

1 Deformation and mechanical properties of quaternary blended cements containing ground  
2 granulated blast furnace slag, fly ash and magnesia

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13 Abstract

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16 Shrinkages of cementitious materials may lead to cracking under restrained conditions. This study  
17 was motivated to develop non-shrinkage quaternary blended cements through blending slag and  
18 fly ash with Portland cement containing reactive MgO. The hydration process, autogenous  
19 shrinkage at early age, long-term volume deformation, mechanical properties, and microstructure  
20 of cement specimens were investigated. Results showed that the autogenous shrinkage of the  
21 cement pastes was effectively mitigated due to the compensation of the MgO present and the

22 reduction of cement content owing to the partial replacements with slag and fly ash. The  
23 mechanical strengths of the blended cement mortars were lower than that of the corresponding  
24 plain Portland cement mortars at early age of 3d, but increased significantly to be similar or  
25 higher at late ages of 28d and 90d. This is attributed to the microstructure densification and the  
26 interface microstructure enhancement due to the reaction of SCMs with clinker phases.

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29 Keywords: A Calorimetry; B Microstructure; C Mechanical Properties; C Shrinkage; D Blended  
30 Cement

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33 1. Introduction

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36 Cement-based materials normally undergo various types of volumetric shrinkage, such as  
37 autogenous shrinkage, drying shrinkage, thermal shrinkage, to name a few. Under restrained  
38 conditions, the volumetric shrinkage could induce tensile stress and may in turn lead to cracking.

39 Autogenous shrinkage, which is caused by the self-desiccation of cement materials [1], normally  
40 contributes significantly to the total shrinkage occurring at early age when the cement materials  
41 are still of low strength and therefore have a high risk of shrinkage cracking. Many strategies  
42 have been developed to mitigate this autogenous shrinkage, e.g. inner curing, substitutions of

43 Portland cement (PC) with supplementary cementitious materials (SCMs) [2-5].

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46 Expansion provided by the hydration of expansive components, e.g. calcium aluminate ( $C_3A$ ),  
47 calcium sulfate aluminate (CSA), calcium oxide (CaO), and magnesia (MgO), was also widely  
48 used to compensate for the shrinkage of cement-based materials [6-8]. For decades, delayed  
49 expansive cement containing MgO was used in China for compensating the thermal shrinkage of  
50 mass dam concrete, in which the MgO was normally formed as dead burnt periclase at high  
51 calcining temperature of up to  $1450^\circ C$  [6]. However, hydration of the dead burnt periclase is very  
52 slow, and hence has no effect on compensating the shrinkage of concrete at early age. Moreover,  
53 the content of MgO in PC was limited to avoid unsoundness [6, 8]. To control the MgO content  
54 and reactivity, the MgO was separately prepared and used as expansive additive in the cement. In  
55 recent years, increasing attentions were attracted on the hydration and expansion properties of  
56 MgO with relatively high reactivity as it has important potential application in normal concrete  
57 [6]. However, much of this research focused on the expansion properties of MgO in cement-based  
58 materials cured in water, while limited work was carried out on their effects on compensating the  
59 autogenous shrinkage at very early age.

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62 With increasing emphasis on sustainability, SCMs have been widely used as replacements of PC  
63 to prepare blended cements [9-14]. The influence of SCMs on the shrinkage and mechanical

64 strengths of cement materials depends on the replacement levels and the pozzolanic reactivity of  
65 the SCMs used [15-21]. It is conceivable that the combined incorporation of SCMs with low and  
66 high reactivity at the same time, e.g. slag and fly ash, in a blended cement system may give rise to  
67 synergetic effects on the properties of blended cement materials, such as improving the  
68 mechanical strength [22-23], resisting sulfate attack and suppressing ASR [24-26].

