Deformation and mechanical properties of the expansive cements produced by inter-grinding cement clinker and MgOs with various reactivities

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Abstract

Magnesia (MgO) either intrinsically contained in cement clinker or prepared separately as expansive additive has been used to compensate for the shrinkage of cementitious materials. In this study, for improving the homogenous distribution of MgOs, the cement clinker was inter-ground with MgO expansive additives with various reactivities ranging from 50s to 400s to prepare series of expansive Portland cements and blended cements with incorporation of slag and fly ash. The deformations and mechanical properties of the expansive cements were...
investigated. Results showed that the expansive cements containing more reactive MgOs produced more rapid expansion under sealed condition or water curing, leading to effective autogenous shrinkage compensations at early age. The reactivities of MgOs caused insignificant influences on the mechanical strengths of expansive cements. The blended cements had lower strengths at early age but higher strengths than that of the corresponding Portland cements at late age due to the pozzolanic reaction.

Keywords: MgO; mechanical strength; autogenous shrinkage; expansion

1 Introduction

Normally cementitious materials undergo various types of shrinkage, such as autogenous shrinkage, drying shrinkage, thermal shrinkage, etc. When restrained, the shrinkage may cause large enough tensile stress to crack the cementitious materials, and thus negatively affect the mechanical performance and durability of the materials. Therefore, to mitigate the shrinkage is of great importance for maintaining the long-term durability and safety of the cementitious materials and relevant structures. Accordingly much work has been focused on this issue and many strategies have been developed, e.g. development of novel curing technology, fiber
application, utilisation of supplementary cementing materials (SCMs), shrinkage compensation, etc. [1-5].

Expansion produced due to the hydration of expansive components contained in cement clinker, such as calcium sulfo-aluminate, free calcium and periclase, has been widely used to compensate for the shrinkage of the cementitious materials, based on which some types of expansive cement were developed [6-8]. Furthermore, to well control the quantity and quality of the expansive components, they were prepared separately from the manufacturing of cement clinker and used as expansive additives [6-8]. Due to the fast hydration of CaO and the relatively high solubility of its hydration product Ca(OH)$_2$, the application of CaO-based expansive additive in normal concrete, particularly in the concrete for hydraulic structures under deep water, was limited. The ettringite-based expansive additive can produce rapid expansion at early age, mainly within 14 days, which has been widely used [7]. However there are some challenges existing. The formation of ettringite consumes a large amount of water, which may intensify the competition on the consumption of water with the hydration of cement clinker [7]. Therefore in concrete with low w/c ratio or in the absence of sufficient exterior water supply, the formation of ettringite may be insufficient to produce enough expansion expected for the complete compensation of shrinkage. In addition, the ettringite is chemically unstable when it undergoes a process with a temperature higher than 70 °C, and thus might not be used in mass concrete with high temperature rise [9].
Free magnesia (MgO), known as periclase intrinsically contained in cement clinker, was used to compensate for the thermal shrinkage at late age in mass dam concrete during the cooling stage in China as the expansion produced by the periclase was very slow owing to its slow hydration rate [6]. Owing to the advantages of MgO used as the expansive additive, e.g. the relatively low water consumption for its transformation into brucite, and the chemical stability and low solubility of the brucite, it has attracted increasing attention [6]. The hydration and the corresponding expansion property of MgO depend on its hydration reactivity associated with its microstructure, which is influenced by the high temperature history during its calcination process [10]. MgO with higher reactivity may produce more rapid expansion at early age [10]. Accordingly, this could be used for the compensation of autogenous shrinkage at early age. Mo et al. [11] demonstrated the effective compensating effects of MgO-based expansive additive on the autogenous shrinkage of cement paste starting at 24h after casting, but the autogenous shrinkage within 24h was not collected due to the limit of strain gauge used. Nevertheless the autogenous shrinkage of cementitious materials starting from the initial setting time is very dramatic at the early age, particularly within the first several hours after the setting time, due to the low shrinkage resistance of the cement matrix, and thus it could not be ignored [12-13]. In fact, some amounts of reactive MgO may hydrate within 24h after being mixed with water owing to its high hydration reactivity, and thus may have some potential to be used for compensating the autogenous shrinkage at very early age. However limited work has been
Two ways are usually taken to apply the MgO in reducing the shrinkage of cementitious materials. One is to increase the periclase contents in cement clinker during the clinker manufacturing process, which is called high magnesia cement and has been used for approximately 40 years in China but mainly in dam concrete [6]. In this case, the MgO was dead-burnt at the clinker temperature of 1450°C, and moreover the content of MgO was limited to be less than 5% by mass in order to avoid the potentially triggered unsoundness problem [6,14]. Therefore the expansion property of the magnesia cement could not be adjusted flexibly according to the practical engineering demands. Another way is to prepare MgO separately through calcining magnesite at given temperature and then mix the MgO into concrete directly as an expansive additive [6]. In terms of expansive additive, the expansion property as well as the addition dosage of MgO can be well controlled. However, it is important to ensure the homogenous distributions of MgO in concrete materials, which always needs special mixing process, i.e. prolonging the mixing time. Otherwise, the heterogeneous expansion might be caused and even lead to destruction of concrete materials.

