in order to stop the hydration of cement. They are then dried and stored in a sealed container before the SEM imaging.

2.2.5. Calorimetry test

The calorimetry test is specially utilized to investigate the addition of D-DCP on the hydration of cement. During the test, about 5% of D-DCP is used to replace cement. The cement and D-DCP are firstly mixed, and then are diluted with deionised water to

Table 3

Recipe of the mixtures for consistency and setting times test.

No.	O-DCP (wt.%)	D-DCP (wt.%)	Cement (wt.%)	Fly ash (wt.%)
P-1	60	0	0	40
P-2	55	0	0	45
P-3	50	0	0	50
P-4	45	0	0	55
P-5	40	0	0	60
P-6	35	0	0	65
A-1	0	0	100	0
A-2	0	5	95	0
A-3	0	10	90	0
A-4	0	15	85	0
A-5	0	20	80	0
A-6	0	25	75	0
A-7	0	30	70	0

Table 4
Recipe of the mixtures for compressive strength test.

No.	O-DCP (wt.%)	D-DCP (wt.%)	Cement (wt.%)	Fly ash (wt.%)	Water/binder ratio	SP (wt.%)
P'-1	25	0	0	75	0.3	0.5
P'-2	30	0	0	70	0.3	0.5
P'-3	35	0	0	65	0.3	0.5
P'-4	40	0	0	60	0.3	0.5
P'-5	45	0	0	55	0.3	0.5
P'-6	50	0	0	50	0.3	0.5
A'-1	0	0	100	0	0.3	0.5
A'-2	0	5	95	0	0.3	0.5
A'-3	0	7.5	92.5	0	0.3	0.5
A'-4	0	10	90	0	0.3	0.5
A'-5	0	12.5	87.5	0	0.3	0.5
A'-6	0	15	85	0	0.3	0.5

bring the total water/binder mass ratio to 0.3. About 0.5% super-plasticizer is utilized to adjust the workability of the cementitious paste. After mixing for 2 min, the paste is injected into a sealed glass ampoule, which is then placed into the isothermal calorimeter (TAM Air, Thermometric). The instrument is set to a temperature of 20 °C. After 7 days, the measurement is stopped and the data are exported and analysed.

3. Experimental results and discussion

3.1. Prefabricated building material based on O-DCP

3.1.1. Required water for normal consistency and setting times

The required water for normal consistency of the fly ash/O-DCP system as a function of the fly ash amount is illustrated in Fig. 1. It is clear that the increasing amount of fly ash can linearly decrease the required water of the fly ash/O-DCP system to reach the normal consistency. For instance, when 40% fly ash is utilized, the required water to binder ratio for normal consistency of the fly ash/O-DCP system is about 0.50, which then sharply decrease to around 0.35 after 65% of fly ash is added. Hence, with the addition of fly ash, the water absorption capacity of O-DCP can be restricted, which is beneficial for the application of the RCWCM. Moreover, Fig. 2 shows the initial and final setting times of the fly ash/O-DCP system with normal consistency. It is clear that the initial and final setting times of fly ash/O-DCP system can be increased with the addition of fly ash. When around 65% of fly ash is used in the mixture, its initial and final setting times are about 92 and 179 min, which are already similarly to that of Portland cement.

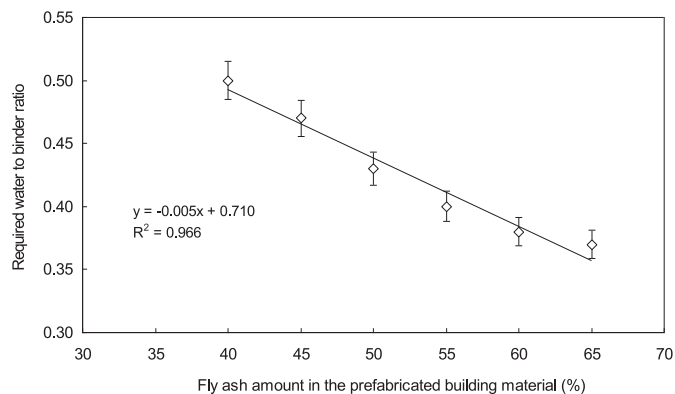


Fig. 1. Variation of the required water for normal consistency of the prefabricated building material mixture as function of fly ash amount.

