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1 (Ref: JCBM 10020)

2 **Investigation of effects of Portland cement fineness and alkali content on**
3 **concrete plastic shrinkage cracking**

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10 **Abstract**

11 From a material viewpoint, modern concrete's frequent propensity to plastic shrinkage cracking can
12 be attributable to a combination of low water-binder ratio use and ever-changing properties of binding
13 materials. To obtain a better understanding of this phenomenon, this paper explores the effects of
14 cement fineness and alkali content on the plastic shrinkage cracking of concrete manufactured with
15 two water-binder ratios. Results indicate that within the range 275-385m²/kg, cement specific surface
16 area is approximately directly and inversely proportional to hydration rate and evaporation rate
17 respectively; a trend generally leading to higher plastic shrinkage and resulting areas of plastic
18 cracking. Similar effects were observed for alkali contents which resulted in increased levels of plastic
19 shrinkage. Furthermore, while decreasing crack tendency was noted as alkali content increased from
20 0.4 to 0.8% by mass of cement, further increases in alkali content caused significant decreases of
21 compressive strength and slump; thereby lowering overall concrete performance. It is also found that
22 plastic shrinkage cracking is closely related to the kinetics of plastic shrinkage. In summary, the
23 experimental programme confirmed that cement with relatively low surface area (less than 340 m²/kg)
24 and low alkali content (less than 0.8%) is preferred for modern concretes with minimal plastic
25 cracking problems.

26 **Keywords:**

27 Shrinkage, Concrete and cement, Concrete structures, Moisture loss

28

1. Introduction

Plastic shrinkage refers to shrinkage of concrete occurring in the first 24 hours after batching, caused by external drying and cement hydration effects [1, 2]. These cracks do not only affect aesthetics of structures, but also permit transport of moisture and other aggressive species. As a result, concrete strength and durability performance can be compromised [3, 4]. Reflecting its seriousness, the topic of plastic shrinkage and cracking has been the focus of concrete researchers and engineers for decades [5-7].

Despite best efforts to avoid the problem [2, 6, 7], plastic shrinkage cracking is still very common in regions where the weather is hot and dry. This is particularly true for modern concretes which appear more sensitive to cracking immediately after setting [8]. From a material point of view, the main factors attributing to this trend include changes in binder material properties, high binder contents, low water/cement ratio (W/C) and admixture use and variability [9, 10]. As such, high cracking frequencies cannot be considered as completely unexpected. While considerable literature exists covering different parameter effects on plastic shrinkage and plastic cracking [2, 9, 11, 12], the influence of cement properties is still relatively unexplored. Clearly this knowledge would provide construction professionals with a relatively straightforward material specification approach to reducing risks associated with plastic cracking.

This guidance would, for example, be particularly welcomed by construction professionals in China. After 20 years of development focussed along its eastern seaboard, considerable infrastructure construction is now underway in the south west of China.

A general concern for the construction industry in this area is plastic cracking due to the demanding environment conditions in this region where temperatures at concrete surfaces in the summer can easily reach 60 °C with wind speeds varying from 5-10 m/s. Furthermore, while properties of local cements have undergone several changes in recent years, few published reports outlining these changes, not to mention their effects on plastic shrinkage cracking, are available.

Conscious of these problems, a western traffic science and technology project was funded in 2009 to survey properties of cement throughout the southwest part of China and investigate their effects on plastic cracking [13]. Chemical and physical properties of cements from 233 manufacturers were examined and the primary results are given **Figure 1**. It can be seen from **Figure 1** that around 86 % of cements have a specific area varying from 320-360 m²/kg, with 9 % having an even higher specific area (>360 m²/kg). The other trend noted is high cement alkali content, with 95 % samples having values higher than 0.6 % by mass. These trends in cement production are similar to those experienced in Western counties, where finer materials were introduced to deliver perceived performance benefits

1 such as increased strengths, reduced cement contents for a given specific strength, earlier removal of
2 formwork, and faster construction times [14-16]. Unfortunately, such benefits are also associated with
3 potential disadvantages such as an increased risk of plastic shrinkage cracking.

4 This paper addresses the effect of Portland cement quality, namely in terms of fineness of cement
5 particles and alkali content, on plastic shrinkage cracking. A comprehensive experimental programme
6 is reported with results for hydration rate, evaporation, plastic shrinkage, crack width and cracking
7 area presented. These results are intended to provide engineers and contractors with an insight into the
8 fundamental behaviour of plastic cracking and assistance in selecting proper approaches to its
9 avoidance.

10 **2. Experimental programme**

11 2.1 Experimental variables investigated

12 Based on data obtained from the aforementioned survey of cement [13] and relevant literature [17-
13 19], the three main parameters considered in this study were cement fineness, cement alkali content
14 and water-cement ratio (W/C). As summarised in **Table 1**, ranges considered for these properties
15 were 275-385 m²/kg, 0.4-1.2 % by mass and 0.35-0.40 respectively.

16 To prepare cements with different fineness and alkali contents, pure clinker manufactured from
17 Lafarge, as characterised chemically in **Table 2**, was used. The clinker was ground for different
18 periods in a ball mill to yield the required fineness levels of 275, 337 and 385 m²/kg. In each case,
19 gypsum was added at a rate of 5 % by mass.

20 Alkali contents were adjusted by adding NaOH (chemical pure) into water during the concrete mixing
21 stage to ensure equivalent cement alkali contents of 0.4, 0.8 and 1.2 % by mass.

22 The effect of W/C (0.35 and 0.4) on shrinkage-induced cracking was also investigated, mainly
23 because low W/C is a key feature of modern concretes generally leading to increased autogenous
24 shrinkage and early age cracking sensitivity [12, 20].

25 As plastic shrinkage cracking relies heavily on numerous parameters, including: water evaporation
26 rate; settlement and capillary pressure; hydration kinetics; concrete materials and mix proportions;
27 and environmental conditions (e.g. temperature, relative humidity and wind speed) [5, 11, 18],
28 assessment of its risk is not straightforward and not easily determined by considering only selective
29 properties [21-23].

1 Therefore, a comprehensive range of assessment techniques was employed to consider general
2 concrete properties (slump and compressive strength), influencing properties (cement hydration, water
3 evaporation rate, plastic shrinkage levels) and response properties (maximum cracking width,
4 cracking area). This testing programme is also summarised in **Table 1**.

5 2.2 Concrete mixes

6 **Table 3** shows the quantities of the constituent materials used in each of the concrete mixes
7 investigated. Ten concretes were tested in total resulting from the two W/C ratios (0.35 and 0.4), three
8 levels of cement fineness (275, 337 and 385 m²/kg) and three levels of cement alkali content (0.4, 0.8
9 and 1.2 % by mass) considered. The approach used was to hold the cement content constant at 420
10 kg/m³ and adjust the water content to achieve the require W/C. In terms of workability, all concrete
11 mixes were designed for a slump range of 160±20 mm. To obtain this, suitable dosages of a
12 polycarboxylic acid-based polymer superplasticiser (SP) were used. The fine aggregate (FA) was
13 medium graded natural sand and the coarse aggregate (CA) crushed limestone comprising both 10 and
14 20 mm sized materials proportioned in a ratio of 3:7. The water used in the study was from the mains
15 supply in Chongqing.

16 Concrete was prepared using a pan mixer with a capacity of 0.035 m³ and tested for slump
17 immediately after mixing according to GB/T 50080 [24]. From **Table 3**, it can be seen that all
18 concretes achieved, or closely achieved, the target slump range. The main exception was the concrete
19 prepared with 0.35 W/C and cement alkali content of 1.2 % by mass. In this instance, the low slump
20 achieved (98 mm) was most likely due to the superplasticiser's inability to function properly at such a
21 high alkali condition.

22 2.3 Test methods

23 2.3.1 Calorimetry

24 The process of cement hydration was measured by an isothermal calorimeter (TAM Air-8 channel)
25 sensitive to ±20 μW. Five minutes after mixing, cement paste samples with a water:cement ratio of
26 0.4 were placed into the calorimeter and the first environment-calibrated reading captured 10 minutes
27 later. All subsequent measurements were carried out at an ambient temperature of 20 °C with a time
28 resolution of 1 min. While it is recognized that cement paste samples do not fully represent concrete
29 hydration rates, the calorimetry results were used to provide an indication of the effect of cement
30 fineness and alkali content on the kinetics of hydration.

31

1 2.3.2 Plastic shrinkage

2 Immediately after casting, plastic shrinkage was assessed using the non-contact method specified in
3 GB/T 50082 [25]. As illustrated in **Figure 2**, a non-contact laser transducer was used to measure
4 linear movement in 100x100x500 mm³ concrete specimens via reflecting plastic probes placed in the
5 end face of each specimen. To limit friction and seal joints, the inner walls of specimen moulds were
6 coated with Teflon tapes and mould surfaces covered with two layers of plastic sheet.

