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STRATEGIES FOR IMPROVING DIMENSIONAL STABILITY OF CONCRETE

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Abstract: Changes in dimension of concrete due to early-age heat generation, long-term drying shrinkage and creep under sustained load could lead to significant movements of the concrete structure and lock-up stresses if the movements are restrained. The lock-up stresses are often large enough to cause cracking and water leakage, thereby adversely affecting the serviceability and durability of the structure. Whilst the dimensional changes are quite variable because of their dependence on the environmental conditions and applied loads, they are all related to the concrete mix proportions. Generally, the dimensional stability of concrete can be improved by reducing its cement content and paste volume. Moreover, since the aggregate also shrinks, the dimensional stability can be improved by suppressing the shrinkage of aggregate as well. In this paper, strategies for improving the dimensional stability of concrete are formulated based on experimental research. Test results are presented to demonstrate their effectiveness and applicability.

Keywords: cracking, dimensional stability; fillers; heat generation; shrinkage.

1. INTRODUCTION

The dimensions of concrete change when there is elastic deformation under applied loading, creep deformation under sustained loading, thermal expansion or contraction under temperature variation, and swelling or shrinkage under moisture content variation. Such dimensional changes may cause deflection, distortion and cracking. Whilst the dimensional changes due to elastic and creep deformations are structural and have to be dealt with in the structural design, the dimensional changes due to temperature and moisture content variations are non-structural and have to be dealt with in the construction planning and, more importantly, the concrete mix design. In fact, most of the cracks in concrete are non-structural, i.e. they are caused by temperature and moisture content variations. The largest temperature variation occurs during curing as heat is generated from the chemical reactions of the cementitious materials and subsequently dissipated. On the other hand, the major source of moisture content variation is the long-term drying of the concrete after curing. This paper deals with concrete mix design strategies for reducing the heat generation and drying shrinkage of concrete.

During curing of concrete, heat is generated. As heat accumulates within the concrete mass, the temperature rises. The temperature rise, which could be as high as 60°C (Wang and Read, 1999; Aparicio *et al.*, 2000; Gajda and Van Geem, 2002), and the subsequent temperature drop would cause thermal movement of the concrete structure. After curing, the concrete would gradually lose its moisture content, thus causing drying shrinkage, which could be as large as 900 $\mu\epsilon$ (Kwan *et al.*, 2002; Ng *et al.*, 2009), and such shrinkage strain would cause significant shortening movement of the concrete structure. If internal or external restraints against such thermal and shrinkage movements exist, tensile stresses would be induced (Klemczak and Knoppik-Wróbel, 2011). The tensile stresses so induced are often large enough to produce early-age thermal cracks and/or long-term shrinkage cracks, which could adversely affect the aesthetics, water tightness, structural integrity and durability of the concrete structure.

To avoid or, at least, alleviate the early thermal cracking problem, we can redesign the concrete mix to reduce the heat generation, apply internal cooling to the concrete to

reduce the increase in temperature, apply external heat insulation to reduce the temperature differential within the concrete mass and add crack control steel to control the crack width (Bamforth, 2007). Among these possible solutions, the fundamental method of adopting a low-heat concrete mix design should always be considered first because the latter methods of internal cooling, external insulation and adding crack control steel are, in general, rather cumbersome and can be costly to apply.

To avoid or, at least, alleviate the shrinkage cracking problem, we can redesign the concrete mix to reduce the drying shrinkage, provide movement joints and late cast strips to allow unrestrained shrinkage movement and add crack control steel to control the crack width (Gilbert and Ranzi, 2011). Among these possible solutions, the fundamental method of adopting a low shrinkage concrete mix design should always be considered first because the latter methods of providing movement joints/late cast strips and adding crack control steel are rather cumbersome and costly to apply, and at times could cause delay.

Both the heat generation and drying shrinkage take place mainly in the cementitious paste (the paste formed of cementitious materials and water). Hence, in theory, it should be possible to reduce the heat generation and drying shrinkage at the same time by reducing the cementitious paste volume. However, since the volume of cementitious paste must be enough to fill up the voids in the bulk volume of aggregate in order to avoid entrapment of air in the voids, there is a certain lower limit for reducing the cementitious paste volume. To allow the cementitious paste volume to be further reduced, the packing density of the aggregate has to be maximized to reduce the volume of voids to be filled, or a filler has to be added to fill into the voids so as to reduce the volume of cementitious paste needed.

Apart from reducing the cementitious paste volume, the heat generation of concrete may also be reduced by adding supplementary cementitious materials to replace part of the cement because generally, supplementary cementitious materials generate less heat of chemical reactions than cement (Siddique and Iqbal Khan, 2011). On the other hand, the drying shrinkage of concrete may also be reduced by pretreating the rock aggregate with polymer latex or water repellent to reduce the water absorption and drying shrinkage of the rock aggregate because in reality, depending on the source, the rock aggregate

would also shrink and thus contribute to the shrinkage of concrete (Kwan and Wong, 2007).

At the University of Hong Kong, extensive studies on the effectiveness of the above methods of adding supplementary cementitious materials to reduce cement content, adding filler to reduce cementitious paste volume, and pretreating the rock aggregate to reduce water absorption so as to reduce the heat generation and drying shrinkage of concrete have been carried out, as summarized herein. Based on these studies, strategies for improving the dimensional stability of concrete are developed. It is envisaged that by ameliorating the dimensional stability of concrete, the risk of non-structural cracking could be minimized.

2. REDUCING HEAT GENERATION OF CONCRETE

One common way of reducing the heat generation of concrete is to lower the cement content by adding supplementary cementitious materials, such as fly ash (FA) and ground granulated blastfurnace slag (GGBS), to replace part of the cement (Bamforth, 1980; Özbay *et al.*, 2016). Various studies on FA and GGBS have shown that the addition of FA or GGBS as cement replacement is generally effective in reducing the heat generation of concrete (Kwan *et al.*, 2011a). However, depending on the material quality, the addition of FA or GGBS to replace part of cement content would usually lower the strength of concrete, especially at a high FA or GGBS content.

Besides FA and GGBS, silica fume (SF) is also used. Studies on SF have revealed that the effectiveness of adding SF as cement replacement for reducing the heat generation are dependent on the SF content, temperature and age (Meland, 1983; Sanchez De Rojas and Frias, 1995; Kadri and Duval, 2009). Nevertheless, in most cases, the addition of SF to replace an equal weight of cement is effective in reducing the heat generation (Kwan *et al.*, 2011b). Furthermore, the addition of SF would increase the strength. Therefore, the addition of SF together with FA or GGBS as cement replacement could effectively reduce the heat generation without lowering the strength (Langan *et al.*, 2002).

In recent years, the addition of inert filler, such as limestone fines (LF), to replace part of the cement has gained popularity. Generally, the addition of a small quantity of LF to

replace an equal weight of cement would not significantly affect the early strength (Bonavetti *et al.*, 2003). However, the addition of a relatively large quantity of LF to directly replace cement without changing the water content would adversely affect the strength, especially the long-term strength. This is because LF is not cementitious and the direct replacement of cement by LF would increase the water/cement ratio. Chen and Kwan (2012) advocated that LF should better be added as replacement of an equal volume of cementitious paste without changing the water/cementitious materials (W/CM) ratio. They have also demonstrated that such addition of LF as cementitious paste replacement can reduce the heat generation and at the same time slightly increase the strength.