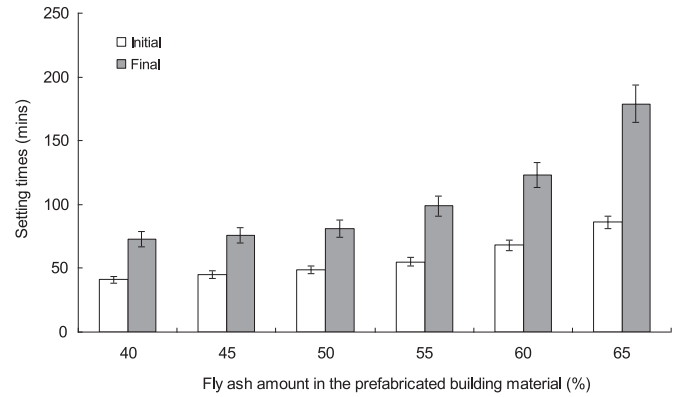


Fig. 2. Setting times of the prefabricated building material with different fly ash amount.

3.1.2. Compressive strength

The variation of compressive strength of the prefabricated samples as a function of the fly ash amount in the mixtures is presented in Fig. 3. When the fly ash amount increases from 50 to 55%, the compressive strength of fly ash/O-DCP system slightly increases. Afterwards, with a further enhancement of the fly ash amount, the compressive strength of fly ash/O-DCP system sharply decreases. From the obtained results in this study, when the fly ash amount is around 55% in the composite, the maximum compressive strength of the prefabricated building material can be obtained (61 MPa). This phenomenon should be attributed to the amount of reaction products generated in the fly ash/O-DCP system (Davidovits, 1982; Poon et al., 2001). When total amount of active CaO and SiO₂ from the raw materials (DCP and fly ash) can fit each other well, more reaction products can be generated and the mechanical properties of the prefabricated building material can be better. In this study, the experimental results show that when the mass ratio of fly ash and O-DCP is around 21/19, the largest compressive strength of the prefabricated building material can be obtained. However, due to the fact that the amount of active CaO and SiO₂ in fly ash is influenced by the production process, which means the optimal ratio of fly ash/O-DCP should be recalculated when the raw material is changed.

3.1.3. Microstructure development

Fig. 4 illustrates the morphological microstructure of the prefabricated samples with different fly ash amount. It is evident that there is quite a morphological difference in the microstructure

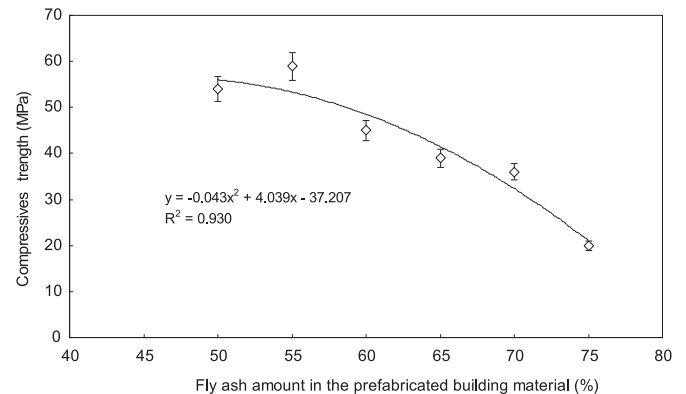


Fig. 3. Variation of the compressive strength of the prefabricated building material with the increase of the fly ash amount.