With the increasing demands on sustainability of cement materials, SCMs have been widely used to prepare blended cement or directly mixed into concrete as partial substitutions of
Portland cement [15]. Due to the relatively slow development of strength at early age for the blended cement, it may be more susceptible to shrinkage cracking. For this case, the prevention of shrinkage at early age is of great importance. The influences of SCMs on the autogenous shrinkage of cementitious materials depend on their pozzolanic reactivity as well as particle size [16-18]. SCMs with high pozzolanic reactivity, e.g. ground slag and silica fume, were reported to increase the autogenous shrinkage [17, 19], while the relatively inert materials, for example the fly ash, was proved to reduce the autogenous shrinkage [18]. Combination of the reactive and inert SCMs may produce the synergetic effects on the performance of blended cement, obtaining high strength and meanwhile stable volume. Incorporation of MgO may also contribute to the volume stability of the blended cement, but this needs to be investigated further, particularly in the ternary blended cement system.

This paper presents part work of our current research project that aims to develop expansive cements containing MgOs with various reactivities and SCMs. In this study, four types of MgO-bearing expansive cement were prepared by inter-grinding the cement clinker and MgO expansive additive with different hydration reactivities. The blended cements were also prepared by mixing the expansive cements with the ground granular blast furnace slag (GGBFS) and fly ash. The effects of MgOs with various reactivities on the autogenous shrinkage at early age under sealed condition, the long term expansion properties with sufficient water supply, and the mechanical strengths of the expansive Portland cement (PC) as well as blended cement
were investigated. This study provides a guide for preparing series of expansive cement with various expansion properties by using proper type of MgO.

2 Experimental

2.1 Raw materials and preparation of expansive cements

Cement clinker provided by the Conch Cement Company, Jiangsu, China was used. Four types of MgO expansive additive with four different reactivity values of 50s, 100s, 200s, and 400s tested according to the citric acid neutralization method [10] were used, which were designated as $M_{50}$, $M_{100}$, $M_{200}$ and $M_{400}$ respectively. The $M_{50}$, $M_{100}$, $M_{200}$ and $M_{400}$ contained MgO contents ranging from 88.52% to 90.27% (Table 1), and had specific surface areas of 22.2, 15.1, 18.7 and 7.1 m$^2$/kg respectively tested by N$_2$ adsorption (BET). The cement clinker was inter-ground with 8% MgO expansive additive by mass as the substitutions of the cement clinker and 5% gypsum by mass in a ball mill for 90 minutes to prepare expansive PCs. The four types of expansive cements prepared with the $M_{50}$, $M_{100}$, $M_{200}$, and $M_{400}$ were designated as PCM$_{50}$, PCM$_{100}$, PCM$_{200}$ and PCM$_{400}$ respectively. The particle size distributions of all the cements are shown in Fig. 1. In order to investigate the expansion behaviour of MgOs and its implication...
on the performance of the blended cement system, the blended cements were prepared by mixing the expansive PCs with 40% GGBFS and 20% fly ash as the cement replacements. According to the research results in our current project, it was showed that the blended cement with that mix proportion exhibited excellent mechanical strengths at long term. These blended cements made with the expansive PCs of PCM\textsubscript{50}, PCM\textsubscript{100}, PCM\textsubscript{200} and PCM\textsubscript{400} were represented by BCM\textsubscript{50}, BCM\textsubscript{100}, BCM\textsubscript{200} and BCM\textsubscript{400} respectively. The GGBFS was supplied by the Bao Steel Company in Shanghai, and fly ash was from Huaneng Power Plant in Nanjing, China. The particle size distributions of the GGBFS and fly ash are shown in Fig. 1. Table 1 presents the chemical compositions of the PC clinker, slag, fly ash and MgO expansive additives.