With the usual practice of adding only FA or GGBS, it would be difficult to achieve low heat generation and desirable strength simultaneously. Atiş (2002) has developed a concrete mix with a very low temperature rise of approximately 30°C by adding a high volume of FA to replace 70% of the cement. This concrete mix has a 28-day compressive strength of only 40 MPa and is thus a fairly low grade concrete. To achieve a low temperature rise of not more than 30°C and a more desirable compressive strength of 65 MPa or higher, for example, it is suggested to add SF and LF, in addition to FA or GGBS. The SF should be added to replace an equal weight of cement, whereas the LF should be added to replace an equal volume of cementitious paste without changing the W/CM ratio.

Herein, the effects of adding FA, SF and LF on the heat generation of concrete are studied. Furthermore, based on the experimental results, a strategy of adding both supplementary cementitious materials and an inert filler to improve the dimensional stability of concrete is proposed.

3. REDUCING DRYING SHRINKAGE OF CONCRETE

To reduce the drying shrinkage of concrete, a common strategy is to decrease the cementitious paste volume because it is the contraction of the hardened paste that constitutes the major part of shrinkage. De Larrard (1999) suggested that limiting the paste volume as much as practicable is the recipe for the production of high-performance concrete with very low shrinkage. Loser and Leemann (2009)

concluded that concrete mixes with large paste volumes tend to have larger shrinkage. They also pointed out that the high water content of the concrete mixes might be the underpinning cause for substantial shrinkage.

Although decreasing the paste volume can effectively reduce the shrinkage, it is not easy to achieve in actual practice. This is because the paste volume has to fill up the voids between aggregate particles in order to avoid entrapment of air and for this reason, there is a necessity to provide a paste volume larger than the voids volume of the aggregate. To decrease the paste volume without entrapping air in the concrete mix, one possible way is to add an inert filler to fill into the voids between aggregate particles so that the amount of paste needed is smaller (Carrasco *et al.*, 2003). The author's research team has proved that the addition of limestone fines (LF) as cementitious paste replacement would allow the paste volume to be decreased to fairly small values without causing air entrapment (Chen and Kwan, 2012). Hence, by adding LF to reduce the paste volume, it should be possible to substantially reduce the drying shrinkage of concrete without causing any adverse effects on strength and durability.

Apart from reducing the paste volume, the author's research team has also proposed to pretreat the rock aggregate with polymer latex or water repellent to avoid water absorption of the aggregate during concrete mixing so as to reduce the drying shrinkage of the aggregate. In reality, rock also shrinks as it dries and the drying shrinkage of the rock aggregate particles would contribute to the drying shrinkage of concrete (Kwan and Wong, 2007; Kwan *et al.*, 2010a). Hence, suppressing the shrinkage of the rock aggregate by whatever means should help to reduce the drying shrinkage of concrete.

Herein, the effects of adding LF as cementitious paste replacement to reduce the paste volume and pretreatment of rock aggregate with polymer latex or water repellent on the drying shrinkage of concrete are studied. Furthermore, based on the experimental results, a strategy of adding an inert filler as cementitious paste replacement, lowering the W/CM ratio and pretreating the rock aggregate to improve the dimensional stability of concrete is proposed.

4. EXPERIMENTAL PROGRAMS

Herein, experimental studies by the authors on the effectiveness of adding LF, FA and SF, and pretreating the aggregate to improve the dimensional stability of concrete are explicated. Details of the experimental programs are summarized in Appendix A. In brief, among the concrete mixes tested for heat generation, the water/cementitious materials (W/CM) ratio varied from 0.40 to 0.50 by weight, the LF volume varied from 0% to 8% by volume of concrete, the FA content varied from 0% to 40% by weight of total cementitious materials, and the SF content varied from 0% to 10% by weight of total cementitious materials. Among the concrete mixes tested for drying shrinkage, the water/cement (W/C) ratio varied from 0.35 to 0.60 by weight, the LF volume varied from 0% to 12% by volume of concrete. Among the concrete mixes tested for investigation of aggregate treatment, the W/C ratio was fixed at 0.48, the paste volume was fixed at 30% and the fine/total aggregate ratio was fixed at 0.42. Readers may consult relevant literature (Kwan *et al.*, 2010b, 2013a, 2013b) for further information.

All the materials used in the experimental program were commonly used materials obtained from the market and thus the test results obtained should be representative of typical mixes in concrete production industry. Both FA and SF were added as cement replacement in such a way that the cement content would be reduced by the FA and SF contents added whereas the a finely ground LF was added as cementitious paste replacement in such a way that the volume of cementitious paste would be reduced by the volume of LF added. The volumetric mean particle size of the LF had been measured to be 10 to 15 μm , which was close to that of cement. In the concrete mix design, the cement, FA and SF contents were each measured by weight as a percentage of the total cementitious materials, the LF volume was measured by volume as a percentage of the total volume of concrete, and the W/CM ratio was measured by weight.

As in usual practice, a superplasticizer (SP) was added to each concrete mix to achieve the required workability. The SP added was of polycarboxylate type supplied in the form of an aqueous solution with a solid mass content of 20% and a relative density of 1.03. It was a commonly used SP in the concrete production industry. Both the fine and

coarse aggregates were obtained from crushed granite rock. The fine aggregate was of 5 mm maximum size, whereas 10 mm and 20 mm maximum size coarse aggregates were used.

Each concrete mix was tested for its workability in terms of slump and flow according to European Standard EN 12350-8: 2010, its compressive strength in terms of 7-day cube strength and 28-day cube strength according to European Standard EN 12390-3: 2009 based on 150 mm cube specimens, its heat generation by a semi-adiabatic curing test with heat loss compensation applied (Ng *et al.*, 2008; Ng and Kwan, 2012), and its drying shrinkage by the test method stipulated in British Standard BS 812: Part 120: 1989.

5. EXPERIMENTAL FINDINGS ON HEAT GENERATION

The SP dosage, workability and strength results are presented in Table 1 while the results of temperature rise, heat generation and thermal strain are listed in Table 2. The mix no. is designated in the form of W/CM-LF-FA-SF. For example, 0.40-4-40-10 refers to the concrete mix with a W/CM ratio of 0.40, a LF volume of 4%, a FA content of 40% and a SF content of 10%. The thermal strain is evaluated as the adiabatic temperature rise multiplied by the coefficient of thermal expansion, which is taken as $10 \times 10^{-6}/^{\circ}\text{C}$ (Neville, 2011). For easier interpretation, the results on adiabatic temperature rise, adiabatic temperature rise per cementitious materials content, 7-day and 28-day cube strengths, and concurrent heat generation and cube strength are presented graphically in Figures 1 to 4.

5.1 Effects of adding LF

Table 1 shows that the SP dosage needed to achieve the required workability was generally lower at higher W/CM ratio and higher at higher LF volume. Hence, the addition of LF would significantly increase the SP demand. This was expected because the addition of LF would increase the powder content and decrease the water content, albeit the W/CM ratio would remain the same. Nevertheless, with sufficient SP added, the concrete mixes all achieved reasonably good workability.

Figure 1 shows that at the same W/CM ratio, the adiabatic temperature rise was generally lower at higher LF volume. For instance, at a W/CM ratio of 0.45, the addition of a LF volume of 8% to reduce the cementitious paste volume from 34% to 26% had reduced the adiabatic temperature rise from 56.9°C to 45.5°C (a reduction of about 20%). Hence, the addition of LF to reduce the cementitious paste volume is effective in reducing the temperature rise.

