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Adding limestone fines to reduce heat generation of curing concrete

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It is well known that the heat generation of curing concrete may be reduced by decreasing the cement paste volume of the concrete. However, as the cement paste must be more than sufficient to fill the voids between aggregate particles, the cement paste volume should not be limitlessly decreased. Herein, it is proposed to add an inert filler, such as limestone fines, to fill into the voids between aggregate particles so that a smaller cement paste volume may be used and the heat generation of the concrete may be further reduced. To study the effectiveness of adding limestone fines in reducing the heat generation of curing concrete, a series of concrete mixes with water/cement ratios ranging from 0·35 to 0·60 and different amounts of limestone fines added were tested for their workability, strength and heat generation. The results revealed that the addition of limestone fines to decrease the cement paste volume would significantly increase the strength and, more importantly, substantially reduce the heat generation of the concrete.

Notation

A	aggregate content
C	cement content
L	limestone fines content
T_A	ambient temperature
T_P	placing temperature of the concrete
T_S	surface mean temperature of the concrete
T_V	volumetric mean temperature of the concrete
t	time after mixing
W	water content
λ	heat loss characteristic of the test set-up
ψ	specific heat capacity of curing concrete

Introduction

During curing of concrete, heat is generated from the chemical reactions inside the concrete mixture. As heat accumulates, the temperature of the concrete rises. Such temperature rise, which could be as high as 60°C (Aparicio *et al.*, 2000; Gajda and Van Geem, 2002; Wang and Read, 1999), and the subsequent temperature drop would cause thermal expansion and contraction of the concrete structure. Any restraint against the thermal movements so caused would induce tensile strains, which are often large enough to produce cracks. The thermal cracks so produced would adversely affect the aesthetics, water-tightness, structural integrity and durability of the concrete structure. To avoid or at least alleviate this early thermal cracking problem, reducing the heat generation of the concrete should be the first consideration as other means of temperature control, such as lowering the placing temperature, internal cooling and external insulation, are rather cumbersome.

As the heat is generated from the chemical reactions of the cementitious materials, decreasing the cementitious materials content should be an effective method for reducing the heat generation of curing concrete (Mather, 2000). In fact, the existing guidelines (ACI Committee 207 (ACI, 1996); Building Research Establishment, 1992) for estimating the heat generation of curing concrete are all based on the presumption that the heat generation is dependent mainly on the cementitious materials content. As the water/cementitious materials (W/CM) ratio is governed by the strength and/or durability requirements, it should be kept constant while decreasing the cementitious materials content to reduce heat generation. Hence, as the cementitious materials content decreases, the cement paste volume (the volume of cementitious materials plus the volume of water, expressed as a percentage of the volume of concrete) also decreases. As the cement paste must be more than sufficient to fill the voids between aggregate particles, there are lower limits for decreasing the cement paste volume and cementitious materials content.

Typically, the packing density of the aggregate particles in concrete is about 0·70 to 0·80. With this typical packing density, the minimum cement paste volume needed for filling the voids between aggregate particles is about 20% to 30%. If the cement paste volume is decreased to smaller than the minimum needed, the concrete will have many air voids entrapped inside no matter how hard it is compacted and there will be no excess cement paste for lubricating the aggregate particles. Therefore, a concrete with a cement paste volume smaller than the minimum needed will not have good strength or workability. One way of decreasing the cement paste volume without adversely affecting the strength and workability is to add an inert filler to fill into the voids between aggregate particles so that the amount of cement paste needed is decreased. If the filler is a powder as fine as the cementitious materials, this may also be taken as adding the filler to the cement paste so as to increase the volume of the powder paste (with an inert filler added, the paste should better be called powder paste) for filling the voids between aggregate particles. As long as the powder paste volume (the volume of powder including cement plus the volume of water, expressed as a percentage of the volume of concrete) is more than sufficient to fill the voids between aggregate particles, the cement paste volume may be further decreased without causing adverse effects on the strength and workability.