2.2 Mechanical strength test

To investigate the mechanical properties of cements, one part of cement was mixed with three parts of sands by weight at a water to binder ratio of 0.5 to obtain homogenous mixtures, and then the mixtures were cast into mould to prepare mortar specimens with size of 40mm×40mm×160mm. All the mortar specimens were cured under moist condition with a relative humidity of 98% and a temperature of 20±2°C. After 24±2h curing, all the specimens were demoulded and continuously stored under the moist condition until the strength test at the age
of 3d, 28d and 90d respectively. According to the ASTM C349 [20], the flexural strength of
the mortar specimen was tested first, and then the two portions of the fractured specimen after
the flexural test were used for examining the compressive strength. For each test, a mean
flexural strength value of three mortar specimens was used, and the compressive strength was
averaged on six mortar portions.

2.3 Deformation examination

The autogenous deformations of cement pastes were investigated according to the ASTM
specification C1698-09 “Standard test method for autogenous strain of cement paste and mortar”
[21] but with minor changes. For each type of cement, it was mixed with water at the same w/c
ratio of 0.38 to obtain a homogeneous fresh mixture. Thereafter the cement mixture was cast
into corrugated low-density polyethylene cylindrical mould with an outer diameter of 28.5mm
and a length of 440 mm. Two ends of the corrugated mould were sealed with two end plugs
and thus the moist exchange between the cement paste and exterior environment was avoided.
Immediately after the sealing, the corrugated cement pastes were then placed into the plastic
tube with a larger diameter of 38mm and very smooth inner wall, which produced minimal
friction on the free linear movement of the corrugated specimen undergoing volume
deformation. To precisely measure the linear deformation of cement paste, one end of the
corrugated mould was fixed on the table, and thus only another end of the specimen was able
to move freely. The intelligent laser optical displacement measurement (MICRO-EPSILON)
with a resolution of 0.1 μm was used to collect the displacement of the free end of specimen
for up to 120h. The whole preparing process of cement specimen was finished within 20
minutes, and then the autogenous deformation of the cement specimen can be recorded
immediately. The autogenous deformation of the cement paste was initialized at the initial
setting time. Fig. 2 shows the setup used for the autogenous shrinkage measurement. For each
mix, three duplicate corrugated cement specimens were prepared and measured, and the
average deformation of the three duplicate specimens was calculated.

In order to investigate the deformation behaviour of MgOs in cement pastes with sufficient
water curing for a long term, the expansive cement pastes were prepared and cured in water for
up to 240d. For each mix, ten cement paste specimens with size of 20mm × 20mm × 80mm
were prepared at a water-to-binder ratio of 0.38. The cement pastes were demoulded after being
cured under the moist condition for 24 ± 2h, and then the initial lengths of the cement pastes
were measured. Thereafter, half of the cement pastes were stored in water with a temperature
of 20 ± 2°C and another half of the cement pastes were cured in 38 ± 2°C water. After different
time intervals, the length changes of the cement pastes were measured. For each test, a mean
value of the five duplicate cement pastes was used.
The morphology of the hydrated MgO contained in the cement paste was investigated by using a FEI Nova NanoSEM 450 coupled with Bruker Energy Dispersive X-ray (EDX). In addition, the cement pastes were sliced, dried, epoxy impregnated, polished and then investigated with backscattered electronic microscopy.