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71 For the blended cements with high substitution levels of SCMs, the strength at early age may be  
72 low and develop slowly, thus it may have low resistance to the tensile stress generated by  
73 autogenous shrinkage. Therefore it is of great importance to mitigate the autogenous shrinkage of  
74 such blended cements at early age. The present study was motivated to develop quaternary  
75 blended cements with stable volume as well as high mechanical strength via mixing the expansive  
76 PC, containing relatively reactive MgO-base expansive agent (MEA), with slag and fly ash. The  
77 hydration behaviour, deformations under sealed condition (autogenous deformation) starting at  
78 early age and under moist curing conditions for long-term, mechanical strength, and  
79 microstructures of the blended cement mortars were investigated. Moreover, the implications of  
80 SCMs as well as MgO on the mechanical strengths and deformation behaviour of the blended  
81 cements were analysed. The research will provide a new approach to preparing non-shrinkage  
82 blended cement that may have important application potential.

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## 85 2 Experimental

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### 87 2.1 Raw materials and preparation of blended cements

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90 Cement clinker, provided by the Conch Cement Company, Jiangsu, China, was used. Two types  
91 of SCMs, namely slag and fly ash, were used for preparing the blended cements. The slag was  
92 supplied by the Bao Steel Company in Shanghai and class I fly ash according to the fly ash code  
93 in China [27] was from Huaneng Power Plant in Nanjing, China. The MEA had a specific surface  
94 area of  $22.2 \text{ m}^2/\text{kg}$  and a reactivity value of 50s according to the citric acid test [28]. Table 1  
95 presents the chemical compositions of the cement clinker, slag, fly ash and MEA. The  
96 conventional PC was prepared by inter-grinding the cement with 5% of gypsum by mass in a ball  
97 mill. In addition, two types of expansive PC were prepared, in which 5% and 8% of the MEA by  
98 mass were added as replacements of the cement clinker during the inter-grinding process, which  
99 are designated as EPCI and EPCII respectively. The particle size distributions (PSD) of the  
100 processed three types of PC, slag, and fly ash were measured with a Marlven Mastersizer 2000  
101 particle size analyzer by dispersing the particles in alcohol, which are shown in Fig. 1. The PSD  
102 of cement plays an important role in the performance of cement-based materials, particularly at  
103 early age [29]. As reported by Zhang et al. [30], finer cement with a coarser fly ash improved the  
104 early-age strength and also maintained a good performance at later age in blended cement  
105 mixtures.

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108 For the preparation of quaternary blended cements, three types of PC were replaced partially with  
109 slag and fly ash and then inter-mixed together in a powder mixer. Two levels of slag, 20% and  
110 40%, as well as two levels of fly ash, 20% and 35%, by mass were used as the substitutions of  
111 EPCII to prepare the blended cements. For comparison, another two blended cements containing  
112 40% of slag and 20% of fly ash as replacements of the PC and EPCI were also prepared. The mix  
113 proportions of these blended cements are shown in Table 2. The mixes in this study were  
114 designated as follows: the letters S and F stand for slag and fly ash respectively, e.g. mix  
115 PC-S40F20 represents the blended cement containing 40% slag and 20% fly ash as replacements  
116 of PC.

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## 119 2.2 Test procedure

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### 122 2.2.1 Isothermal calorimetry

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125 The hydration heat release of PC and the blended cements within the first 72h was measured, on  
126 4g samples, immediately after mixing with water at a water-to-binder (w/b) ratio of 0.38 by using

127 a Tam Air Calorimeter following the external mixing procedure (Method B) described in ASTM  
128 C1702-09 [31]. The cement was placed in a calorimeter specimen tube, and then the water was  
129 injected into the tube by using a syringe with an attached needle penetrating the dry cement  
130 powder. Consequently the tube was agitated by hand to distribute the water evenly throughout the  
131 cement powder.

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#### 134 2.2.2 Deformation measurement

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137 For each cement formulation, it was mixed with water at the same w/b ratio of 0.38 in a cement  
138 paste mixer (Type NJ-160A, Shanghai Luheng Co. Ltd, China.). The cement and water were  
139 mixed firstly for 120s with a mixing blade rotation speed of 140 rpm and then for another 120s at  
140 a high blade rotation speed of 285 rpm to obtain a homogenous fresh cement mixture. Thereafter  
141 the cement mixture was cast into corrugated low-density polythene molds with an outer diameter  
142 of 28.5mm and a length of 440 mm according to the experimental procedure described in  
143 reference [32]. Two ends of the corrugated polythene molds were sealed with two plugs to avoid  
144 any moist exchange between the cement paste and the exterior environment. Immediately after  
145 the sealing, the corrugated cement specimens were placed into plastic tubes with larger diameter  
146 of 38mm and very smooth inner wall, which resulted in minimal friction on the free linear  
147 movement of corrugated specimens as a result of volume deformation. To precisely measure the