Among the various inert fillers, limestone fines (LF) may be a good choice. LF is a by-product of the limestone quarry industry, which, if not used, has to be dumped as waste causing environmental problems. Actually, the use of LF in concrete is not new. Soroka and Setter (1977) showed that the LF could act as nuclei for precipitation of CH and thus speed up the hydration of cement. Malhotra and Carette (1985) observed that replacement of sand by LF might increase or decrease the concrete strength, depending on the W/C ratio and the LF content. They also found that replacement of sand by LF would increase the cohesiveness of the fresh concrete and the drying shrinkage of the hardened concrete. Opoczky (1992) pointed out that the main effects of LF are better packing of the particle system and wider dispersion of the cement grains. Nehdi *et al.* (1996) found that replacement of cement by LF up to 15% would not affect the early strength but would reduce the strength at later age.

Bentz and Conway (2001) suggested that a portion of the relatively coarse cement grains may be replaced by an inert filler with little reduction in the concrete strength. In this regard, Bentz (2005) demonstrated by tests that judicious replacement of coarse cement grains by similarly sized LF may provide economic incentives with little or no loss in hydration, strength and long-term performance. Ghezal and Khayat (2002) found that replacing 100 kg/m^3 of cement with finely ground LF would improve the deformability and stability of the concrete without affecting the one-day strength. Bonavetti *et al.* (2003) observed that the use of LF cement to produce concrete can increase the degree of hydration of cement. Sonebi *et al.* (2004) reported that the addition of LF directly to replace cement without changing the water content would reduce the strength. Recently, Bentz *et al.* (2009) pointed out that the W/CM ratio should not be calculated as the water/(cement + LF) ratio and the strength loss owing to replacement of cement by LF can be restored by decreasing the water content so as to lower the water/(cement + LF) ratio slightly.

From the above literature review, the advantages of using LF in concrete can be summarised as

(*a*) saving the cement to reduce the cost of production and 'carbon footprint'
(*b*) using up the otherwise waste material to mitigate the environmental problems associated with waste disposal
(*c*) improving the cohesiveness and stability of the fresh concrete.

However, there has been limited research on the use of LF to reduce the cement paste volume and improve the dimensional stability of concrete. Furthermore, the LF has been used as sand or cement replacement, but the authors are of the view that LF should better be used as cement paste replacement. The use of LF as cement paste replacement would allow the cement paste volume to be decreased to reduce the heat generation and the mix composition of the cement paste to remain unchanged to avoid causing any adverse effect on the strength, as demonstrated in this study, which is part of a comprehensive research on the use of LF for the production of high-performance concrete with low carbon footprint.

Experimental programme

Materials

An ordinary Portland cement (OPC) of strength class 52·5N complying with British Standard BS 12:1996 (equivalent to ASTM type I) and a finely ground LF were used in all the concrete mixes. The OPC has a 28-day mortar cube strength of 59·0 MPa, as measured in accordance with British Standard BS EN 196: Part 1 (BSI, 2005). By the use of a laser particle size analyser, the volumetric mean particle sizes of the OPC and LF were determined as 11·4 μm and 14·5 μm, respectively. Furthermore, the specific gravities of the OPC and LF were measured as 3·11 and 2·64, respectively. On the other hand, both the coarse and fine aggregates were obtained from crushed granite rock. The coarse aggregate has a maximum size of 20 mm. Its specific gravity and water absorption were measured to be 2·61 and 1·01%, respectively. The fine aggregate has a maximum size of 5 mm. Its specific gravity, water absorption and fineness modulus were measured to be 2·52, 1·89% and 2·68, respectively. Sieve analysis verified that the grading curves of the coarse and fine aggregates were within the allowable limits stipulated in British Standard BS 882 (BSI, 1992).

