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Technical note

Influence of dry ice on the performance of Portland cement and its mechanism

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HIGHLIGHTS

- The standard consistency and the setting time of dry ice on Portland cement were studied.
- The dry ice can better improve the compressive strength of Portland cement paste at 28 days.
- The dry ice retards the early hydration of Portland cement and improves the later hydration.
- Results provide a reference for future application of dry ice in Portland cement-based materials.

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ABSTRACT

This study reports on the effect of dry ice on the hydration and hardening behavior of Portland cement. Dry ice was directly added to fresh Portland cement paste, with its dosage fixed at 0 wt%, 0.3 wt%, 0.6 wt %, 0.9 wt%, 1.2 wt% and 1.5 wt%. Results showed that dry ice had little effect on the standard consistency and setting time of cement paste when its dosage was less than 0.9 wt%, but otherwise the standard consistency as well as the setting time was increased. The compressive strength of the paste at 7 days increased slightly when the dosage of dry ice was less than 0.9 wt%, but the compressive strength was reduced with the addition of 0.9 wt% to 1.5 wt% dry ice. For the compressive strength at 28 days, the cement paste with 0.6 wt% dry ice showed the greatest value, being increased by 30.9% compared to the control cement paste, and the compressive strength of the samples with dry ice was all higher than that of the control. In addition, hydration heat, XRD, DTA-TG and SEM results showed that the incorporation of dry ice retarded the early hydration of Portland cement, improved its later hydration, and optimized the hardened structure of the cement paste. These results can provide a reference for the future application of dry ice in Portland cement-based materials.

1. Introduction

In order to reduce environment impact of CO_2, a number of measures have been taken, such as reducing CO_2 emission [1,2] and sequestrating CO_2 by using cementitious materials [3]. However, the construction industry annually consumes 4.3 billion tons of ordinary Portland cement (OPC) for making concrete, resulting in a great amount of CO_2 emission that accounts for around 7% of global CO_2 emissions. To reduce carbon footprint of cement industry, a number of studies focused on developing low-carbon cement [4–7]. In addition, other relevant research has been performed, which included CO_2 curing [8–13], CO_2 strengthening recycled aggregates [14–19], as well as the transformation of carbon dioxide to carbonate as chemical additives [20–22]. X.Y. Pan [11]studied the strength and permeability of CO_2 surface treatment on one-day age of cement mortar. After 24 h of CO_2 treatment, the results showed that the compressive strength was increased slightly, the impermeability of cementing material was improved, while water absorption was reduced by 15–30%. KOU [23] studied the effect of carbonization on recycled aggregates, and their results showed that CO_2 curing increased the physical properties of recycled aggregates: the longer the curing time, the better the degree of carbonation and the higher the quality of aggregate. W. Kunther [24] investigated the effect of bicarbonate ions on the deterioration of mortar bars in sulphate solutions and found that the presence of bicarbonate ions significantly reduced mortar swelling. J.G. Jang [25] studied the effect of sodium bicarbonate on the performance of cement slurry, and they found that the addition of $NaHCO_3$ caused the internal carbonation of cement slurry, resulting in the consumption of $Ca(OH)_2$. Besides, the compressive strength was

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increased with the addition of 5% $NaHCO_3$; however, the strength degraded for higher concentrations. Rodger [26] found that Li_2CO_3 accelerated the early hydration rate of sulphoaluminate cement. Other studies [27–29] found that lithium carbonate significantly shortened the setting time of sulphoaluminate cement, and improved its early compressive strength and flexural strength. Although there have been a number of studies on the influence of CO_2 curing or carbonate salts on hydration and hardening of Portland cement, little research has been carried out on how dry ice, as an alternative form of CO_2, affects the process of Portland cement hydration.

This study investigates the effect of dry ice on the hydration kinetics, compressive strength, chemical compositions, and microstructure of Portland cement paste.

1.1. Raw materials

Ordinary Portland cement 42.5 grade (conforming to Chinese national standard GB175-2007) [30] was used. The main properties and chemical composition of cement were listed in Tables 1 and 2, respectively. Dry ice was crumbled, and its content of carbon dioxide was 99.99%. Tap water was used throughout this study.

1.2. Testing methods

The procedure for preparing cement paste is as follows: First, cement and water were weighed, and then the crumbled dry ice was weighed. To prevent the volatilization of dry ice, cement was immediately added into agitating pan and thereafter dry ice was added. Finally, water was added to the mixture which was first left for stirring at a slow speed for 90 s and then subjected to a fast stirring for 90 s after an interval of 30 s stop.

Standard consistency and setting time of Portland cement were measured according to Chinese National standard GB/T1346-2011 “cement standard consistency water, setting time, stability test method” [31]. Compressive strength was tested by using 40 mm × 40 mm × 40 mm cubic samples after subjected to standard curing for 7 and 28 days.