7 Moulds were filled with concrete in two layers and compacted on a vibrating table until no air
8 appeared at the surface. Immediately after casting, specimens were subjected to high evaporation rates
9 in a wind tunnel under controlled extreme environment conditions (20 ± 2 °C, 60 ± 5 % relative
10 humidity (RH), and wind speed 8 ± 2 m/s).

11 Plastic shrinkage measurements were recorded and logged on a computer every 10 minutes for 24
12 hours.

13 2.3.3 Plastic cracking

14 Plastic shrinkage induced cracking was measured by a method developed by Chongqing University
15 and similar to that prescribed in ASTM-C1579 [26]. As shown in **Figure 3**, 380×600×70 mm³
16 concrete slabs were cast in moulds comprising a profiled base providing two outer horizontal
17 restraints and a central crack-inducer.

18 After casting and compaction, the test moulds were exposed to the extreme environmental exposure
19 described above for plastic shrinkage assessment (temperature: 20 ± 2 °C; RH: 60 ± 5 %; wind speed:
20 8 ± 2 m/s).

21 Crack initiation was determined visually by inspecting specimen surfaces every 30 minutes. After 6
22 hours, maximum and mean cracking widths were visually measured using a microscope (100x
23 magnification). The length and average width of cracks was recorded and expressed as total cracked
24 area. Two moulds were prepared for each concrete mix and the average value reported.

25 2.3.4 Rate of water evaporation

26 In parallel with studies of plastic shrinkage and plastic shrinkage cracking, evaporation rates were
27 determined for all mixtures using cylindrical water samples ($\Phi 200$ mm×30 mm). Specimens were
28 subjected to the same exposure conditions used for measuring plastic shrinkage cracking
29 (temperature: 20 ± 2 °C; RH: 60 ± 5 %; wind speed: 8 ± 2 m/s) and weighed to a precision of 0.01 g. The
30 rate of water evaporation was determined by dividing the mass loss by the surface of the cylinder.

1 3. Results and discussion

2 3.1 Effect of cement fineness and alkali content on cement hydration and compressive 3 strength

4 Provided in **Figure 4** are established relationships between cement fineness and hydration. Clearly
5 from **Figure 4-a**, total heat of cement hydration is positively related to the specific area of cement
6 particles, with evolved heat increasing from 219 to 253 J/g as the specific area of cement increased
7 from 275 to 385 m²/kg. As a result, and illustrated in **Figure 4-b**, this led to higher rates of total heat
8 release, with a value range of 2.5-3.9mW/g corresponding to cement specific areas of 275-385 m²/kg.
9 Also clear from **Figure 4-b** is that the significant effect of particle size on cement hydration was
10 apparent for the first 12 hours only. Thereafter, paste hydration rates were nearly equivalent. The
11 trends noted in **Figure 4** are, perhaps, not surprising as it is recognised that higher specific area aids
12 the dispersion of cement and speeds reactions during early hours; particular for periods where
13 hydration is controlled by nucleation and growth [27, 28]. Important for this study, rapid hydration is
14 predicted to cause several changes in concrete properties, including less bleeding, loss of workability,
15 and faster development of shrinkage, strength and elastic modulus. As a result, coarser cement is
16 potentially preferable for making modern concrete.

17 Relationships between alkali content and cement hydration are shown in **Figure 5**. Similar to effects
18 of cement fineness, it can be seen that increasing alkali content generally accelerated cement
19 hydration. However, while increases in both heat and rate of hydration were noted as alkali contents
20 increased from 0.4 to 0.8% by mass of cement, this relationship was not positive as the alkali content
21 increased to 1.2% by mass. This finding suggests that hydration is not a simple function of alkali
22 content, which is justifiable given that alkali is known to affect both physical and chemical conditions
23 of hydration [14, 29].

24 With compressive strength being a key concrete property reflecting processes of both hydration and
25 micro-structure development, impacts of cement fineness and alkali content on this parameter are
26 shown in **Figure 6**.

27 As shown in **Figure 6-a**, relationships between concrete compressive strength and cement fineness
28 are similar to the calorimetry-based trends plotted in **Figure 4**, with increasing cement fineness
29 correlating to improved concrete strength. For 0.35 water:cement ratio concrete, for example, 28-day
30 strengths increased from 61-74 MPa as cement fineness increased from 275-385 m²/kg. With respect
31 to effects of alkali content the opposite trend was observed, with compressive strength generally
32 decreasing with increasing alkali content. For 0.35 water:cement ratio concrete, for example, 28-day
33 strengths decreased from 68-49 MPa as alkali contents increased from 0.4-1.2 % by mass of cement.

1 This trend may be attributed to the formation of less favourable microstructures caused by
2 modifications to the morphology of C-S-H and calcium hydroxide phases [15, 27].

3 Also clear from **Figure 6** is that the influences of cement fineness and alkali content described above
4 were more pronounced at the lower W/C ratio concrete, suggesting that modern concretes may be
5 more sensitive to changes in cement properties.

6 3.2 Effect of cement fineness and alkali content on plastic shrinkage of concrete

7 Illustrated in **Figure 7** are influences of W/C ratio and cement fineness on the plastic shrinkage of the
8 six concretes examined in this study. Over the 24-hour test period, plastic shrinkage trends may be
9 summarised in the following distinct stages.

10 In the initial 7 hours, plastic shrinkage of all concretes evolved linearly with time, with rates clearly
11 dependent on cement fineness. Corresponding 7-hour shrinkage values for concrete made with cement
12 fineness 275, 337 and 385 m²/kg were 490, 900 and 1500 µm/m respectively. Conversely, little or no
13 impact of W/C ratio was noted during this period. While rates of plastic shrinkage significantly
14 decreased from 7-12 hours, a clear impact of W/C ratio emerged in this period, with lower W/C ratio
15 concrete exhibiting higher shrinkage at each cement fineness level. For concretes using cement with a
16 fineness of 337 m²/kg, for example, 12-hour shrinkage values for the 0.35 and 0.40 W/C concretes
17 were 2,000 and 1,400 µm/m respectively. Beyond this period, plastic shrinkage increased marginally
18 until constant values were reached at approximately 18 hours.

19 Within the initial 0-7 hour period, plastic shrinkage is known to involve both autogenous and drying
20 shrinkage [2, 6, 20, 23], with the former mainly caused by chemical shrinkage as self-desiccation
21 effects may not have started yet [4, 28]. Equally, it is reported that higher values of cement fineness
22 generally lead to accelerating hydration rates of the clinker particles [30] (evidenced in this study by
23 **Figure 4**), resulting in higher chemical shrinkage levels at early ages.

24 In terms of drying shrinkage effects, increasing cement fineness and decreasing W/C may have
25 resulted in increased levels of induced capillary tension. An explanation for this may be that finer
26 cement and lower W/C results in denser concrete pore structures, thereby raising capillary tension
27 levels. Indeed, according to the Laplace's equation [18, 31, 32] capillary depression is inversely
28 proportional to pore diameter. Effects of cement fineness and W/C ratio on concrete bleeding and
29 surface water evaporation rates may also further justify differences in capillary tension levels. It is
30 proposed, therefore, that the use of fine cement and lower W/C concrete will lead to reduced bleeding
31 rates and increased capillary tension levels, even at relatively low surface water evaporation rates.

1 The effect of cement fineness and W/C on surface water evaporation rate is illustrated in **Figure 8**. As
2 expected, increasing specific area of cement and decreasing W/C led to a decrease in the amount of
3 water evaporation. While previous work [12, 33] has indicated a direct correlation between plastic
4 shrinkage levels and evaporation rates, other factors such as bleeding amount, W/C ratio and
5 environmental conditions are also important. This is because capillary tension is formed and drying
6 shrinkage develops, once water evaporation exceeds bleeding rates.

7 To assess the effect of alkali content, **Figure 9** presents relationships between plastic shrinkage and
8 time for concrete with a W/C ratio of 0.35 and 0.40 and alkali contents varying from 0.4 to 1.2% by
9 mass of cement. As was the case for effects of cement fineness in **Figure 7**, the results in **Figure 9**
10 may be summarised in several distinct stages over the 24-hour test period, including: rapidly and
11 gradually increasing shrinkage from 0-7 and 7-12 hours respectively, followed by minimal increases
12 thereafter.

13 Unlike the influence of cement fineness, however, complex interactions between alkali content, W/C
14 ratio and plastic shrinkage were noted in **Figure 9**. For the 0.40 W/C ratio concrete, for example,
15 concretes with alkali content 0.4 and 1.2 % yielded similar ultimate shrinkage levels (1,300 $\mu\text{m}/\text{m}$)
16 after 24 hours, compared to a higher value (1,500 $\mu\text{m}/\text{m}$) for the 1.2 % alkali content concrete. With
17 higher shrinkage levels measured for the 0.35 W/C ratio concretes, ultimate values of 1,700, 2,500
18 and 1,800 $\mu\text{m}/\text{m}$ were measured for the 0.4, 0.8 and 1.2 % alkali content concretes after 24 hours.