148 linear deformation of the cement pastes, one end of the corrugated mold was fixed on the table,  
149 and thus only the other end of the specimen was able to move freely. The laser optical  
150 displacement measurer supplied by MICRO-EPSILON with a resolution of 0.1  $\mu\text{m}$  was used to  
151 measure the displacement of the end of the corrugated cement specimen after being placed into  
152 the plastic tube. The whole preparation process of the corrugated cement specimens including  
153 mixing with water, casting, sealing, and placing in the plastic tubes was finished within 20  
154 minutes, and thereafter the deformation of the cement specimens could be recorded immediately.  
155 The autogenous deformation was initialized at the initial setting time. For each mix, three  
156 corrugated cement specimens were prepared and measured. The mean deformation value of the  
157 three specimens was used, and the corresponding coefficients of variation for the deformation  
158 ranged from 2.5% to 9.3%.

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161 To investigate the deformation behaviour of the PC and blended cements cured in moist condition  
162 for long term, the aforementioned fresh cement mixtures were cast into molds to prepare prism  
163 cement pastes with size of 20mm $\times$ 20mm $\times$ 80mm. After 24h curing in moist room at a temperature  
164 of 20 $\pm$ 2 $^{\circ}\text{C}$  and a relative humidity of 98%, all the cement paste specimens were demoulded, and  
165 then their initial lengths were tested. Subsequently the cement pastes were cured in water at 20 $^{\circ}\text{C}$ ,  
166 and the length changes of all the cement pastes were measured at different intervals. Each length  
167 change value used was the mean value of five replicate specimens.

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### 170 2.2.3 Mechanical strength

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173 The flexural and compressive strengths of the cement mortars were measured according to the  
174 standard of ASTM C349 [33] but with some minor revisions. For each type of cement, mortar  
175 prisms with size of 40mm×40mm×160mm were prepared. The mortar consisted of 1 part cement  
176 and 3 parts standard sands by weight, and a w/b ratio of 0.5 was used. After three different ages of  
177 curing, namely 3d, 28d and 90d, the flexural strengths as well as compressive strengths were  
178 examined respectively. The flexural strengths of the mortars were first measured and then both of  
179 the two portions of prisms broken in the flexural strength test were used for the compressive  
180 strength test. For each test, three of the flexural strengths and six of the compressive strengths  
181 were averaged.

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### 184 2.2.4 Microstructure analysis

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187 The pore structure of the mortar specimens was examined by using Mercury Intrusion  
188 Porosimetry (MIP). The morphology of the blended cement pastes was investigated with a FEI  
189 Nova NanoSEM 450 coupled with Bruker Energy Dispersive X-ray (EDX). In addition, the paste

190 and mortar samples were sliced, dried, epoxy impregnated, and polished for investigating the  
191 microstructures with backscattered electronic microscopy.

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## 194 3 Results and Discussion

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### 197 3.1 Hydration heat

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200 Fig. 2(a) shows the isothermal calorimetry curves of the different types of cement blends. In  
201 comparison to PC, the addition of 8% MEA in EPCII caused no obvious retardation on the  
202 hydration heat flow during the acceleration period of cement hydration (within 7h) which was  
203 associated with the accelerated formation of calcium silicate hydrate (C-S-H). However it  
204 decreased the maximum value of heat flow and increased the heat flow slightly at the later age  
205 ranging from 12h to 48h. The blended cements with the addition of slag and fly ash exhibited  
206 longer induction and acceleration periods compared to PC and EPCII. Particularly for the  
207 EPCII-S40F20 and EPCII-S20F35, the maxima of the heat flow were reached approximately 2h  
208 later than that of PC. This implies a slight retardation of cement hydration was caused by fly ash  
209 and slag. As reported previously, the retardation of fly ash was dependent on the its replacement  
210 ratio and curing temperature, and prolonged by increasing level of fly ash replacement [34]. The