The exothermal curves were achieved using the Heat conduction calorimetry and SETARAM hydration exothermal analyzer. 500 mg powder was used and the water-to-powder ratio was 1:1. The exothermal curves were recorded continuously for 30 h. X-ray diffraction analysis (XRD) was used to identify the crystalline components of hydration products at different ages. Diffraction patterns were collected between 5° and 70° with a step size of 0.02°. After hydrated cement paste was taken out from the standard curing room at the corresponding age, and its hydration was terminated by anhydrous ethanol. The sample was dried in a vacuum drying oven at 40 °C, and then ground and passed through a 75 μm sieve before it was tested. Jade 5.0 software with the Powder Diffraction File database was employed to elucidate the mineralogy of the samples based on the diffraction patterns. Differential Thermal Analysis (DTA) was carried out under Ar atmosphere using HCT-3 instrument at 10 °C/min up to 800 °C. The samples that were also dried at 40 °C in the vacuum drying oven were used to study the shape and microstructure of the hydration products with 250FEG SEM.

Table 2
Chemical composition of cement/%.

SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	Loss
21.79	63.09	5.36	3.35	2.73	0.34	0.21	0.16

2. Results and discussion

2.1. Performance of cement paste

2.1.1. Standard consistency and setting time

The influence of dry ice on the standard consistency and setting time of cement was studied when dry ice was mixed into the cement at dosages of 0 wt%, 0.3 wt%, 0.6 wt%, 0.9 wt%, 1.2 wt% and 1.5 wt% by the weight of cement, and testing results are shown in Figs. 1 and 2, respectively.

It can be seen from Fig. 1 that the standard consistency first decreases but it then increases as dry ice content increases from

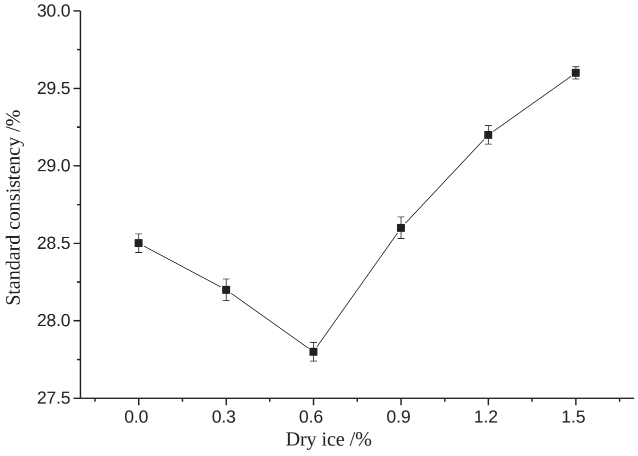


Fig. 1. Effect of dry ice on the standard consistency.

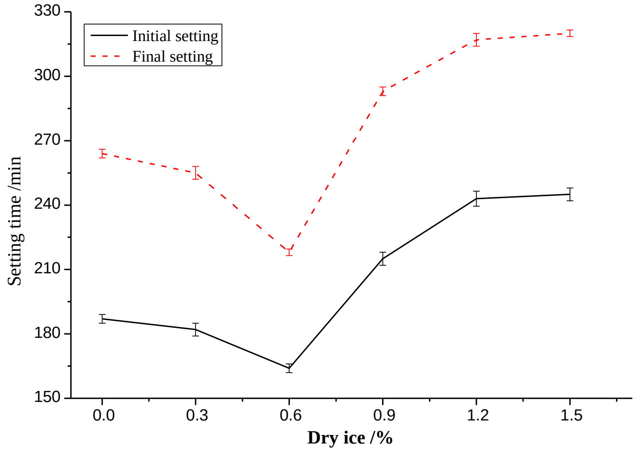


Fig. 2. Effect of dry ice on the setting time.

Table 1
Main properties of P.O42.5.

Cement	Finen-ess/%	Stability	Setting time/min		Flexural strength/ MPa		compressive strength/MPa	
			initial setting	final setting	3d	28d	3d	28d
P.O42.5	1.5	qualified	187	392	5.5	9.6	33.5	50.8

0 wt% to 1.5 wt%. At 0.6 wt%, the standard consistency was amongst the smallest. Compared to the control sample, when the dosage of dry ice was less than 0.9 wt%, dry ice reduced the standard consistency, while when it exceeded 0.9 wt%, dry ice increased the standard consistency. The standard consistency was increased by 3.86% when it went up to 1.5 wt%.

As can be seen from Fig. 2, the effect of dry ice on the setting time of cement was consistent with its effect on the standard consistency. Both the initial setting time and the final setting time first decreased but then increased. When the dry ice dosage was 0.6 wt %, the setting time was the shortest, which means that compared to the control sample, the initial setting time and the final setting time were reduced by 12.3% and 17.4% respectively. When the dosage of dry ice was increased from 0.6 wt% to 0.9 wt%, the setting time had a sharp increase, but when its dosage continued to increase, the increase rate of setting time became slow.

2.1.2. Compressive strength

The effect of dry ice on the compressive strength of hardened cement paste at the ages of 7, 28 days was studied. The water cement ratio was fixed at 0.4. The dosage of dry ice was 0 wt%, 0.3 wt%, 0.6 wt%, 0.9 wt%, 1.2 wt% and 1.5 wt%. The results were plotted in Fig. 3.