3 Results and Discussion

3.1 Mechanical strength

Fig. 3 shows the mechanical strengths of the cement mortars. As shown in Fig. 3(a), the incorporation of MgO expansive additive had very slight influences on the flexural strength regardless of its reactivity and the curing age. At 3d the flexural strengths of PC, PCM_{50}, PCM_{100}, PCM_{200} and PCM_{400} were 6.8, 6.6, 6.6, 7.2 and 6.6 MPa respectively. With the curing age increasing to 28d, the flexural strengths of PC, PCM_{50}, PCM_{100}, PCM_{200} and PCM_{400} were
increased to be 8.6, 8.0, 8.4, 8.2 and 8.4 MPa respectively, and at 90d the strengths were very close to that at 28d. In terms of the compressive strengths, similar increase trend was observed. The incorporation of 8% MgO expansive additive caused slight reductions in the compressive strengths of the cement mortars, particularly at late age. For example, the compressive strengths of PCM$_{50}$ were 34.4, 45.7 and 49.9 MPa at 3d, 28d and 90d respectively, which were lower than that of the conventional PC mortars at the same ages. However the less the reactive MgO expansive additive had, the slightly less the reduction in compressive strengths was caused. The decreases in the mechanical strengths may attribute to the content reduction of PC due to the substitution of MgO expansive additive, which thus resulted in the decrease of cement hydration products.

In comparison to the expansive PCs, the flexural strengths as well as the compressive strengths of the blended cements containing 40% GGBFS and 20% fly ash were significantly reduced at 3d. For example the flexural strengths at 3d were 3.8, 3.4, 3.5, 3.2 MPa for BCM$_{50}$, BCM$_{100}$, BCM$_{200}$, and BCM$_{400}$ respectively, being less than that of the corresponding expansive PC mortars. This is related to the reduction of PC content in the blended cements due to the replacements of cement with GGBFS and fly ash. However, after 28d of curing the flexural and compressive strengths of the blended cement mortars were dramatically increased, being very close to that of the corresponding expansive PC mortars. At 90d, the compressive strengths of the blended cement mortars increased further, being slightly higher than that of the
corresponding expansive PC mortars and the conventional PC mortars. According to the above
results, it is obvious that the reactivity of MgO expansive additive caused insignificant
influences on the mechanical strengths in the cements during the test age in this study.

3.2 Deformation behaviour

Fig. 4 shows the autogenous deformations of the cement pastes. For all the cement pastes,
regardless of the incorporation of MgO, GGBFS and fly ash, the cement pastes underwent rapid
and dramatic shrinkage at early age particularly within the first 3-10h, and then the deformation
curves of the cement pastes reached inflexion points, starting from where the deformation
changed at much lower rate. For example, for the reference cement paste PC, an inflexion point
on the shrinkage curve occurred at approximately 8h, and thereafter the shrinkage curve
continued to decline but at a lower and relatively constant rate to reach -1000 microstrains at
the end of test. With the incorporation of MgO, the autogenous shrinkages of the cement pastes
were largely reduced, and moreover the time for inflexion points appearing as well as the
ultimate deformations of the cement pastes were changed accordingly. Cement pastes
containing more reactive MgO showed inflexion points on their deformation curves at earlier
ages and exhibited less ultimate shrinkages by the end of test. The ultimate autogenous
shrinkages of PCM$_{50}$, PCM$_{100}$, PCM$_{200}$ and PCM$_{400}$ were -180, -600, -620, and -780
microstrains respectively during this test age. Although the incorporation of MgO had not
completely compensated for the whole shrinkage, it reduced the shrinking rate after the
inflexion point as well as the ultimate shrinkage by the end of the test. This is attributed to the
hydration of MgO and the consequently caused shrinkage compensation. This indicates that
the MgO with higher reactivity compensated for more autogenous shrinkage of cement paste
at early age. For instance, PCM_{50} reached the first inflexion point at around 2h with shrinkage
of -107 microstrains, and thereafter the curves climbed up until 20h and then declined again to
reach the shrinkage of -180 microstrains at the end of test.