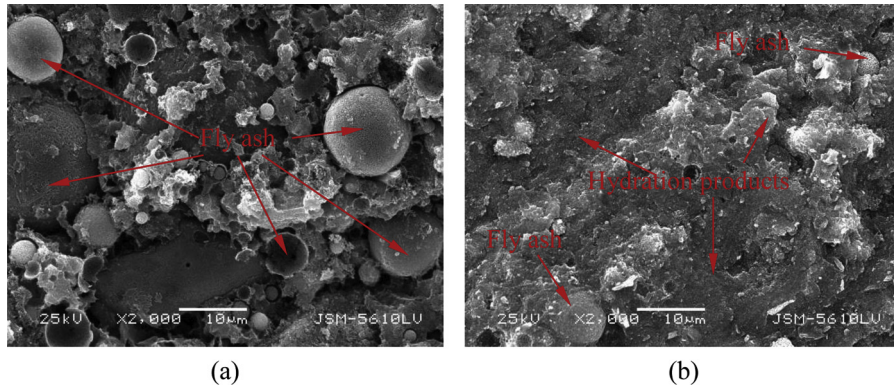


Fig. 4. SEM Micrographs of the prefabricated building material with different amount of fly ash: (a) fly ash content is about 75%; (b) fly ash content is about 55%.

between those two samples. As shown in Fig. 4a, the sample is porous, and many integrated fly ash particles can be easily found. Moreover, the bonding between unreacted fly ash and the generated reaction products is relatively loose. Nevertheless, from Fig. 4b, a large amount of hydration products can be observed and the fly ash particles can seldom be found. Furthermore, the matrix of the prefabricated sample is dense, which imply that its mechanical properties are relatively good.

Hence, the obtained results demonstrate that it is possible to produce a prefabricated building material with an industry by-product (fly ash) and a recycled waste material (O-DCP).

However, to obtain high strength prefabricated building material, the proportions of active CaO and SiO₂ should be focused.

3.2. High performance cement additive based on D-DCP

3.2.1. Required water for normal consistency and setting times

The variation of the required water for normal consistency of cement as function of D-DCP amount is shown in Fig. 5. It is clear that the addition of D-DCP causes the linearly increase of the required water of cement pastes to reach the normal consistency. However, when only around 5% of D-DCP is added, the required

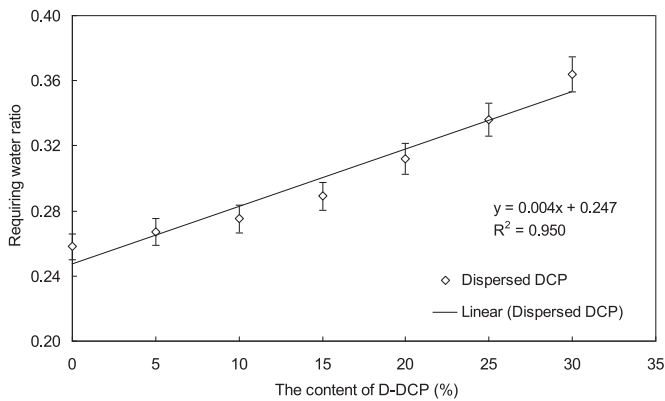


Fig. 5. Variation of the required water for normal consistency of cement as function of additional D-DCP amount.

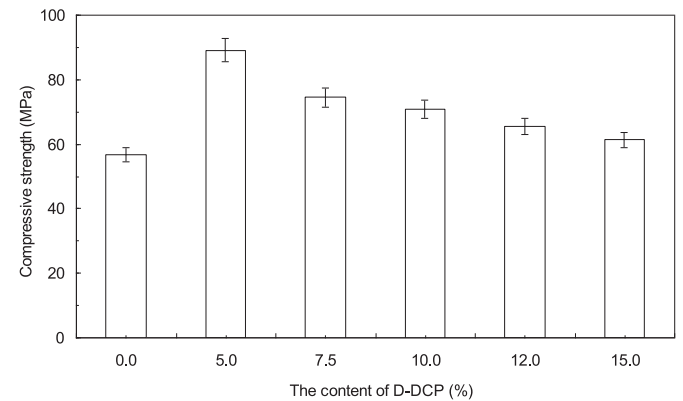


Fig. 7. Compressive strength of cement with different amount of D-DCP at 28 days.