Figure 2 shows that at all W/CM ratios, the adiabatic temperature rise per cementitious materials content increased slightly as the LF volume increased from 0% to 4% and then marginally as the LF volume further increased from 4% onwards. Such increase in adiabatic temperature rise per cementitious materials content reveals that the addition of LF without changing the W/CM ratio would slightly increase the degree of hydration of the cement. Hence, the addition of LF reduced the temperature rise mainly by reducing the cementitious paste volume, not by reducing the degree of hydration of the cement.

The results of heat generation per volume of concrete and heat generation per unit weight of cementitious materials are tabulated in the fourth and fifth columns of Table 2, respectively. It can be seen that the heat generation decreased substantially as the LF volume increased while the heat generation per weight of cementitious materials increased slightly as the LF volume increased from 0% to 4% and then marginally as the LF volume increased from 4% onwards. Since the heat generation per weight of cementitious materials had not been reduced, the addition of LF reduced the heat generation mainly by reducing the volume of cementitious paste and thus the weight of cementitious materials contained therein.

The thermal strain (adiabatic temperature rise multiplied by coefficient of thermal expansion) is given in the last column of Table 2. It represents the maximum thermal contraction of concrete when it cools down from the peak temperature to the ambient temperature. These results reveal that the reduction in thermal strain by adding LF is proportional to the reduction in adiabatic temperature rise. However, it should be noted that although the thermal strain can be reduced by adding LF (for example, at a W/CM ratio of 0.45, the addition of 8% LF reduced the thermal strain from 569 to 455 $\mu\epsilon$), the thermal strain still well exceeds the tensile strain capacity of concrete. Hence, in mass

concrete construction, the risk of thermal cracking is generally quite high and must be duly considered and mitigated.

Figure 3 shows that the addition of LF as cementitious paste replacement without changing the W/CM ratio had significantly increased the 7-day and 28-day cube strengths, although the LF added is chemically inert. Roughly speaking, the addition of LF at 4% volume had increased the 7-day and 28-day strengths by about 7% while the addition of LF at 8% volume had increased the 7-day and 28-day strengths by about 14%. Such increases in strength due to the addition of LF may be attributed to the reduced bleeding of the concrete mix for better bonding at the interfacial transition zones and the nucleation effect of the LF powder for precipitation of gel products.

5.2 Effects of adding LF and FA

Table 1 shows that the SP dosage needed to achieve the required workability decreased as the FA content increased from 0% to 40%. This may be attributed to the spherical shape of the FA particles, which increases the workability of concrete and thus decreases the SP dosage needed for given workability. Hence, the addition of FA would significantly decrease the SP demand.

Figure 1 shows that at the same W/CM ratio and the same LF volume, the adiabatic temperature rise was generally lower at higher FA content. For instance, at a W/CM ratio of 0.45 and a LF volume of 8%, the addition of a FA content of 40% to reduce the cement content had reduced the adiabatic temperature rise from 45.5°C to 36.4°C (a reduction of about 20%). Hence, even after the addition of LF to reduce the cementitious paste volume, the addition of FA to reduce the cement content in the cementitious paste is effective in reducing the temperature rise.

Figure 2 shows that at all W/CM ratios and all LF volume, the adiabatic temperature rise per cementitious materials content decreased quite substantially as the FA content increased from 0% to 40%. Such decrease in adiabatic temperature rise per cementitious materials content reveals that the adiabatic temperature rise due to the pozzolanic reaction of FA was smaller than the adiabatic temperature rise due to the hydration reaction of cement. Hence, the addition of FA as cement replacement reduced the

temperature rise mainly by substituting the more exothermic hydration reaction of cement with the less exothermic pozzolanic reaction of FA.

Table 2 shows that at all W/CM ratios and all LF volumes, both the heat generation per volume of concrete and the heat generation per weight of cementitious materials decreased quite substantially as the FA content increased. Since the addition of FA to replace part of cement changed the total weight of cementitious materials only slightly, it reduced the heat generation mainly by reducing the heat generation per weight of cementitious materials. Furthermore, it is seen that the thermal strain is reduced remarkably by the addition of FA. However, the effects of FA on concrete strength must not be overlooked, as discussed below.

Figure 3 shows that the addition of FA as cement replacement without changing the W/CM ratio had significantly decreased the cube strengths. Roughly speaking, the addition of a FA content of 40% had decreased the 7-day strength by about 40% and the 28-day strength by about 25%. The reduction in early strength was larger because of the slower pozzolanic reaction of the FA compared to the faster hydration reaction of the cement. Hence, although the addition of FA as cement replacement up to 40% of total cementitious materials is effective in reducing the heat generation, it has the major problem that the strength, especially the early strength, would be impaired.

5.3 Effects of adding LF, FA and SF

Table 1 shows that the SP dosage needed to achieve the required workability increased as the SF content increased from 0% to 10%. This may be attributed to the large specific surface area of the SF added, which decreases the workability of concrete and thus increases the SP dosage needed for given workability. Hence, the addition of SF would significantly increase the SP demand. Compared to the other concrete mixes, these concrete mixes containing LF, FA and SF appeared to be the most cohesive, as indicated by their very high stickiness during concrete mixing. Such high cohesiveness would allow a higher SP dosage to be adopted for achieving a higher workability without causing segregation.

Figure 1 shows that at the same W/CM ratio, the same LF volume and the same FA content, the adiabatic temperature rise was generally lower at higher SF content. For instance, at a W/CM ratio of 0.45, a LF volume of 8% and a FA content of 40%, the addition of a SF content of 10% to reduce the cement content had reduced the adiabatic temperature rise from 36.4°C to 30.8°C (a reduction of about 15%). Hence, even after the addition of LF to reduce the cementitious paste volume and the addition of FA to reduce the cement content, the addition of SF to further reduce the cement content is effective in reducing the temperature rise.

Figure 2 shows that within the ranges of mix parameters covered, the addition of SF significantly decreased the adiabatic temperature rise per cementitious materials content. Such decrease in adiabatic temperature rise per cementitious materials content reveals that the adiabatic temperature rise due to the pozzolanic reaction of SF was smaller than the adiabatic temperature rise due to the hydration reaction of cement. Hence, the addition of SF as cement replacement reduced the temperature rise mainly by substituting the more exothermic hydration reaction of cement with the less exothermic pozzolanic reaction of SF.

Table 2 shows that within the ranges of mix parameters covered in the study, both the heat generation per volume of concrete and the heat generation per weight of cementitious materials decreased significantly as the SF content increased. Since the addition of SF to replace part of cement changed the total weight of cementitious materials only slightly, it reduced the heat generation mainly by reducing the heat generation per weight of cementitious materials. Furthermore, it is seen that the addition of SF can lower the thermal strain and hence reduce the risk of thermal cracking.

Figure 3 shows that the addition of SF as cement replacement without changing the W/CM ratio had increased the 7-day and 28-day cube strengths. Roughly, the addition of a SF content of 10% had increased the 7-day strength only marginally and the 28-day strength by about 10%. Hence, the addition of SF as cement replacement is effective not only in reducing the heat generation but also in increasing the 28-day strength. It is therefore suggested that SF may be added together with FA to produce a larger reduction in heat generation than adding FA alone and to partly compensate for the strength loss due to the addition of FA.