19 In general, increasing shrinkage with alkali content was expected due to chemical shrinkage affects,
20 as addition of alkali introduced more OH^- in the matrix; thereby accelerating cementitious reactions,
21 and in particular those associated with C_3A and C_3S [27, 34]. This potential effect is particularly
22 significant for the first 10 hours as shown in **Figure 4**. The non-linear trends noted in **Figure 9** are
23 considered to correspond to induced variations of bleeding, evaporation and surface tension of pore
24 solution caused by increases in alkali contents.

25 Relationships between evaporation rate and alkali content are given **Figure 10**, which clearly shows
26 decreasing rates with increasing alkali content, particularly for the 0.40 W/C concrete. Evaporation
27 rates plotted in **Figure 10** are lower than that shown in **Figure 8**, especially for concretes with a W/C
28 ratio of 0.4. This corresponds to the fact that initial ion concentration is relatively low and additional
29 alkali can raise the concentration significantly. As sodium hydroxide accelerated cement hydration,
30 the time for concrete to maintain its plasticity was shortened, quickly forming a solid skeleton which
31 made it difficult for bleeding water to move to the surface. Meanwhile, it is known that addition of
32 alkali can reduce vapour pressure according to Raoult's law [35]. In other words, it becomes more
33 difficulty to remove bleeding water from the surface. Clearly a combination of lower levels of
34 bleeding water and vapour pressure would result in less surface evaporation occurring.

1 Despite lower evaporation rates, this does not necessarily imply lower plastic shrinkage values. As
2 dictated by fundamental thermodynamic theory [35], the surface tension of liquids is directly related
3 to its concentration of soluble inorganic salt. In this study, sodium hydroxide was added in the system
4 and, as a result, surface tension is believed to increase with increasing alkali contents. Furthermore,
5 less bleeding water on the surface of concrete accelerates build-up of capillary pressure. Assuming all
6 other variables to be constant, therefore, any increase in alkali content should lead to greater surface
7 tension due to formation of a finer concrete pore structure leading to greater capillary pressures.
8 Therefore, plastic shrinkage increases with alkali content due to its induced chemical and drying
9 shrinkage.

10 Note that compressive strength and slump results for concrete with 1.2 % by mass alkali content
11 (shown in **Table 3** and **Figure 6**) exhibited abnormal trends, suggesting that high alkali content not
12 only cause high shrinkage but also raises other practical issues.

13 An interesting aspect to be noted from **Figure 7** and **9** is that the effect of W/C only became
14 significant from 7 to 10 hours. As indicated from the calorimetry data (**Figures 4** and **5**), only very
15 small differences in hydration reactions were noted after 12 hours despite the different cement
16 fineness and alkali contents. It may be deduced that this effect is mainly caused by drying, rather than
17 chemical shrinkage. This means that shrinkage in the first 7 hours was mainly controlled by the
18 properties of cement. Beyond this time, a solid skeleton was developed and the extra water taken up
19 early due to osmotic effects (plus bleeding water, if present) combined with water driven through the
20 membrane by relative humidity and pressure gradients. Accelerated hydration yielded a finer pore
21 structure making moisture transport more difficult. Use of a low W/C (corresponding to low water
22 content) means lack of bleed water to replace evaporating water. As a result, plastic shrinkage of
23 concrete with low W/C and faster hydration rate achieves the highest value. This confirms
24 recommendations of Aictin and Neville [36], who concluded that, under constant testing conditions,
25 high performance concrete tends to have greater shrinkage at early stages than normal concrete.

26 3. 3 Effect of fineness of cement and alkali content on plastic cracking of concrete

27 Maximum crack width is recognised as a common parameter describing plastic cracking behaviour,
28 which should be carefully controlled for the safety of concrete structures. **Figure 11-a** plots measured
29 values in relation to cement fineness and W/C ratio. Clearly from this figure, W/C ratio had a
30 significant influence on crack width, with higher values noted for 0.40, in comparison to 0.35 W/C
31 concretes considered. Also evident is a trend of decreasing crack width with increasing specific area
32 of cement. This was especially pronounced for the 0.40 W/C concrete, with crack widths decreasing
33 by around 50 % (from 2.1 to 1.2 mm) as cement specific area increased from 275 to 385 m²/kg. For
34 the 0.35 W/C concrete, this decrease was lower at around 20 %, with crack widths reducing from 1.1

1 to 0.8 mm as cement specific area increased from 275 to 385 m²/kg. These trends are expected and
2 attributable to increased particle settlement and lower tensile strength associated with concretes with
3 higher W/C and coarser cement. Finer cement speeds up hydration processes resulting in higher
4 tensile strength and improved cracking-resistance. This impact is especially significant for high W/C
5 concrete, as slow rates of tensile strength development mean that relative small restrained shrinkage
6 can be high enough to cause cracking [7, 21, 37].

7 As plastic cracking of concrete is a complicated phenomenon not fully explained by maximum
8 cracking width data alone, the influence of cement fineness on total cracking area was also examined
9 as shown in **Figure 11-b**.

10 It is recognised that cracks less than 0.3 mm wide are considered not to directly influence the safety of
11 concrete structures, so are typically ignored by structural designers. However, these cracks have a
12 significant impact on durability, as detrimental ions or matter can transport more rapidly into
13 concrete. Given also that total cracking area is always associated to the materials (concrete, mortar or
14 paste) in question, this parameter was also considered in this study. Similar to the results in **Figure**
15 **11-a**, W/C ratio had a clear effect, with 0.4 W/C concrete generally yielding significantly greater
16 cracking areas than 0.35 W/C concrete. In this case, however, increasing specific area of cement
17 particles resulted in corresponding increases in total areas of cracking. Furthermore, concrete with the
18 lower W/C of 0.35 appeared more sensitive to cement fineness, with a 20 % increase (from 320 to 390
19 mm²) in cracked area noted. The corresponding increase for 0.4 W/C concrete was around 5 % (from
20 590 to 620 mm²). This trend appears to be somewhat contrary to results in **Figure 11-a**, indicating the
21 complicated nature of plastic cracking.

22 Combining the results in **Figures 11-a** and **b**, it may be deduced that plastic cracks become longer and
23 finer when cement with a higher specific surface is used. In other words, the intensity of plastic
24 cracking increases with decreasing size of cement particles and this feature is more significant for
25 concrete with lower W/C. As the tensile strength of concrete with higher W/C and coarser cement
26 develops more slowly, cracking may occur earlier and, after this, stress is relieved. At the same time,
27 resultant stresses start to redistribute, leading to increasing crack width and depth [32]. Therefore,
28 cracks tend to take place at earlier stages for concrete with a higher W/C and coarser cement, which
29 naturally leads to wider but fewer cracks.

30 **Figure 12** plots the relationship between both maximum crack width and total area of cracking versus
31 cement alkali content. It can be seen from **Figure 12-a** that concrete with higher W/C generally
32 exhibited greater crack widths, albeit that this trend diminished with increasing cement alkali content.
33 This is because cement alkali content had a limited effect on maximum crack width for the 0.40 W/C
34 concrete, whereas crack widths increased rapidly with increasing cement alkali content for the 0.35

1 W/C concrete. Indeed, it can be seen from **Figure 12-a** that at a cement alkali content of 1.2% by
2 mass, the maximum crack width of the 0.35 W/C concrete (1.75 mm) exceeded that of the 0.40 W/C
3 concrete (1.5 mm).

4 It can be seen from **Figure 12-b**, which plots total cracked area as a function of cement alkali content,
5 that total cracked area dramatically decreased as cement alkali content increased from 0.4 to 0.8 % by
6 mass of cement. This decrease was particularly marked for the 0.40 W/C ratio concrete, with cracked
7 areas decreasing from 620 to 400 mm². For the 0.35 W/C concrete, corresponding values of cracked
8 area were 350 and 300mm². As alkali content increased to 1.2 % by mass, further decrease in cracked
9 area for the 0.40 W/C ratio concrete were minimal, while for the 0.35 W/C ratio concrete values
10 increased to 400 mm². This trend suggests that suitable amounts of alkali can reduce plastic cracking,
11 but the opposite may occur if the alkali content is too high. This finding may be explained by the fact
12 that alkali content not only affect rates of hydration acceleration, but also surface tension, bleeding
13 and evaporation processes [27, 28]. As a result, no simple relationship can be established between
14 cement alkali content and cracking behaviour.

15 As one principal cause of plastic shrinkage cracking is evaporation of water, various
16 recommendations, for example ACI 305 [38], have been proposed to assess associated risks. **Figure**
17 **13** plots relationships between evaporation rate at 5 hours and both maximum cracking width and total
18 area of cracking. As expected, both cracking-related parameters generally rise continuously with
19 increasing evaporation rate, but these relationships are broad and do not follow a simple function.