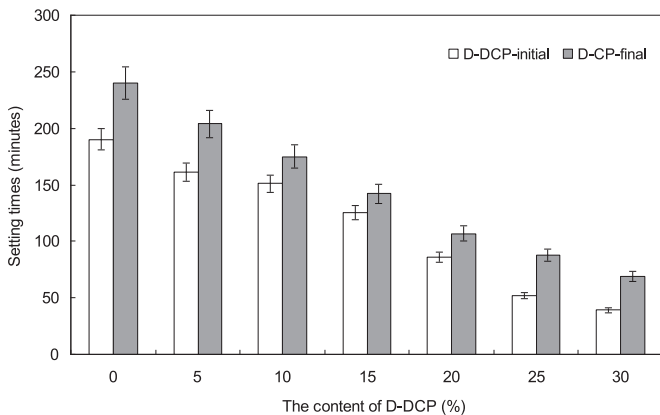


Fig. 6. Setting times of cement with different amount of D-DCP.

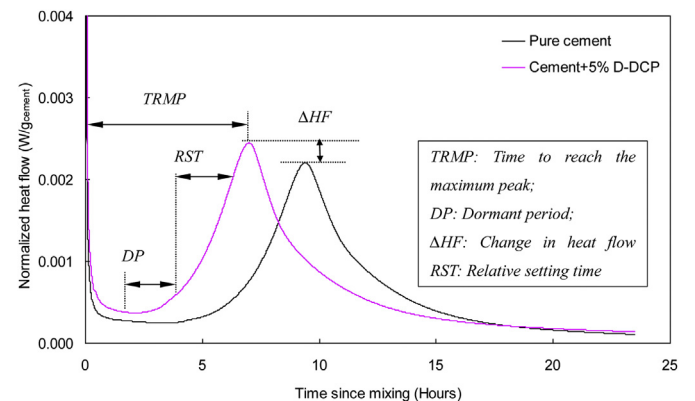


Fig. 8. Isothermal calorimetry test results of cement with and without D-DCP.

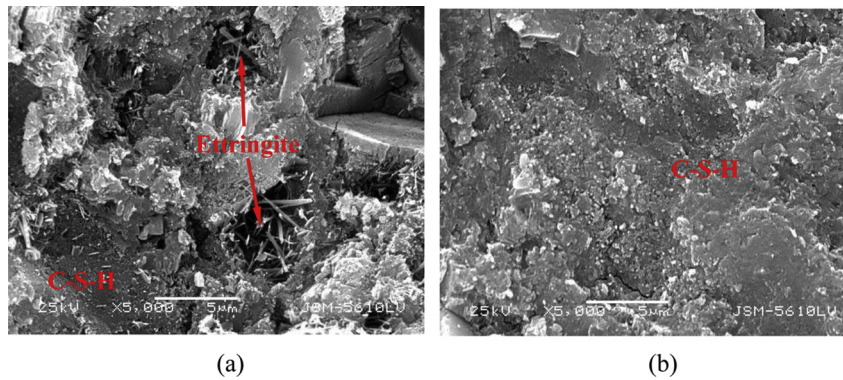


Fig. 9. SEM micrographs of the samples at 28 days: (a) pure cement, (b) cement with 5% of D-DCP.

water for normal consistency is close to that of pure cement (0.258). Fig. 6 presents the initial and final setting times of the cement paste with D-DCP at the normal consistency. As can be seen, with the increase of D-DCP amount, the setting times of cement gradually decrease. However, the paste with about 5% of D-DCP has similar setting times as that of pure cement. Hence, it can be summarized that when the additional amount of D-DCP is about 5%, the required water for normal consistency and setting times of the cement are slightly influenced.