Among these concrete mixes, the mix 0.40-8-40-10 has a workability of 230 mm slump and 533 mm flow, a 28-day cube strength of 68.9 MPa and an adiabatic temperature rise of 29.9°C. This concrete mix may be taken as a low heat concrete for general applications. For special applications, further reduction of the adiabatic temperature rise at the expense of workability should be possible.

Overall, it is seen that the addition of LF to replace an equal volume of cementitious paste, and the addition of FA and SF to replace an equal weight of cement are both effective in reducing the heat generation and adiabatic temperature rise of concrete while still maintaining reasonably high strength and workability of the concrete.

6. STRATEGY FOR REDUCING HEAT GENERATION

6.1 Supplementary cementitious materials as cement replacement

As the heat generated from the pozzolanic reaction of supplementary cementitious materials is smaller than that generated from the hydration of cement, the addition of supplementary cementitious materials as cement replacement is generally effective in reducing the heat generation of concrete. However, the addition of low reactivity supplementary cementitious materials, such as FA and GGBS, without changing the W/CM ratio would significantly lower the strength of concrete (Bamforth, 1980; Helmuth, 1987).

One way of compensating for the loss in strength is to lower the W/CM ratio so as to increase the strength of concrete back to a more reasonable level. However the W/CM ratio should not be unlimitedly lowered because the amount of mixing water added must be more than enough to fill the voids between the cementitious materials (any unfilled voids would adversely affect the strength) and to form water films coating the solid particles (the water films are needed to provide lubrication for workability). If after lowering the W/CM ratio, the strength and workability are not entirely satisfactory, then the addition of SF, which has higher reactivity, in conjunction with FA or GGBS should be considered (Langan *et al.*, 2002). The addition of SF as cement replacement would reduce the heat generation and at the same time increase the strength.

6.2 Inert fillers as cementitious paste replacement

Since the inert fillers, e.g. LF, are not cementitious, they should not be used as cement replacement. Instead, they should be employed to fill into the voids in the bulk volume of aggregate. If the inert fillers have fineness close to that of the cementitious materials, they would be inter-mixed with the cementitious paste to form a powder paste. Since it is the cementitious paste that generates heat, reducing the cementitious paste volume should be an effective way of reducing the heat generation. However, the cementitious paste volume should not be unlimitedly reduced because the paste volume (including the volume of fillers if present) must be more than enough to fill the voids between the aggregate particles (any unfilled voids would adversely affect the strength) and to form paste films coating the aggregate particles (the paste films are needed to provide lubrication for workability).

One way of reducing the cementitious paste volume while filling up the voids and providing paste films is to add (inert) fillers to fill up part of the voids in the bulk volume of aggregate so that a smaller cementitious paste volume is needed to fill up the remaining voids. This is equivalent to adding fillers to increase the packing density of the aggregate and reduce the volume of voids to be filled with the cementitious paste. Alternatively, the fillers, which would be inter-mixed with the cementitious paste to form a powder paste of larger volume (the powder paste volume is equal to the cementitious paste volume plus the volume of fillers), may be considered as a cementitious paste replacement for reducing the cementitious paste volume while maintaining the powder paste volume. So long that the powder paste volume is more than enough to fill the voids and provide paste films, the cementitious paste volume may be reduced to lower than possible without the addition of fillers.

6.3 Combined use of supplementary cementitious materials and inert fillers

The addition of supplementary cementitious materials and the addition of inert fillers are not exclusive and may be applied together (Lundgren, 2005). As demonstrated in this study, the addition of FA and SF as cement replacement can reduce the heat generation by more than 30%, the addition of LF as cementitious paste replacement can

reduce the heat generation by about 20%, whereas the addition of FA and SF as cement replacement in conjunction with LF as cementitious paste replacement can reduce the heat generation by up to around 50%. Hence, the addition of both supplementary cementitious materials and inert fillers is the best strategy for reducing the heat generation of concrete.

However, the FA, SF and LF have different effects on the strength of concrete. For assessing the effectiveness in reducing heat generation on an equal strength basis, the heat generations of the different concrete mixes are plotted against their respective 28-day cube strengths in Figure 4. Each heat generation versus strength curve in the figure presents the concurrent heat generation-strength performance that can be achieved by the concrete with the prescribed FA, SF and LF contents and at W/CM ratios ranging from 0.40 to 0.50. Comparing these curves, it can be seen that on equal strength basis (i.e. with the W/CM ratio adjusted to keep the strength constant), the addition of LF alone, the addition of (LF + FA), and the addition of (LF + FA + SF) have increasing effectiveness in reducing the heat generation of concrete.

7. EXPERIMENTAL FINDINGS ON DRYING SHINKAGE

The SP dosage, workability and strength results are presented in Table 3 while the shrinkage measurement results are listed in Table 4. The mix no. is designated in the form of C-W/C-LF. For example, C-0.40-4 refers to the concrete mix with a W/C ratio of 0.40 and a LF volume of 4%. For easier interpretation, the results of ultimate shrinkage strain, shrinkage half-time, percentage reduction in ultimate shrinkage strain, effects of cement paste volume on shrinkage, and effects of concrete strength on shrinkage are presented graphically in Figures 5 to 9.

For measuring the shrinkage, triplicated specimens were cast from each concrete mix and tested under the same conditions. This allows cross-checking of the shrinkage strain measurements. Test results revealed that the shrinkage strains among each set of triplicated specimens differed slightly and the standard deviation was generally within 40 $\mu\epsilon$. The shrinkage strains of the triplicated specimens are averaged to yield the 30-day, 60-day and 180-day shrinkage strains of the concrete mix. Furthermore, the test results revealed that the shrinkage strains were almost constant after 120 days and, as

such, the 180-day shrinkage strains are taken as the ultimate shrinkage strains. Besides, by plotting the time variations of shrinkage measurements, the shrinkage strain-time curve is obtained for every specimen, and the shrinkage half-time of the specimen is determined as the time required for half of the ultimate shrinkage strain to develop. Then the shrinkage half-times of the triplicated specimens are averaged to yield the shrinkage half-time of the concrete mix.

7.1 Workability and strength results

The workability and strength results of the concrete mixes tested for drying shrinkage (presented in Table 3) are similar to those of the concrete mixes tested for heat generation (presented in Table 1). Basically, the SP dosage increased significantly with the LF volume. This increase in SP demand may be interpreted as a reduction in workability. Nevertheless, such workability reduction can be more than restored by increasing the SP dosage, as indicated by the higher workability of the concrete mixes containing LF compared to the concrete mixes containing no LF. It should be noted that at a W/C ratio of 0.5 or lower, the LF volume was added only up to 8% to avoid producing excessively dry concrete mixes. On the other hand, the strength results revealed that the addition of LF as cementitious paste replacement had significantly increased the 7-day and 28-day cube strengths, even though the W/C ratio was kept constant. The increase in cube strength was generally larger at higher W/C ratio and could amount to more than 20%.

7.2 Shrinkage results

Figure 5 shows that at all W/C ratios, the ultimate shrinkage strain decreased steadily and quite substantially as the LF volume increased from 0% to 8% or 12%. Such decreases in ultimate shrinkage strain may be attributed to the decrease in paste volume when part of the paste was replaced by the LF added. Furthermore, at all LF volumes, the ultimate shrinkage strain generally increased with the W/C ratio. This may be attributed partly to the larger volume of hydrated paste due to the higher degree of hydration at a higher W/C ratio.