As shown in Fig. 3, as the dosage of dry ice increases, the compressive strength of cement paste at 7 days first increased little and then decreased. At the dosage of 0.6 wt%, the compressive strength reached the maximum, being increased by 7.2% compared to the control cement paste. When its dosage exceeded 0.9 wt%, the compressive strength at 7 days decreased. Likewise, as the dosage of dry ice increased, the compressive strength of cement paste at 28 days showed a similar change trend as that of cement paste at 7 days; first increased but then decreased. When the dosage of dry ice was 0.6 wt%, the compressive strength of cement paste reached the maximum value with an increase of 30.9% compared to the control sample. Furthermore, even when the dosage of dry ice was 1.5 wt%, the compressive strength of cement paste at 28 days was higher than that of the control one. These results indicate that dry ice had little effect on the early compressive strength of Portland cement paste, but it was beneficial to the compressive strength at the later stage, especially when the dry ice content was 0.6 wt%, the effect was very obvious.

2.2. Characterization

According to the above analysis, the setting time and compressive strength of Portland cement paste were changed when dry ice was present in the paste, especially for 0.6 wt%~0.9 wt% dry ice. To better understand the mechanism controlling the effect of dry ice on the hydration process of Portland cement, a series of microscopic tests were performed.

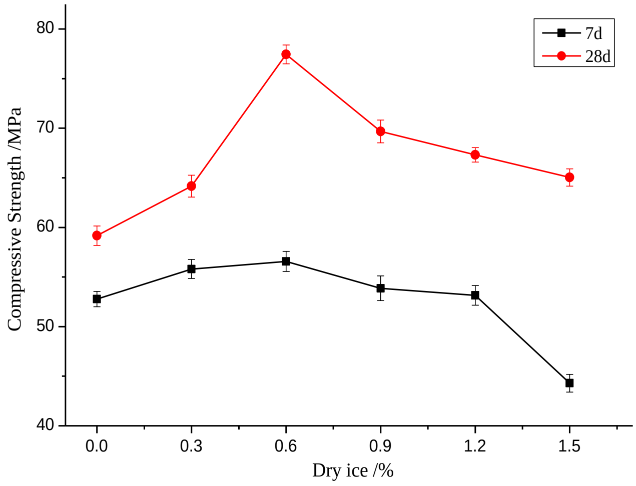


Fig. 3. Effect of dry ice on the compressive strength of cement paste.

2.2.1. Hydration heat test

It can be seen from Fig. 4(a), the value of first peak is 92.452mW, 106.313mW, 119.493mW,122.402mW, 103.880mW and 93.906mW when the content of dry ice increased from 0 wt% to 1.5 wt%, respectively, indicating that with the increase of dry ice content, the value of first exothermic peak increases and then decreases, and the first peak is greater when the content of dry ice is 0.6 wt%–0.9 wt%. The first exothermic peak can be attributed to the formation of ettringite (AFt) [32,33], so the results suggest that dry ice accelerates the early formation of AFt, especially when its content is 0.6 wt%–0.9 wt%, which is also consistent with the results of standard consistency, initial setting time and compressive strength.

It can be seen from Fig. 4(b) that the value of the second peak is 2.564 mW, 2.343 mW, 2.407 mW, 2.389 mW, 2.168 mW and 2.155 mW when the content of dry ice increases from 0 wt% to 1.5 wt%, respectively. The second peak can be assigned to the hydration of tricalcium silicate (C_3S), and the value of second peak gradually reduces as the content of dry ice increases, which indicates that the addition of dry ice may retard the early hydration of C_3S, moreover, the more the content, the more obvious the effect. A peak shoulder appears after almost 17 h behind the second exothermic resulting from the conversion of AFt to calcium monosulfoaluminate (AFm), and the peak shoulder becomes much smaller as the content of dry ice increases. This observation shows that dry ice can prevent the transformation of AFt to AFm to some extent.

When dry ice dissolves in water, the chemical reaction shown in Eq. (1) occurs. The dissolution of dry ice increases the acidity of the solution, which results in an increase of the solubility of gypsum, thus improving the early formation of AFt; however, too much dry ice can cause too much acidity of aqueous solution, which is unfavorable for the early formation of AFt. Accordingly, the hydration heat of AFt shows a trend of decreasing after increasing. Calcium hydroxide will be produced when C_3S hydrates (Eq. (2), and at the same time bicarbonate radical (HCO_3^-) and calcium ion (Ca^{2+}) (Eq. (3) are generated. As the hydration of C_3S continues, the increasing amount of $Ca(OH)_2$ will result in generation of calcium carbonate (Eq. (4) that could cover the surface of C_3S. Both the increment of Ca^{2+} and the cover of $CaCO_3$ retard the early hydration of C_3S. It can be seen in Fig. 4 that the generation peak of C-S-H and $Ca(OH)_2$ gradually reduces as the dosage of dry age increases. At the same time, $CaCO_3$ can react with hydrated calcium aluminate (CAH) to form hydrated calcium carboaluminate ($C_3A{\cdot}CaCO_3{\cdot}11H_2O$), which could prevent AFt transforming into AFm [33]. This result is consistent with the results of the third exothermic peak.