3.2.2. Compressive strength

The compressive strength (at 28 days) of cement with different amount of D-DCP is illustrated in Fig. 7. Note that, compared to the pure cement (56.2 MPa), the addition of D-DCP can significantly enhance the compressive strength of cement (89.1 MPa). Moreover, the tendency of the strength development is firstly increases, and then decreases after reaching an optimal amount of the D-DCP. The phenomenon should be attributed to the fine particles effect of D-DCP, which can promote the cement hydration and improve the microstructure of hardened cement. Nevertheless, when excessive D-DCP is added, the cement amount is simultaneously reduced, which can cause a reduction of the compressive strength. Therefore, there is optimal amount of D-DCP, at which the positive and negative influence of D-DCP can be well balanced.

3.2.3. Hydration process

In this study, the isothermal calorimetry results (Fig. 8) are utilized to analyse the effect of D-DCP on the hydration of cement. Compared to the pure cement, it is clear to see that with the addition of D-DCP, the dormant period (calculated as the time between the lower point of the heat flow curve and the first inflection point in the main peak), the relative setting time (calculated as the time between the first and the second inflection point in the heat flow curve), as well as the time to reach the maximum hydration peak of the cementitious system is significantly reduced, while that the height of the early rate peak is obviously increased. Hence, it is demonstrated that the addition of D-DCP can significantly promote the hydration of cement, which implies that the hydration degree of cement can be enhanced and the microstructure of hardened cement can be denser.

3.2.4. Microstructure development

The SEM micrographs of pure cement and cement with 5% D-DCP (at 28 days) are presented in Fig. 9. As shown in Fig. 9a, one can see ettringite with its needle-like shape and foil-like C-S-H gel. Due to the structural net effect of C-S-H gel, the ettringite distributes into C-S-H gel as fibre modification, which cause that the microstructure of the hardened cement paste is relatively loose

and heterogeneous. Fig. 9b shows the SEM micrograph of the hardened cement with 5% of D-DCP, in which the ettringite is difficult to be found, and a large amount of the cotton-shaped C-S-H gels can be observed. Moreover, compared to the microstructure of pure cement, the microstructure of the cementitious system with 5% D-DCP is denser and more homogeneous.

Consequently, based on the results shown in Figs. 7–9, it is proved that the D-DCP can be treated as a type of high performance cement additive, which can significantly promote the hydration and microstructure development of cement. With the addition of the D-DCP (about wt. 5%), the compressive strength of cement can be enhanced by more than 50% at 28 days. Therefore, if the D-DCP is applied in the production of concrete structure, the efficiency of cement can be improved and the cement consumption in the whole structures will be significantly reduced, which simultaneously decrease the CO₂ emission.

4. Conclusions

This paper addresses the efficiently reuse of the recycled construction waste cementitious materials (RCWCM). After a series of treatments, the O-DCP and D-DCP are firstly produced from RCWCM. Afterwards, the obtained DCPs are utilized to produce prefabricated building material and high performance cement additive. The obtained results show that the O-DCP can effectively activate fly ash and produce a prefabricated building material with relatively high compressive strength (61 MPa). The proportion of the active CaO and SiO₂ amount in the raw materials is the key factor that controls the mechanical properties of the prefabricated building material. Moreover, the D-DCP can be treated as a high performance cement additive, which can significantly promote the hydration and microstructure development of cement. In this study, a small additional amount of D-DCP (about 5%) can enhance the compressive strength (at 28 days) of cement by more than 50%.

In practice, except from the materials testing laboratories, the RCWCM can also be found and collected from other places. If all of these RCWCM can be well utilized to produce O-DCP or D-DCP, great benefits on the sustainable development of construction industry can be obtained.

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