Figure 6 shows that the shrinkage half-time varied only marginally with the LF volume and W/C ratio. In other words, both the LF volume and W/C ratio have little effect on the shrinkage half-time, though it can be observed that for each LF volume, the shrinkage half-time is slightly longer at W/C ratios of 0.45 to 0.50, and slightly shorter at W/C ratios of smaller than 0.45 or larger than 0.50.

Figure 7 shows that the reduction in shrinkage strain was usually larger at lower W/C ratio and could amount to as much as 28%. For instance, at a W/C ratio of 0.35, the maximum reduction in shrinkage strain due to the addition of LF as cement paste replacement was 28% while at a W/C ratio of 0.60, the maximum reduction in shrinkage strain due to the addition of LF as cement paste replacement was 19%.

7.3 Effects of paste volume

Figure 8 shows that the ultimate shrinkage strain is strongly related to the paste volume and W/C ratio and is generally smaller at smaller paste volume and/or lower W/C ratio, whereas the shrinkage half-time is only weakly related to the cement paste volume and W/C ratio. This can be demonstrated by the respective coefficients of correlation as shown in Figure 8 for the numerical regression of experimental data. Hence, as the cement paste volume is decreased by adding LF to replace an equal volume of cement paste, the ultimate shrinkage strain would significantly decrease but the shrinkage half-time would not change much.

7.4 Effects of concrete strength

Figure 9 shows that the ultimate shrinkage strain is strongly related to the concrete strength and cement paste volume and is generally smaller at higher concrete strength and/or smaller cement paste volume, whereas the shrinkage half-time is only weakly related to the concrete strength and cement paste volume. This can be demonstrated by the respective coefficients of correlation as shown in Figure 9 for the numerical regression of experimental data. On the whole, the effect of concrete strength on the ultimate shrinkage strain is larger than the effect of paste volume. Hence, although it may first appear that it is the decrease in paste volume due to the addition of LF that reduces the ultimate shrinkage strain, actually, the increase in concrete strength due to

the addition of LF also contributes to reducing the ultimate shrinkage strain. Summarizing, it may be said that the addition of LF as cementitious paste replacement would reduce the ultimate shrinkage strain in two additive ways: first by reducing the paste volume, which is the most liable to shrinkage; and second by increasing the concrete strength, which would increase the stiffness against shrinkage deformation and thus reduce the shrinkage strain.

Among these concrete mixes, the mix C-0.40-8 has a workability of 245 mm slump and 653 mm flow, a 28-day cube strength of 80.3 MPa and an ultimate shrinkage strain of $410 \mu\epsilon$. This concrete mix may be taken as a low-drying shrinkage concrete for general applications. For special applications, further reduction of the drying shrinkage by way of aggregate treatment as detailed below is possible.

7.5 Effects of aggregate treatment

As pointed out previously, the rock aggregate does exhibit shrinkage when undergoing drying and that would contribute to the drying shrinkage of concrete; the effectiveness of aggregate treatment to reduce the shrinkage of concrete is therefore investigated. The aggregate treatments applied to the granitic rock aggregates before use are shown in Table 5. Group A1 aggregates were untreated and stored in the laboratory for 1 month to have their moisture condition stabilized. The treatment applied to them is described as “as-supplied”. Group A2 aggregates were also untreated but immersed in water at a temperature of 27°C for 7 days so that they became fully saturated. The treatment applied to them is described as “immersion in water”. Group A3 aggregates were first immersed in a polymer latex (20% solution of Ronafix) for 6 hours, rinsed by clean water for 15 minutes and then dried in a condition chamber at a temperature of 50°C and a relative humidity of 50% for 7 days. Group A4 aggregates were first immersed in a water repellent (0.6% solution of Darapel) for 6 hours, rinsed by clean water for 15 minutes and then dried in a condition chamber at a temperature of 50°C and a relative humidity of 50% for 7 days. The treatment applied to Groups A5 and A6 aggregates mimicked those of Groups A3 and A4 aggregates, respectively, except that the 6-hour immersion in polymer latex or water repellent was extended to 3 days. This was to examine the effectiveness of prolonged immersion.

The water absorptions of the aggregates and the shrinkage results of concrete mixes made with the treated aggregates are shown in Table 6. It is seen that the water absorptions of the aggregates decreased significantly after treatment. This indicates that both the polymer latex and water repellent are effective in filling the pores in the aggregate to hamper the ingress of water when the aggregate is wetted or immersed in water. It is also seen that the ultimate shrinkage strains of the concrete mixes made with treated aggregates are significantly smaller than those of the concrete mixes made with untreated aggregates. Overall, the treatment applied to the aggregates had reduced the ultimate shrinkage of concrete by more than 20%. Hence, the proposed aggregate treatment could be an emerging technology for reducing concrete shrinkage.

Regarding the strength and workability, the concrete mix was designed to be grade 40 with target slump of 150 mm. The average 28-day cube compressive strength of the concrete mixes produced from aggregate groups A1, A2, A3, A4, A5 and A6 were 57.0, 52.8, 57.6, 52.6, 51.4 and 52.3 MPa respectively, and the target slump was achieved for all concrete mixes by using SP within the normal dosage range. Though in general the strength of concrete mixes made with treated aggregates is lower than that of concrete mixes made with untreated aggregates, the difference is minor and could be compensated with ease by adopting lower W/C or W/CM ratio in actual concrete production. On the other hand, the aggregate treatment did not appear to have significant influence on the workability of concrete.

It is envisaged that the method of aggregate treatment, which reduces the shrinkage of concrete by reducing the shrinkage of the rock aggregate, can be applied together with the method of adding LF as cement paste replacement, which reduces the shrinkage of concrete by reducing the shrinkage of the paste matrix. With both methods applied at the same time, the effectiveness in concrete shrinkage reduction could be enhanced.

8. STRATEGY FOR REDUCING DRYING SHRINKAGE

8.1 Inert fillers as cementitious paste replacement

Since the drying shrinkage takes place mainly in the cementitious paste, reducing the cementitious paste volume should be an effective way of reducing the drying shrinkage

of concrete. However, the cementitious paste volume should not be unlimitedly reduced because the paste volume (including the volume of fillers if present) must be more than enough to fill the voids between the aggregate particles (any unfilled voids would adversely affect the strength) and to form paste films coating the aggregate particles (the paste films are needed to provide lubrication for workability). One way of reducing the cementitious paste volume while filling up the voids and providing paste films is to add fillers to fill up part of the voids in the bulk volume of aggregate so that a smaller cementitious paste volume is needed to fill up the remaining voids. Such reduction in the cementitious paste volume would not only reduce the drying shrinkage but also the heat generation of the concrete.

8.2 Lowering W/CM ratio to increase concrete strength

In actual fact, the effect of concrete strength on the ultimate shrinkage strain is larger than the effect of paste volume. Hence, the drying shrinkage of concrete may be effectively reduced by lowering the W/CM ratio to increase the concrete strength. If the increase in concrete strength could be utilized to enhance the structural efficiency by reducing the dead weight and concrete cover of the concrete structure, this may be the best method of mitigating shrinkage cracking and improving the serviceability and durability of concrete structures. It should however be borne in mind that after lowering the W/CM ratio, the concrete would need better and longer period of curing. This is because it is the actual achieved concrete strength on site when drying starts rather than the concrete strength at 28 days measured in a laboratory under perfect curing condition that governs the ultimate shrinkage strain (this is usually referred to as a workmanship problem but most engineers could not explicitly spell out what the workmanship requirements are).