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+ \tag{1}$$

$$C_3S + nH_2O \rightarrow xC-S-H + (3-x)Ca(OH)_2 \tag{2}$$

$$HCO_3^- + H^+ + Ca^{2+} + OH^- \rightarrow HCO_3^- + Ca^{2+} + H_2O \tag{3}$$

$$HCO_3^- + Ca^{2+} + OH^- \rightarrow CaCO_3 \downarrow + H_2O \tag{4}$$

2.2.2. DTA results

DTA-TG is used to investigate the effect of dry ice on cement hydration products. The results are shown in Fig. 5. From Fig. 5, we can see that DTA-TG mainly includes three endothermic peaks

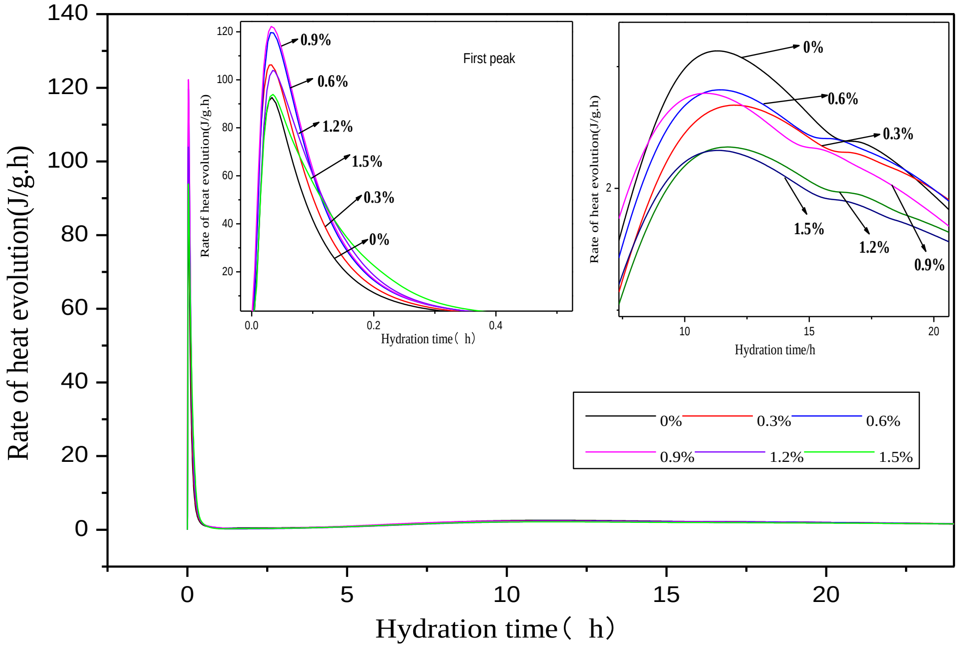
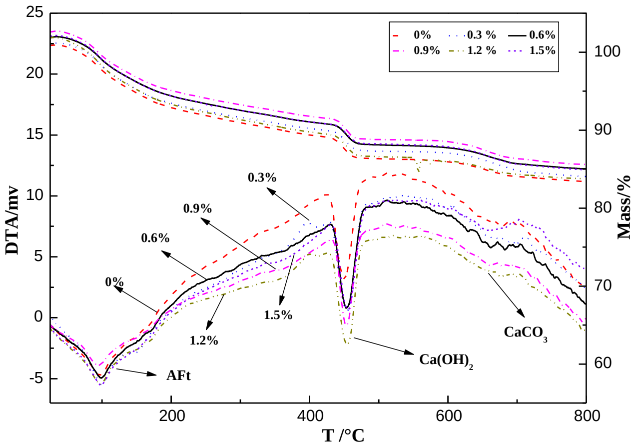
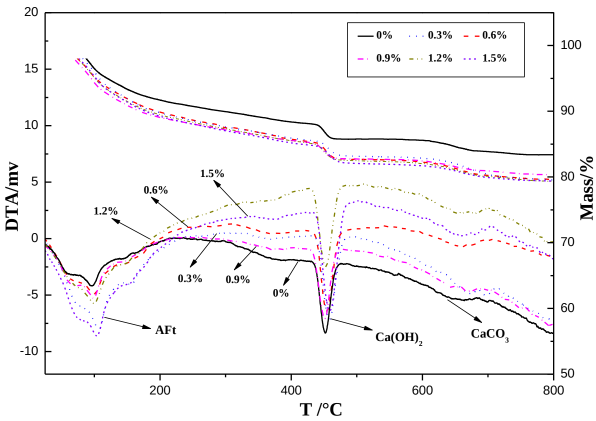


Fig. 4. Hydration heat release curve.