211 more fly ash was incorporated, the more retardation on the hydration heat was caused. Increasing  
212 content of fly ash reduced the heat flow as well as the total heat release. On the one hand, the fly  
213 ash may contribute little to the hydration heat release directly at early age due to its slow  
214 hydration process. As reported by Sakai et al [35], regardless of the glass content and composition,  
215 fly ash in cement pastes cured at 20°C did not react until 7 days. On the other hand, it influenced  
216 the hydration of cement due to the dilution effects [36], as the replacements of fly ash increased  
217 the real water-to-cement ratio, which may facilitate the cement hydration. The hydration of slag  
218 could also contribute to the heat release. The hydration of slag is more rapid than that of FA [37].  
219 Nevertheless, compared to the PC hydration, the hydration of slag was still slower and had a  
220 much longer induction period. It is interesting that a second heat release peak occurring around  
221 24h was observed for the blends of EPCII-S40F20, which may correspond to the formation of  
222 C-S-A-H [38].

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224

225 Fig. 2(b) shows the cumulative hydration heat of the five types of mixes. Accordingly within the  
226 first 24h after mixing with water, large magnitudes of hydration heat was released. PC released  
227 the largest amount of hydration heat among all the mixes. For EPCII, addition of 8% MEA as  
228 replacement of cement decreased slightly the hydration heat release within 24h but after then  
229 caused a very slight increase in the hydration heat, which may be attributed to the hydration of  
230 MgO. This indicates that the addition of MEA insignificantly influenced the hydration of cement  
231 at early age. For the blended cement, the incorporation of slag as well as fly ash reduced the

232 hydration heat liberation.

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235 3.2 Deformation

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238 Fig. 3 shows the autogenous deformations of all the cement pastes. The PC paste exhibited  
239 significant shrinkage in the first 6 hours, and after then the curves continued to go down but at  
240 relatively lower rate. At 115h, the autogenous shrinkage of cement paste PC reached around  
241 -1000 microstrains. With addition of 5% and 8% of MEA, the autogenous shrinkages of cement  
242 pastes EPCI and EPCII have been greatly reduced, being -720 and -195 microstrains respectively  
243 at the end of test. This indicates the autogenous shrinkage of cement pastes have been effectively  
244 compensated for due to the hydration of MgO. For the blended cements, regardless of the addition  
245 of MEA, the shrinkages were less than that of the corresponding PCs. The more Portland cement  
246 was replaced with slag and fly ash, the shrinkage was reduced more considerably. More  
247 importantly, the blended cements prepared with EPCII exhibited no shrinkage at the end of test  
248 age. Moreover, cement specimens EPCII-S20F20 and EPCII-40F20 showed gentle expansions,  
249 being around 200 microstrains. The general deformation of cement pastes depended on the  
250 competitive effects of MgO hydration and cement hydration on the volume change. For example,  
251 the cement paste shrinks when the expansion produced by MgO hydration is not sufficient to  
252 compensate the autogenous shrinkage. As the fixed w/b ratio of 0.38 was used, in the blended

253 cements more water was supplied for the hydration of MgO and thus may have an acceleration  
254 effects on MgO hydration. More MgO hydrated at the early age in blended cements produced  
255 more expansion, which not only completely compensated for the autogenous shrinkage caused by  
256 the hydration of cement but even produced gentle expansions.

257

258

259 Fig. 4 shows the deformation of cement pastes cured in 20°C water at long term. None of the  
260 cement pastes showed shrinkage. For the cement pastes EPCI and EPCII, obvious expansions of  
261 cement pastes were caused due to the hydration of the incorporated MEA in comparison to PC.  
262 The cement pastes expanded rapidly within 42d, and then gradually slowed down. After 120d, the  
263 deformation curves of EPCII leveled off, while for PC and other blended cement pastes the  
264 expansion curves leveled off at 90d. The ultimate expansions of EPCI and EPCII are 0.12% and  
265 0.21% respectively. With the increasing addition of slag and fly ash, the expansion of the blended  
266 cement pastes decreased. This is due to the reduction of MgO content contained in the blended  
267 cement with the decreasing content of expansive Portland cement. The ultimate expansions of the  
268 blended cement pastes prepared with the expansive PC were on the order of 0.06% to 0.08%.