20 This suggests that moisture loss at early ages is a main driving force for plastic cracking occurrence,
21 but that considering this parameter alone may not be sufficient to more accurately predict cracking
22 performance. In addition, all evaporation rates plotted in **Figure 13** are less than the ‘high-risk’
23 evaporation rate of 1.0 kg/m²h specified in ACI 305 [38]. This observation is perhaps not surprising,
24 given the approach employed in the current study. Firstly, rates of evaporation clearly rely on
25 bleeding associated with specific concretes. As indicated in previous sections, the concretes tested in
26 this study had relatively low W/C, resulting in corresponding low bleeding rates. Secondly, drying at
27 early ages is a very complex process, involving various chemical and physical processes [4, 15, 38].
28 As such, properties of concrete can no longer be considered constant and simplified calculations
29 cannot be used to make predictions. Accurate predictions of cracking, therefore, cannot be
30 successfully performed based on magnitudes of water evaporation alone. This agrees with work by
31 Bjøntegaard et al. [10] and Kwak and Ha [21] who have pointed out similar issues associated with
32 assessing risks of plastic cracking using evaporation rates.

33 Against this background, careful consideration of several parameters is required to better understand
34 effects of cement fineness and alkali content on plastic cracking. Internal concrete properties and

1 external actions of significance include tensile strength, elastic modulus (E-modulus), creep, restraint
2 conditions and shrinkage at early ages [11, 17, 37]. If shrinkage of concrete is restrained, tensile
3 stresses generated lead to cracking when the tensile strength of concrete is exceeded. As cement
4 hydration progresses, increasing tensile strength is beneficial in terms of avoiding cracking risk while
5 increasing E-modulus is potentially detrimental as a given restrained deformation will produce a
6 higher stress [6, 33]. Furthermore, to estimate plastic shrinkage-induced stress, values of net shrinkage
7 (equal to total shrinkage minus creep) and effect of restrict conditions are required. Although the
8 restraint condition is a constant in this study owing to the test set-up used, it is difficult and
9 expensive to obtain values of creep relaxation for early age concrete [18, 21]. An alternative approach
10 is to consider total values and kinetic characteristics of shrinkage to assess risks of plastic cracking, as
11 they are directly related to the magnitude of creep and shrinkage-induced stress [28, 32].

12 For concrete with a W/C of 0.40 only, **Figure 14** plots shrinkage values and derived growth rates of
13 shrinkage against time up to a period of six hours after mixing. These properties are plotted to
14 investigate the influence of both cement fineness (**Figures 14-a** and **-b**) and alkali content (**Figures**
15 **14-c** and **-d**). From **Figure 14-a**, concrete made with finer cement (385 versus 275 m²/kg) exhibited
16 significantly larger shrinkage after six hours (1,200 versus 450 μm/m). **Figure 14-b** confirms
17 corresponding higher rates of shrinkage development with time for the finer cement concrete, with
18 peak rates occurring around four hours after mixing. Peak shrinkage rates for the 385 and 275 m²/kg
19 cement fineness concrete were 200 and 85 μm/m.h respectively. These trends indicate that relaxation
20 due to creep becomes lower, yielding higher induced stresses. Consequently, it is reasonable to predict
21 higher cracking areas for concrete made with finer cements.

22 Compared with **Figure 14-a**, similar trends for the effect of cement alkali content are clear from
23 **Figure 14-c**, with higher alkali content (0.8 versus 0.4 % by mass) resulting in larger shrinkage after
24 six hours (1,150 versus 740 μm/m). A feature to note from **Figure 14-d** is the effect of alkali content
25 on the rate of shrinkage growth within the first few hours of hydration. Clearly the concrete
26 containing low alkali cement (0.4 % by mass) exhibited significantly greater growth rates within first
27 2-3 hours. This may be associated with both lower evaporation rates due to increased surface tension
28 and acceleration of hydration. This implies that stress relaxation increases with alkali content up to 2-
29 3 hours after mixing, giving a reduced cracking risk. After 2-3 hours, corresponding to the time of
30 initial setting, the network of the solid particles becomes progressively stiffer, leading to higher
31 tensile strength and ability to resist cracking. Consequently, it may be concluded that total cracking
32 areas are likely to decrease with increasing cement alkali content.

33 Special attention should be given to effects of alkali content, however, as decreased cracking tendency
34 may not always be seen, especially for concrete with low W/C ratio. Furthermore, high alkali contents

1 may also contribute to longer term concrete durability problems [39, 40] and incompatibility with
2 admixtures such as superplasticisers [27, 28].

3 **Conclusions**

4 In the southwest of China, Portland cement properties are highly variable, with fineness values
5 generally in the range 320-360 m²/kg and alkali contents typically below 0.9 % by mass of cement.
6 Experimental results from the comprehensive research study reported indicate that both cement
7 fineness and alkali content have a significant influence on hydration kinetics, bleeding, evaporation,
8 plastic shrinkage and plastic shrinkage cracking of cement-based materials. Based on the data
9 reported, the following main conclusions can be drawn:

- 10 1. Increasing cement fineness results in increased hydration and decreased evaporation rates for a
11 given W/C and constant cement hydration environment. As such, both plastic shrinkage and
12 compressive strength of concrete increase with increasing cement fineness. Concrete made using
13 coarser cement is likely to exhibit slightly higher cracking widths, but reduced intensity of plastic
14 cracking in comparison to finer cement concretes. Although no up limit of cement fineness is
15 specified in the Chinese national standard (Common Portland cement: GB-175), Portland cement
16 fineness should ideally be limited at around 350 kg/m² to prevent plastic cracking. This limit will
17 also have positive energy and greenhouse gas impacts due to reduced grinding times.
- 18 2. While increasing cement alkali content accelerates cement hydration and decreases water
19 evaporation rates, other key concrete properties are not improved. For example, slump, plastic
20 shrinkage and compressive strength values of concrete are all impacted upon negatively as
21 cement alkali content increases above 0.8 % by mass. With respect to plastic shrinkage cracking,
22 an appropriate level of alkali content (less than 0.8 % by mass) is beneficial for reducing
23 cracking widths and areas, especially for concrete with high W/C ratios.
- 24 3. Results of testing undertaken to assess water evaporation rates alone are not reliable and
25 sufficient to assess risks of concrete plastic cracking. This is because plastic shrinkage cracking
26 is a complex phenomenon involving various interdependent influencing factors, including tensile
27 strength, creep, E-modulus, restraint conditions and shrinkage characteristics.
- 28 4. To enable predictions of plastic cracking risk, it is critical to appreciate overall characteristics of
29 shrinkage at different stages (total shrinkage and shrinkage kinetics) which are helpful to control
30 potential cracking. Results indicate that concrete with a high shrinkage rate in the first 2-3 hours
31 after mixing is prone to higher cracking areas. Beyond this time, concrete develops sufficient
32 strength to resist plastic cracking. For construction professionals, this emphasises the fact that
33 any approach adopted to avoid extensive surface water evaporation should be applied as soon as
34 possible.

1 **Industry recommendations**

- 2 1. Cement manufacturers need to control material properties including fineness and alkali
3 content carefully, as they influence plastic shrinkage and cracking of concrete significantly.
- 4 2. For major projects, engineers/contractors need to specify concrete with limits imposed on
5 cement fineness (less than 350 m²/kg) and alkali content (less than 0.8 % by mass of cement).
6 Furthermore, the use of internal curing, shrinkage reducing admixtures and paraffin should be
7 considered to reduce plastic shrinkage risks in critical projects.
- 8 3. Effective curing according to Chinese code for construction of concrete structures (GB50666-
9 2011) needs to be applied on site to limit surface water evaporation and risk of plastic
10 cracking.
- 11 4. Addition of suitable amounts of supplementary cementitious materials and/or fibres should be
12 considered to improve plastic cracking resistance. Moreover, essential cracking experiments
13 should be undertaken when using chemical or mineral admixtures in concrete.

14 **Acknowledgement**

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List of tables and figures

Table

- Table 1 Summary of experimental variables
- Table 2 Chemical composition of cement clinker used (% by mass)
- Table 3 Mix proportions and slump of concretes tested in this study

Figure

- Figure 1 Summary of results of fineness and alkali content for cements commonly used across southwest China
- Figure 2 Illustration of the test set-up for determination of concrete plastic shrinkage
- Figure 3 Illustration of the test set-up for determination of plastic cracking of concrete
- Figure 4 Relationship of cement hydration and specific area of cement
- Figure 5 Relationship of cement hydration and alkali content
- Figure 6 Influence of cement fineness and alkali content on compressive strength of concrete
- Figure 7 Effect of cement fineness and W/C on concrete plastic shrinkage
- Figure 8 Relationship between water evaporation rate and cement specific area
- Figure 9 Effect of alkali content and W/C on plastic shrinkage concrete
- Figure 10 Relationship between water evaporation rate and alkali content
- Figure 11 Effect of cement fineness on maximum cracking width and cracking area
- Figure 12 Effect of alkali content on maximum cracking width and cracking area
- Figure 13 Relationship between water evaporation rate and behaviours of plastic cracking
- Figure 14 Summary of total plastic shrinkage and derived shrinkage for concrete with different size cements and alkali contents

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Table 1 Summary of experimental variables

Factors and levels			
Factor	Cement fineness	Alkali content	W/C
Level	275, 337, 385 m ² /kg	0.4, 0.8, 1.2% by mass of cement	0.35, 0.40
Property determined			
General property	Slump, Compressive strength at the age of 3, 7 and 28 days		
Influencing property	Cement hydration, Water evaporation rate, Plastic shrinkage		
Response property	Maximum cracking width, Cracking area		

Note: the value of 275, 337, 385 m²/kg refers to specific area of cement particles; the value of 0.4, 0.8, 1.2% refers to alkali content, calculated based on Na₂O mass percent.