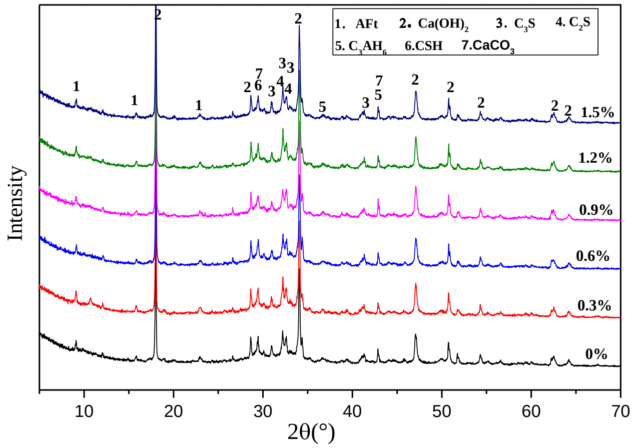


a. 7d

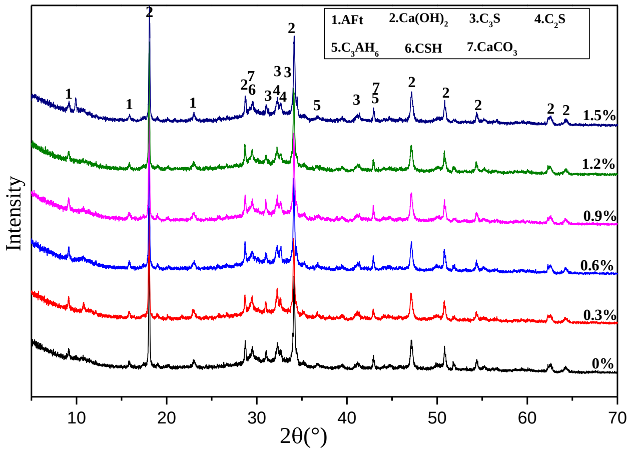


b. 28d

Fig. 5. DTA-TG diagram of the effect of dry ice on cement hydration.