For the blended cement pastes, with the incorporation of GGBFS and fly ash, the shrinkages
were much less than that of the corresponding expansive PC pastes. This is related to that less
cement contents were used in these blended cements. Moreover, as the water-to-binder ratio
was the same, the replacement of PC with the GGBFS and fly ash contributed a dilute effect,
which therefore provided more water in the sealed cement pastes and thus facilitated the
hydration of MgO as well as the accordingly shrinkage compensating. As shown in Fig. 4, the
cement paste BCM_{50} shrank quickly in the first several hours and reached the maximum
shrinkage of -76 microstrains but thereafter the deformation curve climbed up, implying some
expansion was caused due to the hydration of MgO. By the end of test, the cement paste BCM_{50}
showed gentle expansion, being 220 microstrains. Similarly the deformation curves of BCM_{100},
BCM_{200} and BCM_{400} went up after their corresponding inflexion points, indicating the
expansion produced due to the hydration of MgO was larger than the shrinkage caused by the cement hydration in the mean time. However the time for the inflexion points occurring on the curves were different. The lower the reactivity of MgO expansive additive had, the longer the time was needed for the inflexion points to occur. For example, the deformation curves of BCM$_{50}$, BCM$_{100}$, BCM$_{200}$, and BCM$_{400}$ started to climb up around 9h, 22h, 34h, and 34h respectively.

Fig. 5 shows the deformations of cement pastes cured in water at 20°C and 38°C. As shown in Fig. 5(a), all the cement pastes expanded. The cement paste PCM$_{50}$ expanded more rapidly and reached an expansion of 0.19% at the age of 70d and then expanded at lower rate, and eventually ceased around 0.22% at 120d. For the cement pastes containing less reactive MgO, after 70d, their expansion curves kept going up but at lower rate until the end of test at 240d. PCM$_{400}$ exhibited smaller expansion at early age compared to other cement pastes, but after 150d the expansion of PCM$_{400}$ was slightly higher than that of PCM$_{100}$ and PCM$_{200}$. At the age of 240d the expansions of PCM$_{100}$, PCM$_{200}$ and PCM$_{400}$ were 0.195%, 0.195% and 0.21% respectively, and all these cement pastes still showed slight increase trend and therefore were supposed to expand further. In the blended cement, the expansions produced were smaller than that generated in the corresponding PC pastes. This is understandable as in the blended cement system, only 40% expansive PC was used and as a result the corresponding MgO contents were reduced accordingly. Dissimilar to the expansive PC pastes, the blended cement paste prepared
with the most reactive MgO (BCM_{50}) showed the smallest expansion, being 0.075% at 70d. This may due to the more amount of MgO in the M_{50} had been hydrated within 24h but the accordingly caused expansion was not recorded during this test. The blended cement pastes BCM_{100}, BCM_{200}, and BCM_{400} showed similar expansions, and slight expansion trend was also observed at the late age.

When cured in 38°C water, due to the increased curing temperature, more rapid expansions were caused in the expansive PC pastes as well as the blended cement pastes. This relates to that the hydration of MgO was accelerated at the elevated temperature. As shown in Fig. 5(b), all the expansive cement pastes expanded fast within 70d, and then the expansion curves gradually leveled off. It is interesting that the PCM_{50} with the highest reactivity exhibited the smallest ultimate expansion, which was 0.20% at 70d. It was less than that of the PCM_{100}, PCM_{200}, and PCM_{400}, which were 0.24%, 0.26%, and 0.26% respectively. The expansions of the blended cement pastes were much less than that of the corresponding expansive PC pastes. Particularly for the blended cement pastes, the BCM_{50} produced the smallest expansion, being around 0.04%. Comparison between the expansion properties of the cement pastes cured in 20°C and 38°C water, it indicates that the curing temperature had more significant influences on the expansion of cement pastes containing MgO with lower reactivity. For instance, the expansions of PCM_{50} cured in 20°C and 38°C at 240d were 0.22% and 0.20% respectively, while that of the PCM_{400} were 0.17% and 0.25% respectively. This is consistent with the results in previous
studies, which showed that higher curing temperatures resulted in more rapid and larger expansion of MgO [14] and particularly influenced more strongly on the expansion of less reactive MgO [22].

