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℃ [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 m^2/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 μm 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×20mm×80mm. After 24h curing in moist room at a temperature

164   of 20 ± 2°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°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℃ 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.

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258

259   Fig. 4 shows the deformation of cement pastes cured in 20℃ 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 μm. Blended cement mortars

304   (EPCII-S20F20, EPCII-S40F20, EPCII-S40F35) had more pores with size less than 0.02μm. At

305   90d, the pore volume decreased and there were less pores at the size range of 0.02-0.2μm. 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.

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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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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].

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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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387 4 Conclusions

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390 Quaternary blended cements with low hydration heat release, low autogneous 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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412   Acknowledgements

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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_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	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.