a. 7d

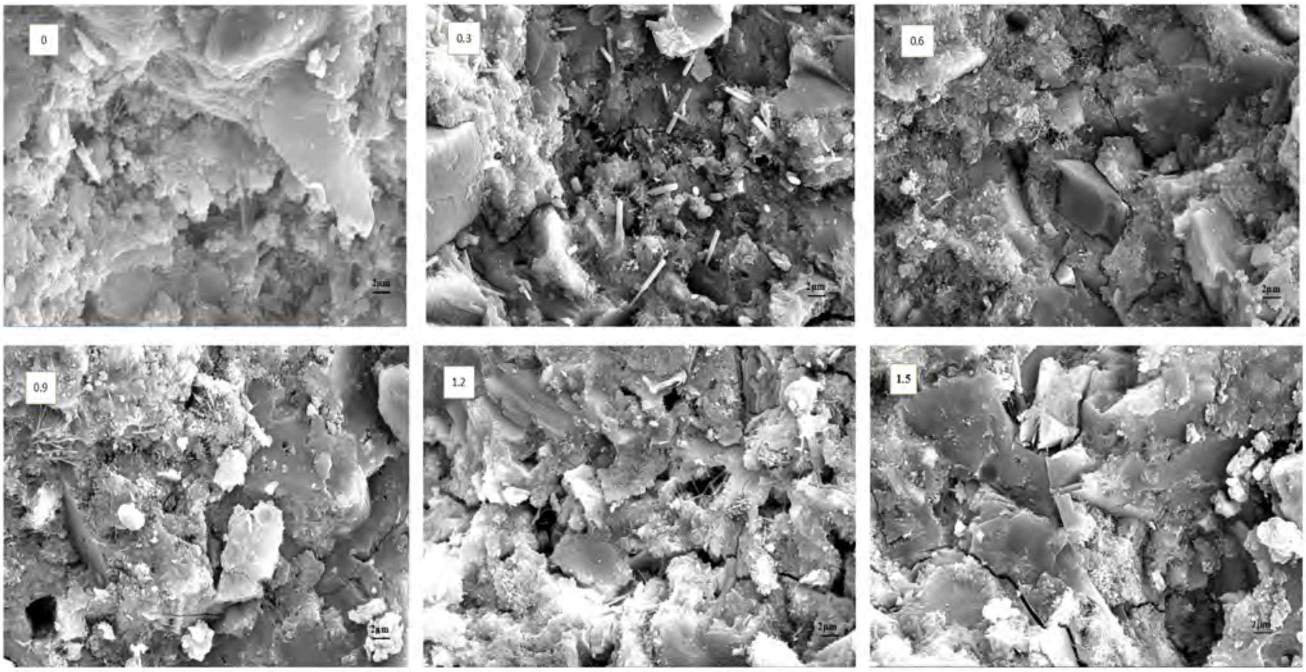


b. 28 d

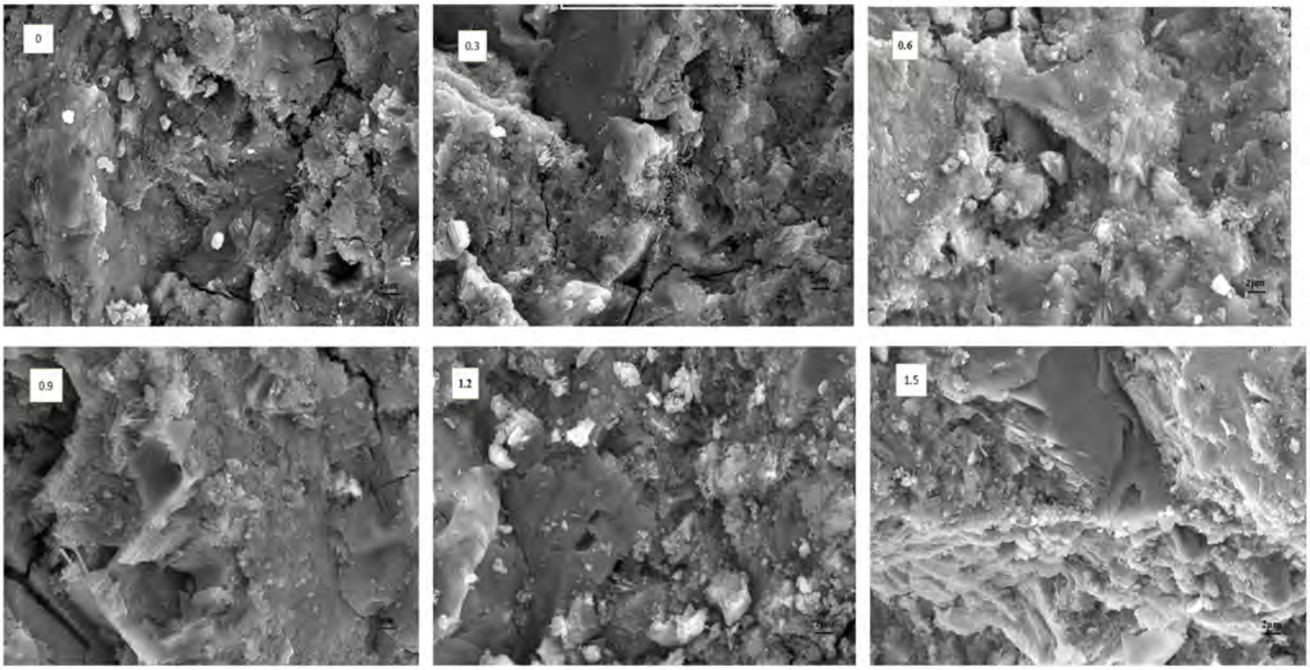
Fig. 6. XRD patterns of hydrated samples at 7 and 28 days.

at 110 °C, 460 °C and 650 °C. Compared with DTA-TG atlas, it can be seen that the endothermic peak of AFt is at 110 °C, the endothermic peak at 460 °C is attributed to $Ca(OH)_2$, and the endothermic peak at 650 °C is assigned to $CaCO_3$.

It can be seen from Fig. 5(a) at 7 days that at 110 °C –130 °C the sequence of weight loss rate of AFt is 2.411%, 2.347%, 2.268%, 2.191%, 2.144%, and 1.866%, when the dosage of dry age is 0.3 wt%, 0 wt%, 1.2 wt%, 1.5 wt%, 0.6 wt%, and 0.9 wt%, respectively, which shows that dry ice reduces the early amount of AFt, except 0.3 wt%; the sequence of weight loss rate of $Ca(OH)_2$ is 8.61%, 8.546%, 8.551%, 8.248%, 8.164%, and 7.649% showing a decrease trend when the dosage of dry age is 0.3 wt%, 1.2 wt%, 1.5 wt%, 0 wt%, 0.6 wt%, and 0.9 wt%, respectively, which shows that dry ice improves the early hydration of C_3S when its dosage is 0.3 wt%, 1.2 wt%, and 1.5 wt%, compared to the control sample. As can be seen from Fig. 5(b) at 28 days that at 110 °C –130 °C the sequence of weight loss rate of AFt is 3.866%, 3.656%, 3.205%, 3.053%, 2.44%, and 2.298% from big to small when the dosage of dry age is 1.5 wt%, 0.3 wt%, 1.2 wt%, 0.9 wt%, 0.6 wt%, and 0 wt%, respectively, which shows that dry ice enhances the amount of AFt at late ages; the sequence of weight loss rate of $Ca(OH)_2$ is 9.49%, 7.346%, 7.181%, 7.15%, 6.195%, and 5.897% from big to small when the dosage of dry age is 1.5 wt%, 0.3 wt%, 1.2 wt%, 0.6 wt%, 0.9 wt%, and 0 wt%, respectively, which shows that dry ice



a. 7d



b. 28d

Fig. 7. SEM images of cement paste with different dry ice content at 7 and 28 days.

improves the hydration of C_3S at 28 days compared to the control sample. In addition, the peak of $CaCO_3$ at 650 °C is less obvious, indicating that the influence of dry ice on generation of $CaCO_3$ can be negligible at the given dosage.

Based on the analysis, at the early age, dry ice restricts the early hydration of Portland cement, and generally, the greater its dosage, the more obvious the inhibiting effect, which agrees with the results of compressive strength of cement paste at 7 days. As the age increases, the hydration products of cement paste with dry ice gradually increases, resulting in higher compressive strength of the cement paste with dry ice compared to the control sample.

2.2.3. XRD results

The influence of dry ice on the cement hydration products were studied by XRD when the dosage of dry ice was 0 wt%, 0.3 wt%, 0.6 wt%, 0.9 wt%, 1.2 wt% and 1.5 wt%, and the results are shown in Fig. 6.