8.3 Pretreating aggregate to reduce water absorption

Pretreating the rock aggregate particles with polymer latex or water repellent so as to reduce the water absorption of the aggregates before use is effective in reducing the drying shrinkage of concrete. It is only that such aggregate treatment is not cheap and thus is more suitable for special applications where the savings arising from the reduction in drying shrinkage of concrete, e.g. saving in cost of providing crack control

steel, saving in cost of crack repair and saving in cost of water-proofing, could outweigh the increase in cost due to aggregate treatment.

9. CONCLUSIONS

The effects of adding LF as cementitious paste replacement, adding FA and SF as cement replacement, and pretreating aggregates with polymer latex or water repellent on the workability, strength, heat generation and drying shrinkage of concrete have been studied. Based on the test results, the following conclusions are drawn:

- (1) Adding LF as cementitious paste replacement up to 8% by volume of concrete would increase the superplasticizer demand, slightly increase the strength and substantially reduce the heat generation of concrete.
- (2) Adding FA and/or SF as cement replacement (to reduce the cement content without changing the cementitious paste volume and the W/CM ratio) would substantially reduce the heat generation of concrete.
- (3) On equal strength basis, the addition of LF alone, the addition of (LF + FA), and the addition of (LF + FA + SF) have increasing effectiveness in reducing the heat generation of concrete. With (LF + FA + SF) added, a low-heat generation concrete with a slump of 200 mm, a 28-day cube strength of 65 MPa and an adiabatic temperature rise of only 30°C has been developed.
- (4) Adding LF as cementitious paste replacement up to 8% or even up to 12% by volume of concrete would effectively reduce the drying shrinkage of concrete.
- (5) Lowering the W/CM ratio to increase the concrete strength would effectively reduce the drying shrinkage of the concrete. With 8% LF added and the W/CM ratio lowered to 0.40, a low-drying shrinkage concrete with a slump of 240 mm, a 28-day cube strength of 80 MPa and an ultimate shrinkage strain of only 410 $\mu\epsilon$ has been developed.
- (6) Pretreating the rock aggregate particles with polymer latex or water repellent and drying the aggregates before use would effectively reduce the drying shrinkage of concrete.

Finally, based on the above results, it is advocated that the best strategy for reducing the heat generation of concrete is to add supplementary cementitious materials as cement replacement and add inert fillers as cementitious paste replacement at the same time.

This strategy can reduce the heat generation by up to 50%. It is also advocated that the best strategy for reducing the drying shrinkage of concrete is to add inert fillers as cementitious paste replacement to reduce the paste volume, lower the W/CM ratio to increase concrete strength and if affordable also pretreat the aggregate to reduce its water absorption. This strategy can reduce the ultimate shrinkage strain down to about 400 $\mu\epsilon$ or even lower. With the heat generation and drying shrinkage so reduced, the dimensional stability of the concrete would be improved and the risk of non-structural cracking would be minimized.

REFERENCES

- Aparicio, A.C., Ramos, G., and Casas, J.R. 2000. Externally prestressed high strength concrete viaduct. *Journal of Bridge Engineering* 5(4): 337–343. doi: 10.1061/(ASCE)1084-0702(2000)5:4(337).
- Atiş, C.D. 2002. Heat evolution of high-volume fly ash concrete. *Cement and Concrete Research* 32(5): 751–756. doi: 10.1016/S0008-8846(01)00755-4.
- Bamforth, P.B. 1980. In-situ measurement of the effect of partial Portland cement replacement using either fly ash or ground granulated blast furnace slag on the performance of mass concrete. *Proceedings of the Institution of Civil Engineers* 69(2): 777–800. doi: 10.1680/iicep.1980.2377.
- Bamforth, P.B. 2007. *Early-age Thermal Crack Control in Concrete*, CIRIA C660, Construction Industry Research and Information Association, UK, 112 pp.
- Bonavetti, V., Donza, H., Menendez, G., Cabrera, O., and Irassar, E.F. 2003. Limestone filler cement in low w/c concrete: a rational use of energy. *Cement and Concrete Research* 33(6): 865–871. doi: 10.1016/S0008-8846(02)01087-6.
- Carrasco, M.F., Bonavetti, V.L., and Irassar, E.F. 2003. Drying shrinkage of mortars with limestone filler and blast-furnace slag. *Materiales de Construcción* 53(271-272): 5–16. doi: 10.3989/mc.2003.v53.i271-272.284.
- Chen, J.J., and Kwan, A.K.H. 2012. Adding limestone fines to reduce heat generation of curing concrete. *Magazine of Concrete Research* 64(12): 1101–1111. doi: 10.1680/macr.11.00193.
- De Larrard, F. 1999. Chapter 5: Applications: various concrete families. *Concrete Mixture Proportioning: A Scientific Approach*. E&FN Spon, London, UK, pp. 337–388.

- Gajda, J., and Van Geem, M. 2002. Controlling temperatures in mass concrete. *Concrete International* 24(1): 58–62.
- Gilbert, R.I., and Ranzi, G. 2011. *Time-Dependent Behaviour of Concrete Structures*. Spon Press, Oxon, UK, 426 pp.
- Helmuth, R.A. 1987. *Fly Ash in Cement and Concrete*. Portland Cement Association, USA, 203 pp.
- Kadri, E.H., and Duval, R. 2009. Hydration heat kinetics of concrete with silica fume. *Construction and Building Materials* 23(11): 3388–3392. doi: 10.1016/j.conbuildmat.2009.06.008.
- Klemczak, B., and Knoppik-Wróbel, A. 2011. Early age thermal and shrinkage cracks in concrete structures - description of the problem. *Architecture-Civil Engineering-Environment* 2: 35–48.
- Kwan, A.K.H., Au, F.T.K., and Lee, P.K.K. 2002. Minimizing shrinkage cracks in concrete structures for better serviceability and durability. *Proceedings, Innovative Buildings Symposium, Hong Kong*, pp. 117–136.
- Kwan, A.K.H., Au, F.T.K., Wong, H.H.C., and Ng, P.L. 2010a. Shrinkage of Hong Kong granite aggregate concrete. *Magazine of Concrete Research* 62(2): 115–126. doi: 10.1680/mac.2008.62.2.115.
- Kwan, A.K.H., Fung, W.W.S., and Wong, H.H.C. 2010b. Reducing drying shrinkage of concrete by treatment of aggregate. *Magazine of Concrete Research* 62(6): 435–442. doi: 10.1680/mac.2010.62.6.435.
- Kwan, A.K.H., Fung, W.W.S., Chen, J.J., and Ng, P.L. 2011a. Heat generation of curing fly ash concrete at different w/cm. *ACI Materials Journal* 108(3): 307–315.
- Kwan, A.K.H., Chen, J.J., Fung, W.W.S., and Ng, P.L. 2011b. Effects of silica fume on heat generation of curing concrete. *ACI Materials Journal* 108(6): 655–663.
- Kwan, A.K.H., Chen, J.J., Ng, P.L., and Fung, W.W.S. 2013a. Adding limestone fines, fly ash and silica fume to reduce heat generation of concrete. *Magazine of Concrete Research* 65(14): 865–877. doi: 10.1680/mac.12.00209.
- Kwan, A.K.H., McKinley, M., and Chen, J.J. 2013b. Adding limestone fines as cement paste replacement to reduce shrinkage of concrete. *Magazine of Concrete Research* 65(15): 942–950. doi: 10.1680/mac.13.00028.
- Kwan, A.K.H., and Wong, H.H.C. 2007. Shrinkage characteristics of concrete in Hong Kong. *Proceedings, Materials Science and Technology in Engineering Conference, Hong Kong*, pp. 1–10.