3.3 Morphology of the hydrated MgO in cement paste

Fig. 6 shows the typical SEM morphology of the hydrated M₅₀ in the cement paste. As shown in Fig. 6(a), a small particle of MgO circled by white dash elliptic line was surrounded by the cement hydration products. Closer investigation shows that the dense inner hydration products agglomerated together and however it is quite difficult to identify very clearly the individual brucite crystals (Fig. 6(b)). Fig. 6(c) shows the SEM image of M₄₀₀ contained in the cement paste, the M₄₀₀ was also surrounded by the cement hydration products. At high magnification of ×10000, many sheet like brucites were observed, and all the brucite agglomerated tightly and some of the inner pores were not filled up. As reported in the previous studies, the reactive MgO has smaller inner pores while the less reactive MgO has larger inner pores which was more difficult to be filled up due to the localized formation of brucite [10]. Fig. 7 shows the typical BSE image of the blended cement paste. Accordingly there are obvious pozzolanic reaction rims formed around the coarse GGBFS particles and some tiny particles of GGBFS were hydrated completely.
For the expansive cements containing MgO, the total deformation of cement paste depended on the competitive effects between the volume shrinkage produced due to the hydration of cement as well as SCMs and the expansion generated by the hydration of MgO. At given curing age, when the expansion produced in cement matrix due to the hydration of MgO was larger than the shrinkage induced by cement hydration in the meantime, the overall deformation would be expansion and thus the deformation curves went up, and vise versa. MgO with low reactivity reacted relatively slowly and correspondingly produced insufficient expansion to completely compensate the shrinkage caused in the meantime. At early age, owing to the low resistance of cement matrix, the autogenous shrinkage of cement paste is dramatic [12]. Therefore in order to compensate for the autogenous shrinkage at early age, reactive MgO should be used as it hydrates relatively fast to produce enough expansion. Accordingly the reactivity of MgO had strong influence on compensating for the autogenous shrinkage particularly at early age.

Although the water consumption for MgO hydration is relative low, being 0.45, there is still
an competition on water consumption between the hydration of cement and MgO, particularly under the sealed condition during the autogenous shrinkage test. For the blended cements, as the pozzolanic reaction at early age was ignorable due to its extremely slow hydration process, more water was provided for the hydration of cement clinker and MgO. This facilitated the hydration of MgO and the corresponding compensation effects. In addition, only 40% PC was used in the blended cement, which reduced the hydration products of cement, and accordingly reduced the autogenous shrinkage. Thus the blended cement pastes showed less autogenous shrinkages than the PC pastes. For example, PCM$_{50}$ showed autogenous shrinkage whereas the BCM$_{50}$ produced gentle expansion in stead of shrinkage. Cured in water, with the sufficient water supply for the hydration of MgO, expansions were produced for all the cement pastes regardless of the hydration reactivity of MgO. The expansions caused by MgO expansive additives with various reactivities between 100s and 400s were very similar. This may relate to the fine particles and homogenous distributions of MgOs. During the intergrinding process, the MgO particles were ground into small particles (as shown in Fig. 6) and homogenously distributed in the cement. This leaded to less expansion paricularly for the less reactive MgO [14, 23].

Curing temperature had influences on the expansion properties of the expansive cement pastes. This is related to the hydration process of MgO, the elevated temperature accelerated the hydration of MgO and therefore speeded up the expansion process. Besides the expansion rate,
the temperature affected the ultimate expansion of the cement paste. The less reactive MgO may produce more ultimate expansion. This may because, as reported by Chatterji [24], the MgO hydrated faster and produced more Mg\(^{2+}\) near the surface of MgO in a short time at higher temperatures, which results in larger supersaturations and thus increased crystal growth pressure.