Table 2 Chemical composition of cement clinker used (% by mass)

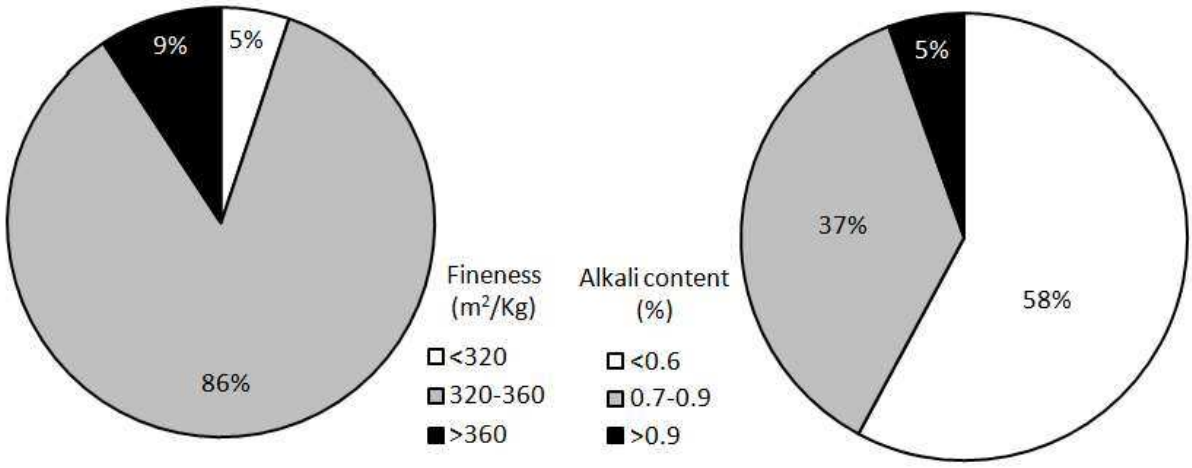
CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	Na ₂ O	K ₂ O	f-CaO	Loss on ignition
63.60	20.20	5.89	3.92	1.46	1.37	0.18	0.34	1.46	1.58

Note: f-CaO represents the ‘free’ CaO in the clinker.

Table 3 Mix proportions and slump of concretes tested in this study

Factor	Cement (kg/m ³)	Sand (kg/m ³)	CA (kg/m ³)	Water (kg/m ³)	SP (%)	W/C (%)	Cement fineness (m ² /kg)	Alkali content (%)	Slump (mm)
Effect of cement fineness	420	689	1123	168	0.60		275		170
	420	689	1123	168	0.65	0.40	337	0.4	155
	420	689	1123	168	0.70		385		160
	420	697	1136	147	0.90		275		150
	420	697	1136	147	1.00	0.35	337	0.4	160
	420	697	1136	147	1.10		385		150
Effect of alkali content	420	689	1123	168				0.4	167
	420	689	1123	168	0.65	0.40	275	0.8	155
	420	689	1123	168				1.2	130
	420	697	1136	147				0.4	155
	420	697	1136	147	1.00	0.35	275	0.8	130
	420	697	1136	147				1.2	98

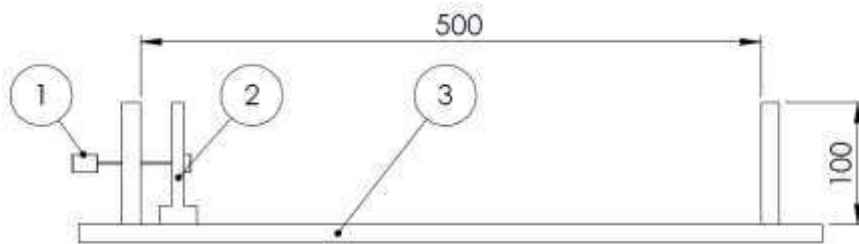
Note: CA represents coarse aggregate contents; SP refers to superplasticiser dosage as a percentage by mass of the total binder content.



(a) Cement fineness

(b) Alkali content

Figure 1 Summary of results of fineness and alkali content for cements commonly used across southwest China



Note:

- 1 represents the part connecting with laser sensor
- 2 represents the part embedded in concrete
- 3 represents the mould

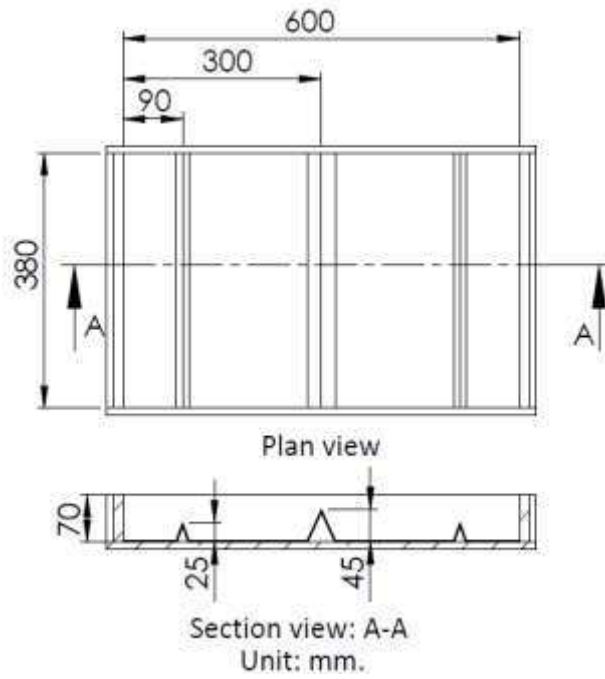
unit: mm

(a) Mould for plastic shrinkage measurement



(b) Test set-up for shrinkage measurement

Figure 2 Illustration of the test set-up for determination of concrete plastic shrinkage



(a) Mould for plastic cracking test

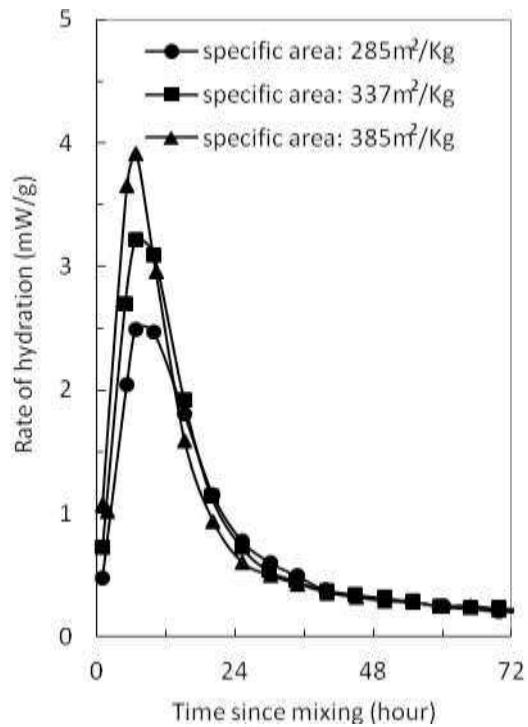
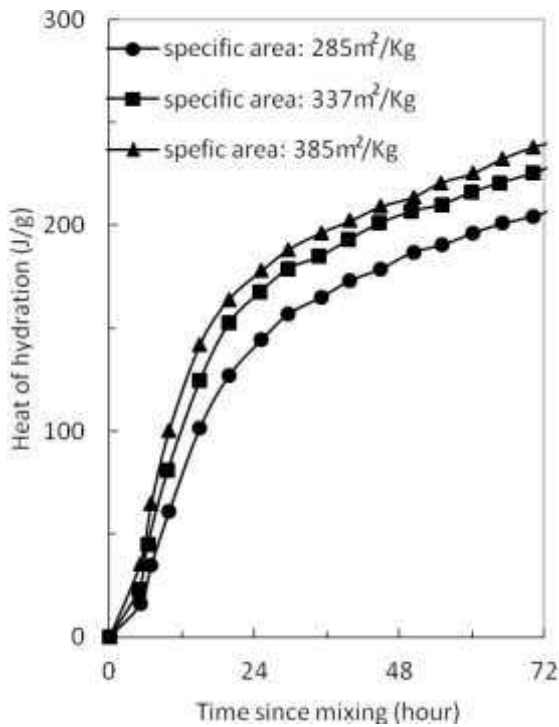