- Langan, B.W., Weng, K., and Ward, M.A. 2002. Effect of silica fume and fly ash on heat of hydration of Portland cement. *Cement and Concrete Research* 32(7): 1045–1051. doi: 10.1016/S0008-8846(02)00742-1.
- Loser, R., and Leemann, A. 2009. Shrinkage and restrained shrinkage cracking of self-compacting concrete compared to conventionally vibrated concrete. *Materials and Structures* 42(1): 71–82. doi: 10.1617/s11527-008-9367-9.
- Lundgren, M. 2005. Development of Strength and Heat of Hydration of Young Concrete at Low Temperature: Influence of Granulated Blast Furnace Slag, Silica Fume and Limestone Filler, Report TVBM-3129, Lund Institute of Technology, Lund, Sweden.
- Meland, I. 1983. Influence of condensed silica fume and fly ash on the heat evolution in cement pastes. ACI Special Publication SP-79, American Concrete Institute, USA, 665–676.
- Neville, A.M. 2011. *Properties of Concrete*, 5th Edition, Person, Harlow, UK, 846 pp.
- Ng, P.L., Fung, W.W.S., and Kwan, A.K.H. 2009. Experimental evaluation of shrinkage reducing agents using fibre-optic sensor. *Proceedings, Materials Science and Technology in Engineering Conference, Hong Kong*, pp. 85–97.
- Ng, P.L., and Kwan, A.K.H. 2012. Semi-adiabatic curing test with heat loss compensation for evaluation of adiabatic temperature rise of concrete. *HKIE Transactions, The Hong Kong Institution of Engineers* 19(4): 11–19. doi: 10.1080/1023697X.2012.10669000.
- Ng, P.L., Ng, I.Y.T., and Kwan, A.K.H. 2008. Heat loss compensation in semi-adiabatic curing test of concrete. *ACI Materials Journal* 105(1): 52–61.
- Özbay, E., Erdemir, M., and Durmuş, H.I. 2016. Utilization and efficiency of ground granulated blast furnace slag on concrete properties - a review. *Construction and Building Materials* 105: 423–434. doi: 10.1016/j.conbuildmat.2015.12.153.
- Sanchez De Rojas, M.I., and Frias, M. 1995. The influence of silica fume on the heat of hydration of Portland cement. ACI Special Publication SP-153, American Concrete Institute, USA, 829–844.
- Siddique, R., and Iqbal Khan, M. 2011. *Supplementary Cementing Materials*. Springer-Verlag, Berlin and Heidelberg, Germany, 287 pp.
- Wang, S.D., and Read, A.S. 1999. Trials of grade 100 high-strength concrete. *Magazine of Concrete Research* 51(6): 409–414. doi: 10.1680/mac.1999.51.6.409.

TABLES

Table 1 Workability and strength results of concrete mixes tested for heat generation

Mix no. (W/CM-LF -FA-SF)	SP dosage, % by weight of powder content	Slump, mm	Flow, mm	7-day cube strength, MPa	28-day cube strength, MPa
0.40-0-0-0	0.98	225	530	65.2	74.8
0.45-0-0-0	0.78	230	501	52.0	63.8
0.50-0-0-0	0.89	230	569	47.0	56.0
0.40-4-0-0	1.23	245	555	70.8	80.5
0.45-4-0-0	1.04	253	678	60.7	67.6
0.50-4-0-0	0.98	235	575	53.5	62.0
0.40-8-0-0	1.94	255	679	74.1	85.1
0.45-8-0-0	1.74	245	728	65.2	76.0
0.50-8-0-0	1.57	255	733	58.8	68.7
0.40-4-40-0	1.21	260	663	40.1	60.6
0.45-4-40-0	0.79	260	648	32.5	50.4
0.50-4-40-0	0.49	240	678	27.0	45.9
0.40-8-40-0	0.61	255	745	42.6	61.5
0.45-8-40-0	0.74	270	600	35.7	56.8
0.50-8-40-0	0.74	275	708	29.0	45.5
0.40-4-40-10	1.94	270	725	38.3	66.8
0.45-4-40-10	0.99	260	698	33.4	55.1
0.50-4-40-10	1.11	250	593	27.0	48.5
0.40-8-40-10	1.21	230	533	42.3	68.9
0.45-8-40-10	1.06	255	628	36.3	61.6
0.50-8-40-10	0.81	230	538	29.5	52.4

Table 2 Temperature rise and heat generation results

Mix no. (W/CM-LF -FA-SF)	Adiabatic temperature rise		Heat generation		Thermal strain, με
	Temperature rise after heat loss compensation, °C	Per cementitious materials content, °C/(100 kg/m ³)	Per volume of concrete, MJ/m ³	Per unit weight of cementitious materials, MJ/(100 kg)	
0.40-0-0-0	54.9	11.7	141.0	30.0	549
0.45-0-0-0	56.3	12.8	145.6	33.1	563
0.50-0-0-0	50.7	12.3	131.7	31.9	507
0.40-4-0-0	52.0	12.6	131.0	31.6	520
0.45-4-0-0	52.6	13.6	133.1	34.3	526
0.50-4-0-0	48.1	13.2	122.3	33.6	481
0.40-8-0-0	46.7	13.0	115.0	32.0	467
0.45-8-0-0	45.5	13.6	112.6	33.5	455
0.50-8-0-0	45.0	14.3	111.8	35.5	450
0.40-4-40-0	35.9	9.1	87.6	22.3	359
0.45-4-40-0	36.6	9.9	90.0	24.4	366
0.50-4-40-0	41.0	11.8	101.5	29.2	410
0.40-8-40-0	35.3	10.4	84.7	24.9	353
0.45-8-40-0	36.4	11.4	87.9	27.5	364
0.50-8-40-0	32.4	10.8	78.6	26.1	324
0.40-4-40-10	33.2	8.6	80.4	20.8	332
0.45-4-40-10	35.0	9.7	85.3	23.6	350
0.50-4-40-10	32.4	9.5	79.4	23.2	324
0.40-8-40-10	29.9	8.9	71.2	21.3	299
0.45-8-40-10	30.8	9.8	73.8	23.5	308
0.50-8-40-10	31.0	10.5	74.7	25.2	310

Table 3 Workability and strength results of concrete mixes tested for drying shrinkage