The incorporation of 8% MgO expansive additive reduced slightly the flexural strengths and compressive strengths, which is mainly due to the reduction of cement content in the mortars. In the blended cement pastes, the pozzolanic reaction of GGBFS as well as fly ash contributed to the strength increase. This is related to not only the densification as a result of pozzolanic reaction but also the enhanced interface between the SCMs and the cement hydration products [25]. According to this study, the expansive PC could be mixed with SCMs to prepare blended cements with non-shrinkage and meanwhile maintained high mechanical strengths. In addition, not only the hydration reactivity of MgO but also the mixed contents of MgO as well as SCMs will influence the expansion behavior and mechanical strengths of cements, which are also being investigated in our study.

4 Conclusions
Expansive cements were prepared by inter-grinding the cement clinker and MgOs with different reactivities. The influence of the reactivity of MgO on the deformation behaviour including the autogenous shrinkage at very early age as well as the long-term expansion property with sufficient water supply, mechanical performance, and the microstructure of the expansive cement were investigated. Main conclusions can be drawn as follows:

(i) In comparison to the conventional PC, by incorporating with MgO, the autogenous shrinkage of expansive PC paste at early age could be effectively compensated for. The higher reactivity the MgO had, the more the autogenous shrinkage of cement paste was reduced. This is due to that the reactive MgO hydrated more rapidly and thus produced more expansion at early age to offset the shrinkage of cement paste.

(ii) With the addition of GGBFS and fly ash, the autogenous shrinkages of the blended cement pastes were much less than the corresponding expansive PCs. This may not only attribute to the replacement of PC with the SCMs but also relate to the compensation effect of MgO. In the blended cement system under the sealed condition, more water was supplied owing to the dilution effects of SCMs, and thus facilitated the hydration of MgO and produced more expansion to compensate for the autogenous shrinkage accordingly. For example, PCM$_{50}$ exhibited an autogenous shrinkage of -180 microstrains while BCM$_{50}$ showed an expansion of 220 microstrains at the end of test (115h).

(iii) Under moist curing condition, with sufficient supply of water, all the expansive cements regardless of the incorporation of SCMs produced obvious expansions. By curing in 20℃
water, MgO with a high reactivity value of 50s reached an ultimate expansion at age of around 90d, whereas the cement pastes containing less reactive MgOs still showed gentle expansion trend by the end of test in this study. However, at higher temperature of 38℃, all the cement pastes expanded more rapidly and the expansion curves ceased at around 90d. Accordingly the elevated temperature accelerated the hydration of MgO effectively and thus the expansion ceased at earlier time.

(iv) Incorporation of 8% MgO expansive additive reduced slightly the mechanical strengths of cement mortars. The blended cement pastes had lower strengths than that of the corresponding expansive PCs at early age of 3d, but at late ages of 28d and 90d the mechanical strengths of the blended cement mortars were higher than that of the corresponding expansive PC mortars as well as that of the conventional PC mortars. The reactivity of MgO showed insignificant influences on the strengths of cement mortars.

According to the results in this study, series of expansive cement could be prepared with MgOs of various reactivities. The expansion behaviour could be adjusted by changing not only the reactivities of MgOs but also the incorporation contents. This is now being further studied in our research.

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References


Table 1 Chemical compositions of PC clinker, GGBFS, fly ash and MgO expansive additive
Table 1 - Chemical compositions of PC clinker, GGBFS, fly ash and MgO expansive additive

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<th>Type</th>
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Figures

Fig. 1 Particle size distributions of PCs, GGBFS and fly ash
Fig. 2 Setup for the autogenous shrinkage measurement
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strength

Fig. 4 Autogenous deformations of the cement pastes

Fig. 5 Expansions of the cement pastes cured in water: (a) 20°C and (b) 38°C

Fig. 6 Typical SEM morphology of the hydrated MgOs with different reactivities: (a) M_{80} in PCM_{80} (38°C, 90d), (b) closer observation at Zone A in (a) at higher magnification of ×10000, (c) M_{400} in PCM_{400} (38°C, 90d), and (d) closer observation at Zone A in (c) at higher magnification of ×10000

Fig. 7 Typical BSEM of the hydrated blended cement pastes (BCM_{400}, cured in 38°C water, 90d)