(b) Test set-up for plastic cracking measurement

Figure 3 Illustration of the test set-up for determination of plastic cracking of concrete

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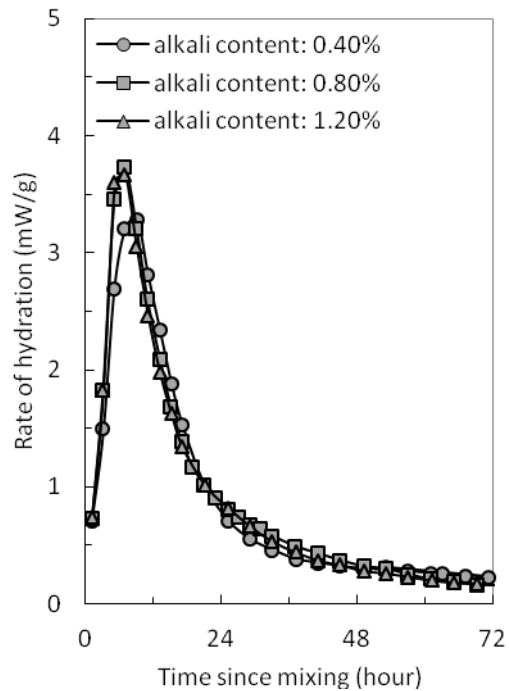
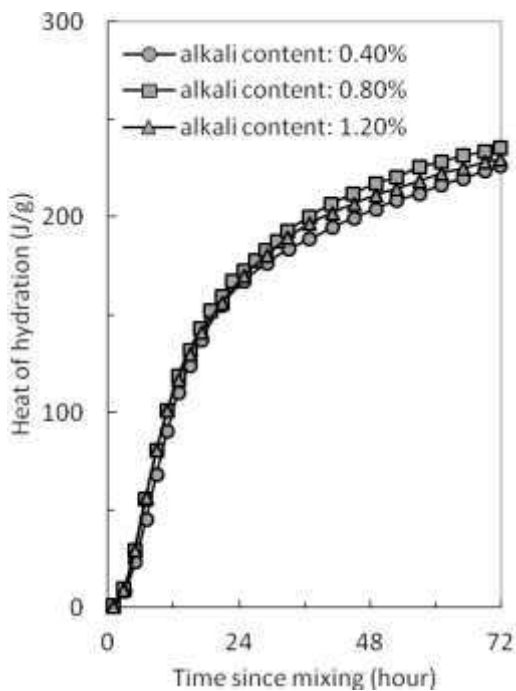


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(a) Relation between fineness and heat of cement hydration

(b) Relation between fineness and rate of cement hydration

Figure 4 Relationship of cement hydration and specific area of cement

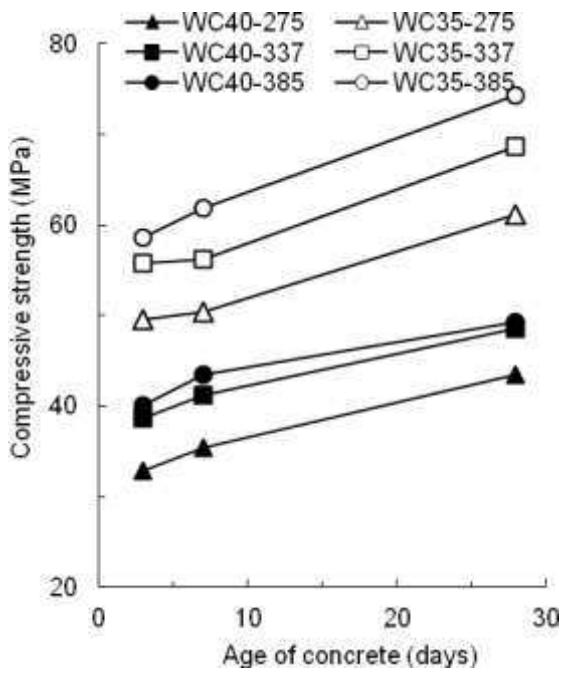


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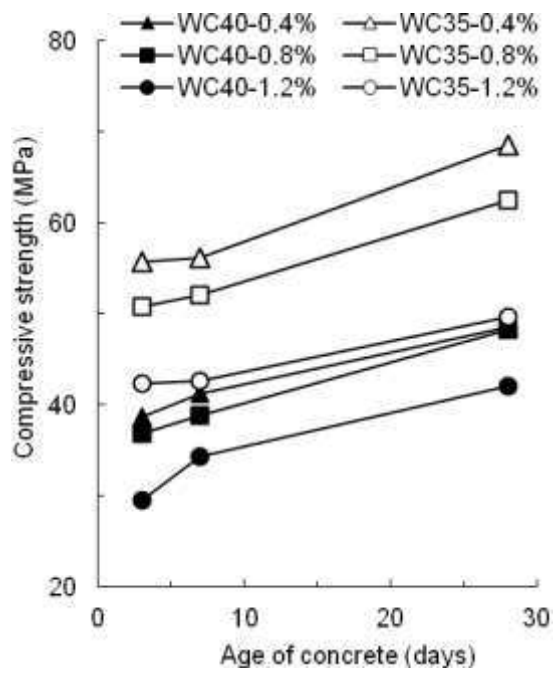
(a) Relation between alkali content and heat of cement hydration

(b) Relation between alkali content and rate of cement hydration

Figure 5 Relationship of cement hydration and alkali content (The specific area of cement is 275 m²/kg)



(a) Influence of cement fineness on compressive strength of concrete



(b) Influence of alkali content on compressive strength of concrete

Figure 6 Influence of cement fineness and alkali content on compressive strength of concrete

(WC40, WC35 refers to the W/C ratio; 285, 337, 385 refers to the specific area, m^2/kg ; 0.40 %, 0.8 %, 1.2 % refers to alkali content.)

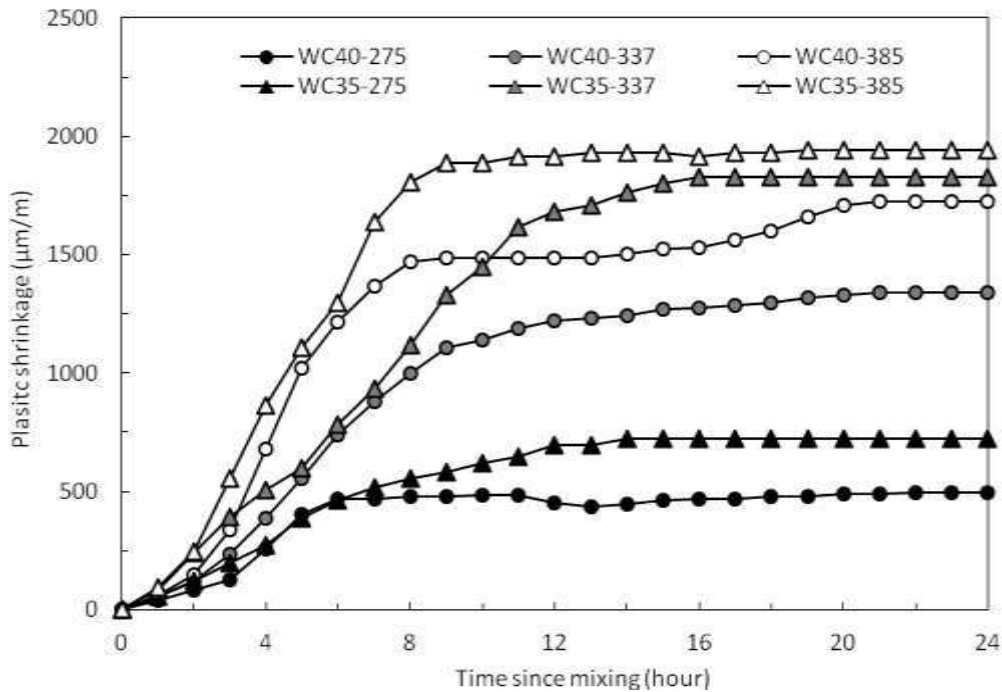
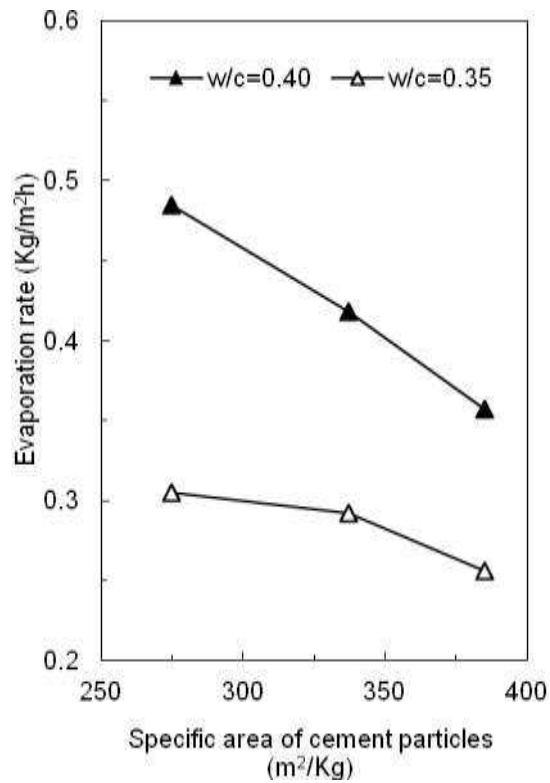