Mix no. (C-W/C-LF)	SP dosage, % by mass of powder	Slump, mm	Flow, mm	7-day cube strength, MPa	28-day cube strength, MPa
C-0.35-0	1.00	240	583	71.3	82.2
C-0.35-4	1.60	250	623	77.8	87.6
C-0.35-8	2.13	265	650	78.6	89.8
C-0.40-0	0.88	240	640	61.6	72.6
C-0.40-4	1.11	260	673	70.7	78.2
C-0.40-8	1.80	245	653	72.1	80.3
C-0.45-0	0.70	250	693	55.2	62.9
C-0.45-4	0.90	230	645	57.4	66.6
C-0.45-8	1.25	260	655	65.3	75.8
C-0.50-0	0.63	240	686	46.5	55.9
C-0.50-4	0.88	230	640	55.1	63.4
C-0.50-8	1.08	210	605	60.5	69.9
C-0.55-0	0.55	220	675	43.2	52.3
C-0.55-4	0.84	235	693	49.1	58.2
C-0.55-8	0.98	245	648	50.8	62.5
C-0.55-12	1.73	260	615	54.4	65.1
C-0.60-0	0.49	225	630	36.7	45.3
C-0.60-4	0.72	250	685	42.3	50.9
C-0.60-8	0.91	255	626	44.6	52.6
C-0.60-12	1.60	235	645	49.7	58.2

Table 4 Shrinkage measurement results

Mix no. (C-W/C-LF)	30-day shrinkage strain, $\mu\epsilon$	60-day shrinkage strain, $\mu\epsilon$	Ultimate shrinkage strain, $\mu\epsilon$	Shrinkage half-time, days
C-0.35-0	402	456	517	8.7
C-0.35-4	338	383	443	9.0
C-0.35-8	305	340	374	7.4
C-0.40-0	437	500	546	9.7
C-0.40-4	372	433	467	9.2
C-0.40-8	337	389	410	8.9
C-0.45-0	492	581	626	10.7
C-0.45-4	447	513	588	9.7
C-0.45-8	405	467	511	9.1
C-0.50-0	516	603	684	10.8
C-0.50-4	449	525	615	10.3
C-0.50-8	416	484	544	9.0
C-0.55-0	527	618	702	10.0
C-0.55-4	497	573	655	9.9
C-0.55-8	481	536	605	8.8
C-0.55-12	440	515	574	9.5
C-0.60-0	621	683	771	8.6
C-0.60-4	531	629	706	9.5
C-0.60-8	528	607	683	8.2
C-0.60-12	480	538	622	8.7
Note: The ultimate shrinkage strain is taken as the 180-day shrinkage strain; the shrinkage half-time refers to the time required for half of the ultimate shrinkage strain to develop.				

Table 5 Treatment applied to aggregate and water absorption

Aggregate group designation	Treatment applied	Water absorption, %		
		Fine aggregate	10 mm aggregate	20 mm aggregate
A1	As supplied	1.54	0.95	0.76
A2	Immersion in water	1.54	0.95	0.76
A3	Immersion in Ronafix for 6 hours and then drying	1.09	0.77	0.59
A4	Immersion in Darapel for 6 hours and then drying	1.06	0.77	0.67
A5	Immersion in Ronafix for 3 days and then drying	0.91	0.76	0.62
A6	Immersion in Darapel for 3 days and then drying	0.87	0.78	0.61

Table 6 Mass loss and shrinkage of concrete

Aggregate group designation	Mass loss, %	Ultimate shrinkage strain, $\mu\epsilon$	Reduction in shrinkage strain, %	Shrinkage half-time, days
A1	3.09	822	-	36
A2	3.44	812	-	33
A3	3.02	712	-13.4	34
A4	3.12	717	-12.8	40
A5	2.26	599	-27.1	18
A6	2.31	653	-20.6	22
Note: Each value reported is the averaged value of the four specimens tested.				

FIGURES

Figure 1 Adiabatic temperature rise

Figure 2 Adiabatic temperature rise per cementitious materials content

Figure 3 Cube compressive strengths

Figure 4 Concurrent heat generation per volume of concrete and cube strength

Figure 5 Effect of LF volume on ultimate shrinkage strain

Figure 6 Effect of LF volume on shrinkage half-time

Figure 7 Percentage reduction in ultimate shrinkage strain due to addition of LF

Figure 8 Effects of cement paste volume on ultimate shrinkage strain and shrinkage half-time

Figure 9 Effects of concrete strength on ultimate shrinkage strain and shrinkage half-time (CPV means cement paste volume)

Figure 1

Figure 2

(a) 7-day cube strength

(b) 28-day cube strength

Figure 3

(Note: The three points along each heat generation vs. strength curve correspond to concrete mixes with W/CM ratios of 0.40, 0.45 and 0.50)

Figure 4

Figure 5

Figure 6

Figure 7

(a) Ultimate shrinkage strain versus cement paste volume

(b) Shrinkage half-time versus cement paste volume

Figure 8

(a) Ultimate shrinkage strain versus 28-day cube strength

(b) Shrinkage half-time versus 28-day cube strength

Figure 9

APPENDIX 1

App Table 1 Mix proportions of concrete mixes tested for heat generation

Mix no. (W/CM-LF -FA-SF)	Water content, kg/m ³	Cement content, kg/m ³	LF content, kg/m ³	FA content, kg/m ³	SF content, kg/m ³
0.40-0-0-0	188	470	0	0	0
0.45-0-0-0	198	440	0	0	0
0.50-0-0-0	207	413	0	0	0
0.40-4-0-0	166	415	106	0	0
0.45-4-0-0	175	388	106	0	0
0.50-4-0-0	182	364	106	0	0
0.40-8-0-0	144	359	211	0	0
0.45-8-0-0	151	336	211	0	0
0.50-8-0-0	158	315	211	0	0
0.40-4-40-0	157	235	106	157	0
0.45-4-40-0	166	221	106	147	0
0.50-4-40-0	174	208	106	139	0
0.40-8-40-0	136	204	211	136	0
0.45-8-40-0	144	192	211	128	0
0.50-8-40-0	150	180	211	120	0
0.40-4-40-10	154	193	106	154	39
0.45-4-40-10	163	181	106	145	36
0.50-4-40-10	171	171	106	137	34
0.40-8-40-10	134	167	211	134	33
0.45-8-40-10	141	157	211	126	31
0.50-8-40-10	148	148	211	118	30

App Table 2 Mix proportions of concrete mixes tested for drying shrinkage

Mix no. (C-W/C-LF)	Cement paste volume, %	Water content, kg/m ³	Cement content, kg/m ³	LF content, kg/m ³
C-0.35-0	34	177	505	0
C-0.35-4	30	156	445	106
C-0.35-8	26	135	386	211
C-0.40-0	34	188	470	0
C-0.40-4	30	166	415	106
C-0.40-8	26	144	359	211
C-0.45-0	34	198	440	0
C-0.45-4	30	175	388	106
C-0.45-8	26	151	336	211
C-0.50-0	34	207	413	0
C-0.50-4	30	182	364	106
C-0.50-8	26	158	315	211
C-0.55-0	34	214	389	0
C-0.55-4	30	189	343	106
C-0.55-8	26	164	297	211
C-0.55-12	22	138	251	317
C-0.60-0	34	221	368	0
C-0.60-4	30	195	325	106
C-0.60-8	26	169	281	211
C-0.60-12	22	143	238	317

App Table 3 Mix proportions of concrete specimens for investigation of aggregate treatment

Grade	40
Paste volume, %	30
Water content, kg/m ³	179
Cement content, kg/m ³	374
Fine aggregate, kg/m ³	764
10 mm aggregate, kg/m ³	352
20 mm aggregate, kg/m ³	703
Note: Design mean compressive strength = 48 MPa, W/C ratio = 0.48, fine/total aggregate ratio = 0.42.	