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271 3.3 Mechanical strength

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274 Fig. 5 shows the flexural and compressive strengths of the mortar specimens. PC mortars  
275 developed strengths very quickly, the flexural and compressive strengths at 3d reached 6.8 MPa  
276 and 37.8 MPa, and at 90d they were 8.7 MPa and 62.1 MPa respectively. For EPCI and EPCII  
277 mortars, addition of MEA induced slight reductions in the flexural strengths but more decreases in  
278 compressive strengths. At late age of 90d, the compressive strengths of EPCI and EPCII mortars  
279 were decreased by 8.5 MPa and 12.2 MPa respectively in comparison to that of PC mortars. The  
280 reduction of late compressive strength when using MEA could be due to the less formation of  
281 C-S-H due to the reduction of PC in the blends which is replaced by MEA. The incorporation of  
282 slag and fly ash decreased the strengths at the early age. At 3d, the strengths of the mortar  
283 specimens made with the blended cements were lower than that made with PC. The more volume  
284 of slag and fly ash added, the lower the flexural and compressive strengths were gained. However,  
285 at 28d, the strengths of blended cement mortars increased significantly, being close to or even  
286 higher than that of the PC mortars. At 90d, all the blended cement mortars made with EPCII had  
287 higher strengths than the EPCII mortars. With the increasing curing age from 3d to 90d, the  
288 blended cement mortars exhibited more increase in both the flexural and compressive strengths  
289 than that of the corresponding PC mortars. For example, when the curing age increased from 3d  
290 to 90d, approximately 57%, 271%, 313%, and 257% increases in compressive strength were  
291 produced by mortars EPCII-S20F20, EPCII-S20F35, EPCII-S40F20 and EPCII-S40F35  
292 respectively, which were much higher than the increase of 47% produced in the EPCII mortars.  
293 This may attribute to the hydraulic or pozzolanic reaction of slag and fly ash. Increase of slag  
294 from 20% to 40% caused ascent in strengths of the mortars whereas increase of fly ash from 20%

295 to 35% decreased the strength. This may be due to that slag has higher hydraulic and pozzolanic  
296 reactivity than fly ash.

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### 299 3.4 Microstructure

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302 Fig. 6 shows the pore structures of the cement mortars. At 28d, most of the pores in the mortars  
303 made with PC and EPCII were with pore diameter range of 0.02-0.2  $\mu\text{m}$ . Blended cement mortars  
304 (EPCII-S20F20, EPCII-S40F20, EPCII-S40F35) had more pores with size less than 0.02 $\mu\text{m}$ . At  
305 90d, the pore volume decreased and there were less pores at the size range of 0.02-0.2 $\mu\text{m}$ . As  
306 shown in Fig. 6b, compared to the PC mortars, the blended cement mortars exhibited smaller total  
307 porosities at 28d. EPCII-S40F20 has the smallest porosity of 8.7% at 28d and it decreased further  
308 to 6.0% at age of 90d. This is due to that the hydraulic or pozzolanic reaction of slag and fly ash  
309 caused a densification of the cement paste at later ages.

310

311

312 Fig. 7 shows typical SEM and BSE images of the hydrated blended cement paste EPCII-S40F20.  
313 As shown in Fig. 7(a), some hydration products were formed on the surface of fly ash particle and  
314 in the region nearby, which tightly bound together the fly ash particle with the surrounding  
315 hydration products matrix. The dense interface structure is beneficial for the increase of strength.

316 In Fig. 7(b), hydration rims were formed around the slag particle, and the hydraulic or pozzolanic  
317 reaction products grown gradually from the outer area of slag into the inner part of unhydrated  
318 slag. As seen the BSE image of Fig. 7(c), it shows some hydration rims of slag in the blended  
319 cement pastes. The interface structures of slag and fly ash particles were dense and therefore  
320 contributed to the strength augment. The contributions of the hydraulic or pozzolanic reaction of  
321 slag and fly ash may not only due to the densification on the pore structure but also closely related  
322 to the interface structure enhancement.

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324

325 Fig. 8 presents the typical BSE images of the mortars prepared with blended cement mortars  
326 EPII-S40F20 after 90d curing in water. Fig. 8(a) shows the BSE image of blended cement mortar  
327 at magnification of x300. Lots of slag with coarse particles remained unhydrated. As shown in Fig.  
328 8(b), close investigation of zone A indicates that the slag with small particle size had been  
329 hydrated completely while the larger slags were not completely hydrated but with obvious  
330 hydration rims.