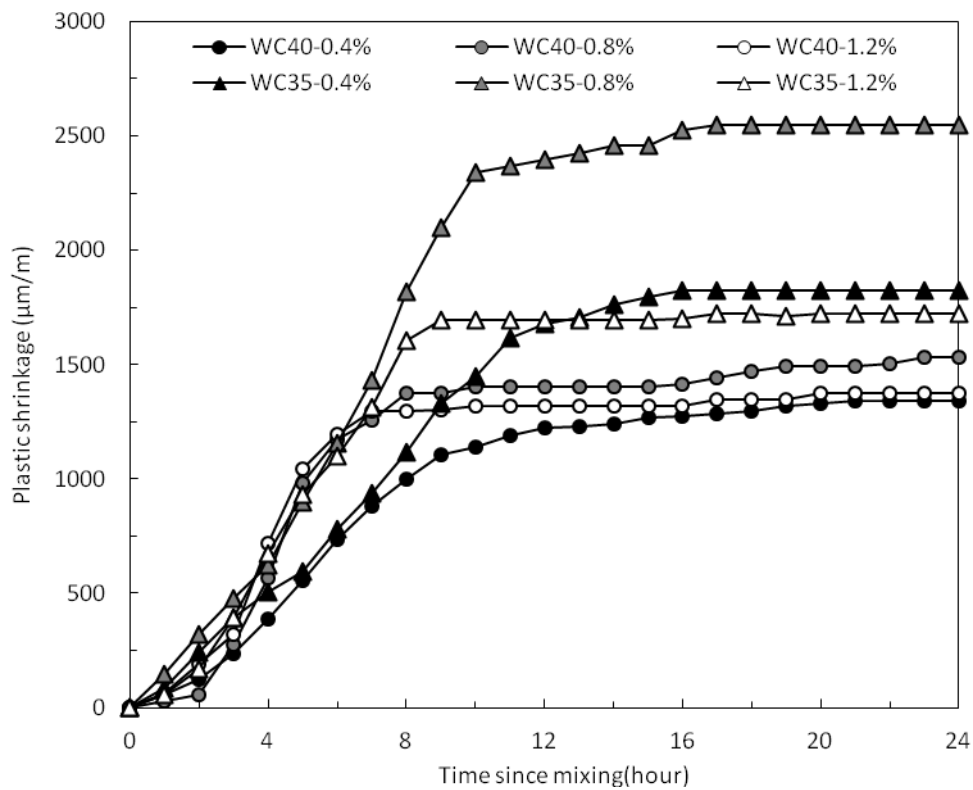
Figure 7 Effect of cement fineness and W/C on concrete plastic shrinkage

(WC40, WC35 refers to the W/C ratio; 285, 337, 385 refers to the specific area, m^2/kg and alkali content is 0.4 %.)



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Figure 8 Relationship between water evaporation rate and cement specific area



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Figure 9 Effect of alkali content and W/C on plastic shrinkage concrete (WC40, WC35 refers to the W/C ratio; 0.40%, 0.8%, 1.2% refers to alkali content and the specific area of cement is 285 m²/kg.)

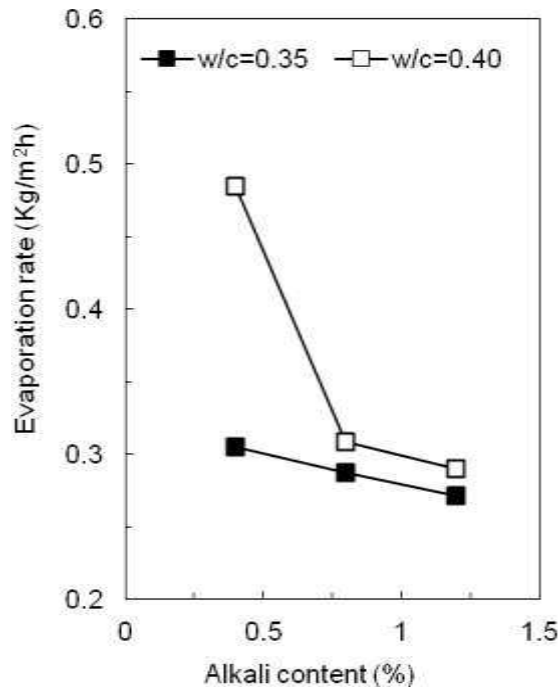
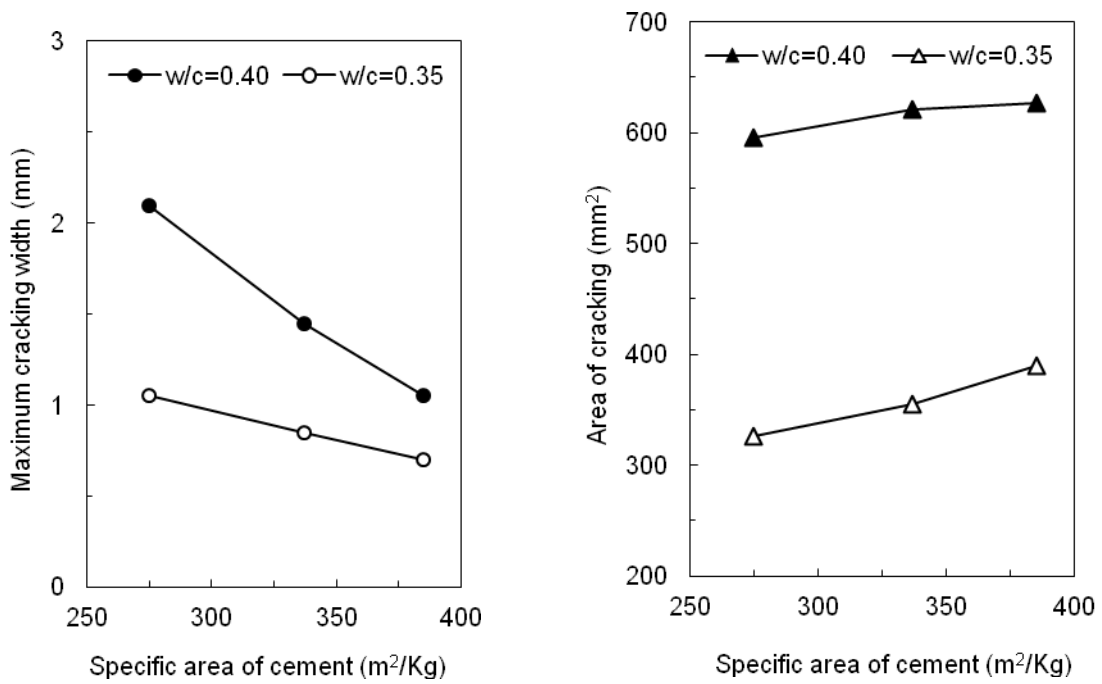


Figure 10 Relationship between water evaporation rate and alkali content



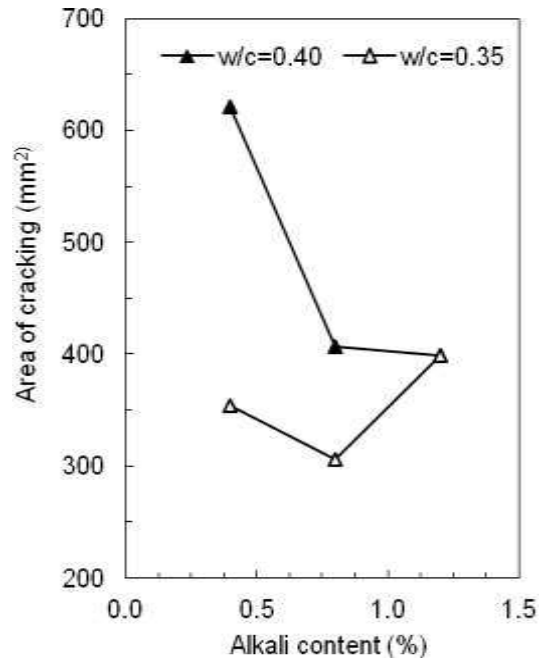
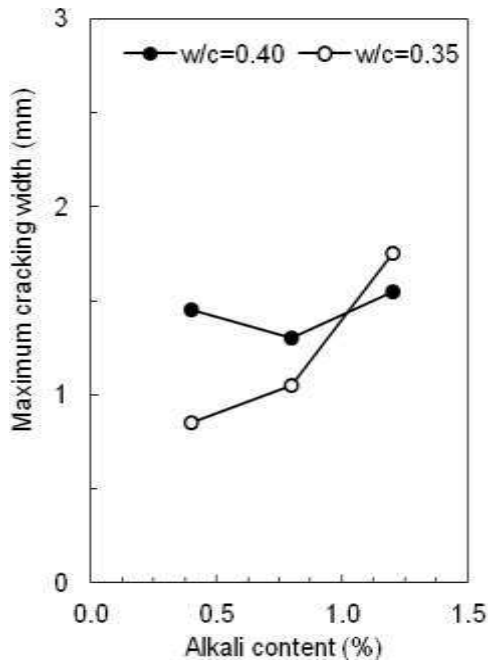
(a) Effects of fineness and W/C on the maximum cracking width