Fig. 6 shows the diffraction peaks of AFt, $Ca(OH)_2$, C-S-H, $CaCO_3$ and C_3AH_6 that are the hydrated as well as unhydrated C_3S and C_2S of cement pastes at the age of 7 and 28 days. As can be seen from Fig. 6(a), the incorporation of dry ice does not cause significant changes to the XRD peaks of the aforementioned hydration products, indicating that at 7 days, the effect of dry ice on the product of cement hydration process cannot be characterized by XRD, which is consistent with the slight change in the strength of hydrated sample at 7 days. However, as shown in Fig. 6(b), the diffraction peak ($2\theta \approx 9°$) of hydrated product AFt at 28 days increases with the increase of dry ice content. The diffraction peak of $Ca(OH)_2$ also increases with the increase of dry ice content, which indicates that the incorporation of dry ice improves the hydration of Portland cement at 28 days.

2.2.4. SEM results

SEM characterization was used to compare the effects of dry ice on the morphology and microstructure of hardened cement pastes, and the results are displayed in Fig. 7.

It can be seen in Fig. 7(a) that for cement paste at 7 days, the addition of dry ice changes the morphology of AFt. A typical example is that the morphology of AFt changes from needle-like to rod-like shape when the dosage of dry ice is 0.3 wt%, and AFt crystals interconnect with each other to be like dendrites when it is 0.9 wt%. The hardened cement pastes at the dry ice dosage of 0.6 wt%, 0.3 wt%, 0.9 wt%, 0 wt% are much denser than those at the dry ice dosage of 1.2 wt% and 1.5 wt%, which corresponds to the compressive strength at 7 days.

It can be seen in Fig. 7(b) that the structure of hardened pastes at 28 days becomes more compact compared to that of pastes at 7 days. Furthermore, the hardened pastes with dry ice are denser that those without dry ice, which can be seen clearly from the SEM image of paste with 0.6 wt% dry ice. It can be concluded that dry ice can change the hydration process of Portland cement and optimize the structure of hydrated paste.

3. Conclusions

Dry ice was incorporated at 0 wt%, 0.3 wt%, 0.6 wt%, 0.9 wt%, 1.2 wt%, and 1.5 wt% by weight of Portland cement, the effect of dry ice on the standard consistency, setting time, compressive strength, hydration-hardening process and product of Portland cement were studied. Main conclusions are as follows:

(1) With the increase of dry ice content, the standard consistency of Portland cement first decreases but then increases, reaching its smallest value at 0.6 wt%. Similarly, with the increase of dry ice dosage, the patterns of the initial and final setting are similar to that of standard consistency. When the dosage of dry ice is 0.6 wt%, the setting time is at its lowest value: the initial setting time decreases by 12.3%, and the final setting time reduces by 17.4% compared to the control cement paste.

(2) The influence of dry ice on compressive strength at 7 days is subtle when its dosage is less than 0.9 wt%, and the compressive strength at 28 days drops notably when its dosage is more than 0.9 wt%. With the increase of dry ice content, the compressive strength of cement paste at 28 days first increases and then decreases. Compared to the control sample, the compressive strength at 28 days increases by 30.9% when its dosage is 0.6 wt%, and the compressive strength of the cement pastes at the given dosage of dry ice is higher than that of the control sample.

(3) The results of hydration heat analysis, XRD, and DTA-TG show that the incorporation of dry ice has a retarding effect on the early hydration of Portland cement, however, dry ice improves its later hydration. The SEM results of show that dry ice could change the morphology of AFt and optimize the hardened structure of cement paste.

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References

[1] F. Golzar, M. Astaneh, R. Roshandel, et al., Reducing CO_2 emission from exhaust gases using molten carbonate fuel cells: a new approach, Int. J. Ambient Energy 37 (4) (2014) 331–340.

[2] N. Zugravu-Soilita, K. Millock, G. Duchene, The factors behind CO_2 emission reduction in transition economies, Social Sci. Electron. Publishing 75 (2008.58) (2008) 461.

[3] Y.L. Gao, L. Cheng, Study on CO_2 sequestration property of cement based composite cementitious materials containing steel slag used in road, Adv. Mater. Res. 311–313 (2011) 1949–1952.

[4] Z. Cao, L. Shen, J. Zhao, et al., Modeling the dynamic mechanism between cement CO_2 emissions and clinker quality to realize low-carbon cement, Resour. Conserv. Recycl. 113 (113) (2016) 116–126.

[5] J.L. Vizcaíno, S.S. Berriel, S.D. Carrera, et al., Industrial trial to produce a low clinker, low carbon cement, Mater. Constr. 65 (317) (2015).

[6] A. Maldonado-Alameda, A.M. Lacasta, J. Giro-Paloma, et al., Magnesium phosphate cements formulated with low grade magnesium oxide incorporating phase change materials for thermal energy storage, Constr. Build. Mater. 155 (2017) 209–216.

[7] L.F. Cabeza, C. Barreneche, L. Mir Oacute, et al., Low carbon and low embodied energy materials in buildings: a review, Renew. Sustain. Energy Rev. 23 (2013) 536–542.