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### 333 3.5 Discussion

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336 In the blended cement systems, due to the reduction of cement clinker content associated with the

337 substitutions of slag and fly ash, the hydration heat release was reduced significantly. Accordingly  
338 this is beneficial for minimising the thermal shrinkage in concrete, particularly in the mass  
339 concrete. Replacements of PC with slag and fly ash in this study reduced the autogenous  
340 shrinkage of cement pastes. This is attributed to the dilution effects of SCMs on the blended  
341 cement system [34, 39]. Less water was consumed by the cement hydration and less C-S-H was  
342 formed at early age, reducing the shrinkage. However, the reaction of slag and fly ash consumes  
343 water, and hence may contribute to self-desiccation. Fly ash had a slow pozzolanic reaction rate  
344 and therefore contributed little to the autogenous shrinkage at early age. Slag had higher reactivity  
345 than that of fly ash but its reaction (hydraulic and pozzolanic) was also much slower compared to  
346 cement hydration. Accordingly it may also contribute insignificantly to the autogenous shrinkage  
347 at the early age. However, for a long term the pozzolanic reaction would contribute to the  
348 autogenous shrinkage. In addition to the pozzolanic reaction effects, the filler effects of fly ash  
349 may also influence the properties of cement materials. The unhydrated fly ash may behave like  
350 micro-aggregate in the cement paste, which is helpful to reduce the autogenous shrinkage [40].

351

352

353 Hydration of MgO produced expansion and thus partly or fully compensated for the autogenous  
354 shrinkage of cement paste. To some extent, there is some competition on the water consumption  
355 between the hydration of MgO and cement. When cured in water, with sufficient supply of water,  
356 the expansive cement pastes EPCI and EPCII produced obvious expansions. Under sealed  
357 condition without exterior water supply, the autogenous shrinkage of EPCI and EPCII were partly

358 but not completely compensated at early age (Fig. 3). Nevertheless, as the same w/b ratio was  
359 used in the blended cement in this study, the real w/b ratio was higher, and therefore more water  
360 was supplied for the hydration of MgO. Thus the blended cement pastes prepared with EPCII  
361 exhibited no shrinkage but even produced gentle expansion. Accordingly incorporation of  
362 appropriate addition of MEA as well as SCMs could produce non-shrinkage blended cements.  
363 Dissimilar to the delayed expansive cement containing relatively high content of periclase used in  
364 China, MEA with high reactivity was incorporated into cement during the inter-ground process in  
365 this study, and thus the MgO content can be easily adjusted according to the requirements. This  
366 provides a new approach to produce MgO-based expansive Portland cement. The incorporation of  
367 MgO into cement by inter-grinding is more homogenous compared to being mixed in concrete as  
368 an expansive additive during the concrete mixing process.

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371 The mechanical strengths of blended cement mortars at early age were lower and developed more  
372 slowly compared to that of the normal PC mortars. This is due to that less cement hydration  
373 products were formed in the blended cement mortars at the early age. However, at the late age,  
374 with increasing curing time, the pozzolanic reaction of slag as well as fly ash increased the  
375 strengths significantly although the corresponding hydration products in the blended cement  
376 system were much less than that of the PC. As shown in Fig. 8, there are still significant quantities  
377 of slag that remained unhydrated and most of the fly ash could not hydrate completely. The  
378 strength increase of blended cement mortars at late age may not only attribute to the pore

379 structure densification but also be related to enhancement of the interface structure between the  
380 cement hydration products and SCM particles (fly ash, slag) due to their hydraulic or pozzolanic  
381 reaction [41, 42]. Incorporation of MEA caused gentle reductions in the strengths of cement  
382 mortars as it reduced the cement content. Moreover, the expansion produced by MgO hydration  
383 may also influence the strength depending on the magnitude of expansion and its corresponding  
384 influence on the microstructure of cement materials [6].