(b) Effects fineness and W/C on the area of cracking

Figure 11 Effect of cement fineness on maximum cracking width and cracking area

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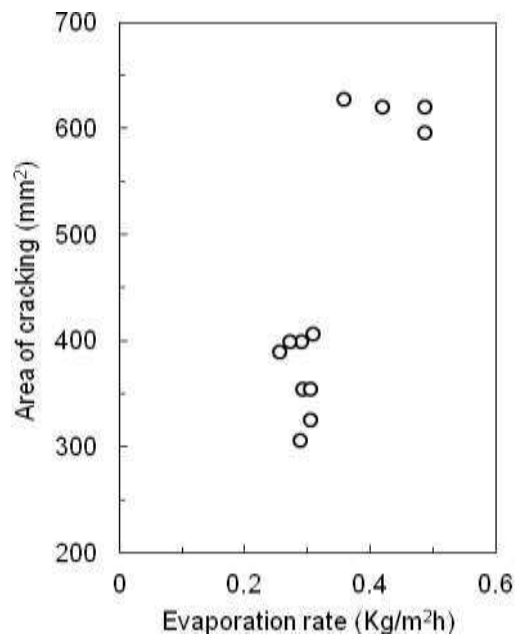
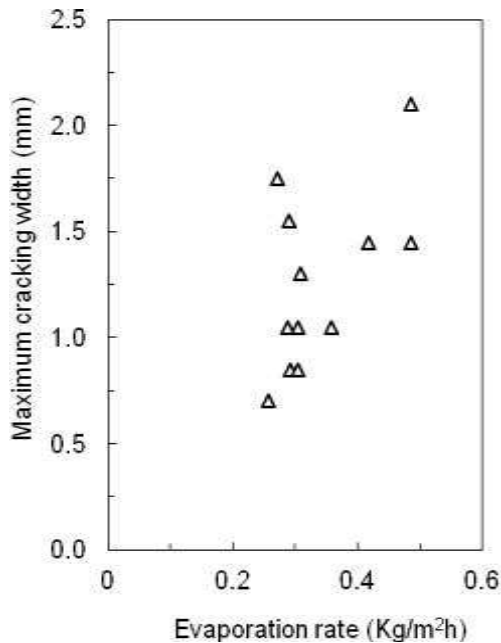
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(a) Effects of alkali content and W/C on the maximum cracking width

(b) Effects alkali content and W/C on the area of cracking

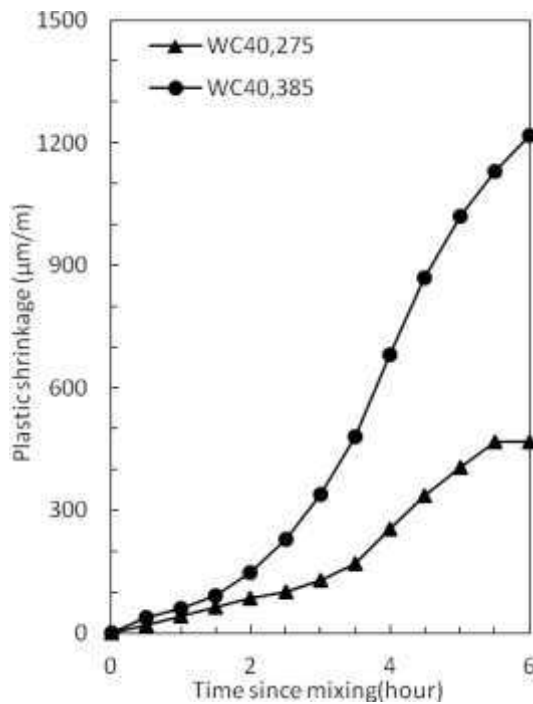
Figure 12 Effect of alkali content on maximum cracking width and cracking area for concretes with different W/C ratios



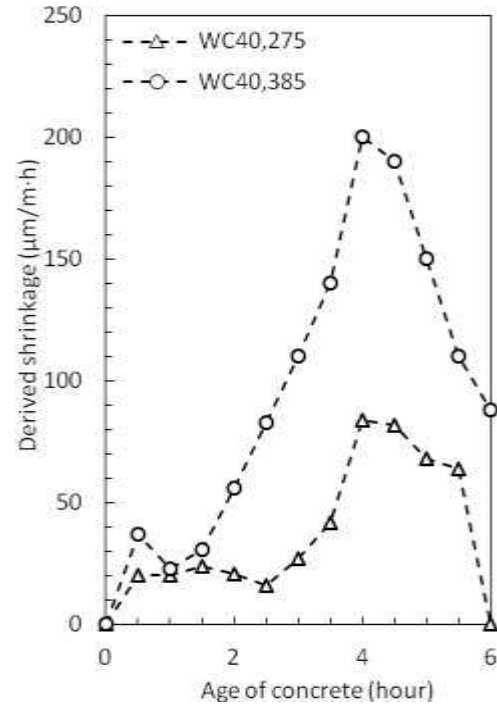
(a) Relationship between maximum cracking width and evaporation rate

(b) Relationship between cracking area of cracking and evaporation rate

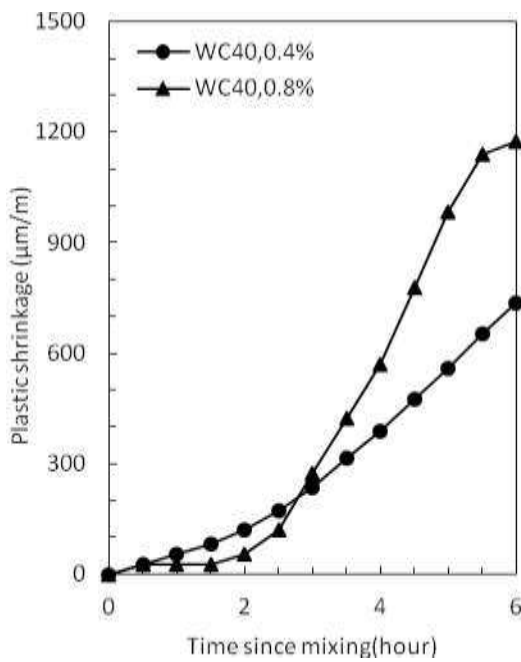
Figure 13 Relationship between water evaporation rate and behaviours of plastic cracking (maximum cracking width and cracking area)



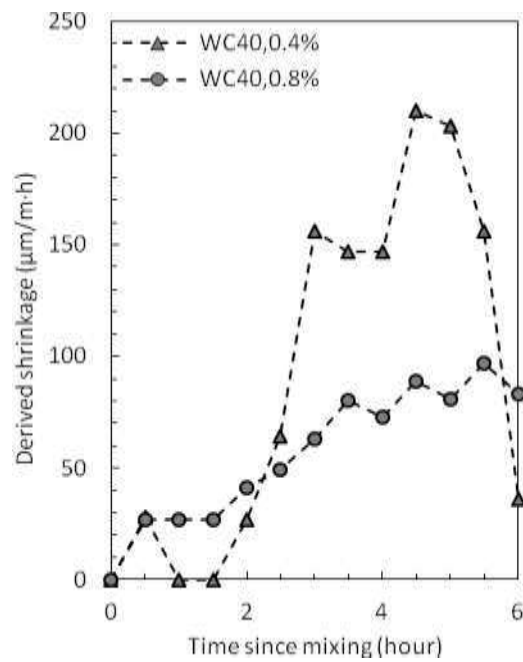
(a) 6 hour plastic shrinkage of concrete with different size cements



(b) Derived shrinkage of concrete with different size cements



(c) 6 hour plastic shrinkage of concrete with alkali contents



(d) Derived shrinkage of concrete with alkali contents

Figure 14 Summary of total plastic shrinkage and derived shrinkage for concrete with different size cements and alkali contents