[8] C. Shi, Q. Zou, F. He, Study on CO_2 curing kinetics of concrete, J. Chin. Ceram. Soc. 38 (7) (2010) 1179–1184.

[9] W.A. Klemm, R.L. Berger, Accelerated curing of cementitious systems by carbon dioxide : Part I. Portland cement, Cem. Concr. Res. 2 (5) (1972) 567–576.

[10] S. Ahmad, R.A. Assaggaf, M. Maslehuddin, et al., Effects of carbonation pressure and duration on strength evolution of concrete subjected to accelerated carbonation curing, Constr. Build. Mater. 136 (2017) 565–573.

[11] X. Pan, C. Shi, X. Hu, et al., Effects of CO_2 surface treatment on strength and permeability of one-day-aged cement mortar, Constr. Build. Mater. 154 (2017) 1087–1095.

[12] S. Monkman, Y. Shao, Carbonation curing of slag-cement concrete for binding CO_2 and improving performance, J. Mater. Civ. Eng. 22 (4) (2010) 296–304.

[13] P. He, C. Shi, Z. Tu, et al., Effect of further water curing on compressive strength and microstructure of CO_2-cured concrete, Cem. Concr. Compos. 72 (2016) 80–88.

[14] B. Johannesson, P. Utgenannt, Microstructural changes caused by carbonation of cement mortar, Cem. Concr. Res. 31 (6) (2001) 925–931.

[15] B.J. Zhan, D.X. Xuan, S.P. Chi, et al., Effect of curing parameters on CO_2 curing of concrete blocks containing recycled aggregates, Cem. Concr. Compos. 71 (2016) 122–130.

[16] G. Pan, M. Zhan, M. Fu, et al., Effect of CO_2 curing on demolition recycled fine aggregates enhanced by calcium hydroxide pre-soaking, Constr. Build. Mater. 154 (2017) 810–818.

[17] J. Zhang, C. Shi, Y. Li, et al., Performance enhancement of recycled concrete aggregates through carbonation, J. Mater. Civ. Eng. (2015) 27(11).

[18] V.W.Y. Tam, A. Butera, K.N. Le, Carbon-conditioned recycled aggregate in concrete production, J. Cleaner Prod. 133 (2016) 672–680.

[19] B. Zhan, C. Poon, C. Shi, CO_2 curing for improving the properties of concrete blocks containing recycled aggregates, Cem. Concr. Compos. 42 (9) (2013) 1–8.

[20] Y. Zhang, Y. Wang, T. Li, et al., Effects of lithium carbonate on performances of sulphoaluminate cement-based dual liquid high water material and its mechanisms, Constr. Build. Mater. 161 (2018) 374–380.

[21] J. Camiletti, A.M. Soliman, M.L. Nehdi, Effect of nano-$CaCO_3$ on early-age properties of ultra high-performance concrete, Mag. Concr. Res. 65 (5) (2013) 297–307.

[22] K. Yang, C. Zhang, Z. Liu, The influence of calcium lignosulphonate–sodium bicarbonate on the status of ettringite crystallization in fly ash cement paste, Cem. Concr. Res. 32 (1) (2002) 51–56.

[23] S.C. Kou, B.J. Zhan, C.S. Poon, Use of a CO_2 curing step to improve the properties of concrete prepared with recycled aggregates, Cem. Concr. Compos. 45 (1) (2014) 22–28.

[24] W. Kunther, B. Lothenbach, K. Scrivener, Influence of bicarbonate ions on the deterioration of mortar bars in sulfate solutions, Cem. Concr. Res. 44 (1) (2013) 77–86.

[25] J.G. Jang, H.J. Kim, S.M. Park, et al., The influence of sodium hydrogen carbonate on the hydration of cement, Constr. Build. Mater. 94 (4) (2015) 746–749.

[26] S.A. Rodger, D.D. Double, The chemistry of hydration of high alumina cement in the presence of accelerating and retarding admixtures, Cem. Concr. Res. 14 (1) (1984) 73–82.

[27] X. Li, X. Shen, J. Xu, et al., Hydration properties of the alite–ye'elimite cement clinker synthesized by reformation, Constr. Build. Mater. 99 (2015) 254–259.

[28] B. Jewell, K. Mahboub, T. Robl, et al., Interfacial bond between reinforcing fibers and calcium sulfoaluminate cements: fiber pullout characteristics, ACI Mater. J. 112 (1) (2015) 39–48.

[29] M. García-Maté, A.G.D.L. Torre, L. León-Reina, et al., Effect of calcium sulfate source on the hydration of calcium sulfoaluminate eco-cement, Cem. Concr. Compos. 55 (2015) 53–61.

[30] GB175-2007, Common Portland Cement.

[31] GB/T1346-2011, Test Methods for Water Requirement of Normal Consistency, Setting Time and Soundness of the Portland Cement.

[32] J. Bensted, P. Barnes, Structure & Performance of Cements, The Taylor & Francis e-Library, London and New York, 2008. 90-91.

[33] Z. Xiong, P. Wang, Y. Wang, Hydration behaviors of portland cement with different lithologic stone powders, Int. J. Concr. Struct. Mater. 9 (1) (2015) 55–60.