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386

#### 387 4 Conclusions

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390 Quaternary blended cements with low hydration heat release, low autogenous shrinkage at early  
391 age and high mechanical strength at later ages were prepared by mixing slag and fly ash with  
392 expansive PC containing MgO. Main conclusions drawn are as follows:

393 (i) The autogenous shrinkage of blended cement pastes at the early age up to 5 days was less than  
394 that of the corresponding control PC pastes. Moreover, the blended cement pastes (EPCII-S40F20,  
395 EPCII-S40F35) prepared with the expansive PC containing 8% MEA, 40% slag and 20% or 40%  
396 fly ash exhibited gentle expansions of 200 microstrains rather than shrinkages under the sealed  
397 condition. This is attributed to the dilution effects of slag and fly ash on the PC component and  
398 the expansion caused by the MEA. Under moist curing condition, with the sufficient supply of  
399 water, both the expansive PC containing MEA and the relevant blended cements produced

400 obvious expansions.

401 (ii) Replacement of PC clinker with up to 8% of MEA resulted in strength decrease. The blended  
402 cement mortars had lower strengths at early age of 3d, but gained equivalent or higher strengths at  
403 late ages of 28d and 90d compared to the corresponding control PC mortars. This is attributed to  
404 the microstructure densification as well as the interface microstructure enhancement due to the  
405 formation of pozzolanic reaction products of slag and fly ash.

406 (iii) Addition of slag and fly ash in the blended cements caused a delay of up to 2h on the  
407 hydration kinetics compared to the control cements. The hydration heat flow as well as the total  
408 hydration heat was reduced significantly. This is beneficial for reducing the temperature rise and  
409 thus mitigating thermal cracking at early age.

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411

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527 TABLES

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530 Table 1 Chemical compositions of Portland cement clinker, slag, fly ash and MgO-based  
531 expansive additive

532 Table 2 Mix proportions of Portland cement and blended cement

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535 FIGURES

536

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538 Fig. 1 Particle size distributions of PC, EPCI, EPCII, fly ash and slag

539 Fig. 2 Isothermal calorimetry hydration heat liberation of cement: (a) heat flow and (b)  
540 cumulative hydration heat

541 Fig. 3 Autogenous deformation of cement pastes

542 Fig. 4 Deformation of cement pastes cured in water at 20°C

543 Fig. 5 Mechanical strength of mortar specimens: (a) Flexural strength and (b) Compressive  
544 strength

545 Fig. 6 Typical pore structure of cement mortars: (a) derivative porosity curve (pore size  
546 distribution) and (b) cumulative porosity curve

547 Fig. 7 SEM and BSE images of the hydrated blended cement EPCII-S40F20: (a) SEM image of  
 548 hydrated fly ash, (b) SEM image of hydrated slag, and (c) BSE image of hydrated blended cement  
 549 paste. S: slag, F: fly ash.

550 Fig. 8 BSE images of blended cement mortars EPCII-S40F20

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556 Table 1 Chemical compositions of Portland cement clinker, slag, fly ash and MgO-based  
 557 expansive additive

Type	Chemical compositions /%								
	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	CaO	MgO	K <sub>2</sub> O	Na <sub>2</sub> O	SO <sub>3</sub>	Loss
Cement clinker	21.18	3.76	5.36	63.47	1.13	1.05	0.13	2.16	1.61
Slag	34.65	0.25	14.54	39.84	7.10	0.35	0.38	-	0.00
Fly ash	49.77	15.09	20.50	5.39	1.42	1.16	0.69	2.03	2.01
MEA-50	2.76	0.26	0.42	3.18	88.52	0.03	0.06	0.61	3.62

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567 Table 2 Mix proportions of Portland cement and blended cement

ID	Type of cement used	Mix proportions / % by mass		
		Cement	Slag	Fly ash
PC	PC	100	0	0
EPCI	EPCI	100	0	0
EPCII	EPCII	100	0	0
EPCII-S20F20	EPCII	60	20	20
EPCII-S40F20	EPCII	40	40	20
EPCII-S20F35	EPCII	45	20	35
EPCII-S40F35	EPCII	25	40	35
PC-S40F20	PC	40	40	20
PCI-S40F20	EPCI	40	40	20

568 Note: PC, EPCI, and EPCII represent the Portland cements incorporated with 0%, 5% and 8% of

569 MgO-based expansive additives respectively.