Concrete mixes and specimens

In total, 20 concrete mixes were produced for testing, as depicted in Table 1. Their W/C ratio was varied from 0·35 to 0·60 in increments of 0·05. For concrete mixes with W/C $\leqslant$ 0·50, the LF volume (the volume of LF, expressed as a percentage of the volume of concrete) was varied among 0%, 4% and 8% while for concrete mixes with W/C $\geqslant$ 0·55, the LF volume was varied among 0%, 4%, 8% and 12% (at W/C $\leqslant$ 0·50, the LF volume was not increased to 12% so as to avoid producing very dry

Mix no.	W/C ratio	LF volume: %	Cement paste volume: %	Water content: kg/m^3	Cement content: kg/m^3	LF content: kg/m^3
C-0·35-0	0·35	0	34	177	505	0
C-0·35-4		4	30	156	445	106
C-0·35-8		8	26	135	386	211
C-0·40-0	0·40	0	34	188	470	0
C-0·40-4		4	30	166	415	106
C-0·40-8		8	26	144	359	211
C-0·45-0	0·45	0	34	198	440	0·0
C-0·45-4		4	30	175	388	106
C-0·45-8		8	26	151	336	211
C-0·50-0	0·50	0	34	207	413	0
C-0·50-4		4	30	182	364	106
C-0·50-8		8	26	158	315	211
C-0·55-0	0·55	0	34	214	389	0
C-0·55-4		4	30	189	343	106
C-0·55-8		8	26	164	297	211
C-0·55-12		12	22	138	251	317
C-0·60-0	0·60	0	34	221	368	0
C-0·60-4		4	30	195	325	106
C-0·60-8		8	26	169	281	211
C-0·60-12		12	22	143	238	317

Table 1. Mix proportions of concrete mixes

concrete mixes). Each concrete mix was assigned an identification code of C-X-Y, in which C denotes concrete, X denotes the W/C ratio and Y denotes the LF volume. In terms of quantity per volume of concrete, the water content varied from 135 to 221 kg/m^3, the cement content varied from 238 to 505 kg/m^3 and the LF content varied from 0 to 317 kg/m^3. It should be noted that the LF was added as cement paste replacement, not as cement replacement. In other words, when LF was added, the cement paste volume was reduced by the LF volume whereas the W/C ratio was kept constant.

In all the concrete mixes, the powder paste volume (the cement paste volume plus the LF volume) was fixed at 34%. This relatively large powder paste volume, which should be large enough for the production of a high-flowability concrete, was adopted because one major goal of this study was to develop a high-flowability concrete with a low cement content (and thus low carbon footprint) and a high dimensional stability suitable for use as a pumpable concrete, tremie concrete or self-consolidating concrete. With the powder paste volume fixed, the aggregate volume was also fixed. In each concrete mix, the fine aggregate content, 10 mm aggregate content and 20 mm aggregate content were fixed at 672, 504 and 504 kg/m^3, respectively. As in usual practice for the production of high-flowability concrete, a superplasticiser (SP) was added to each concrete mix. The SP was added to the concrete mix in increments until a slump of at least 200 mm and a flow of at least 500 mm were achieved. The SP dosage needed and the slump and flow actually achieved of each concrete mix are listed in the second to fourth columns of Table 2 (these results will be discussed in detail later).

Each concrete mix was tested for its workability in terms of slump and flow, its strength in terms of 7-day cube strength and 28-day cube strength, and its heat generation by a semi-adiabatic curing test with heat loss compensation applied. The slump was measured by the slump test as the drop in height of the concrete after filling the concrete into the slump cone and lifting the slump cone while the flow was measured as the average diameter of the patty formed after the slump test. The cube strengths were measured by casting six 150 mm cubes from the concrete, removing the moulds one day after casting, applying water curing at a temperature of 27 ± 2°C, and testing three of the cubes at the age of 7 days and the other three cubes at the age of 28 days. The heat generation was measured by casting one 0·40 m cube specimen inside a heat insulated box for semi-adiabatic curing test, as shown in Figure 1 and explained below.

Measurement of heat generation

The test method employed was the same as the semi-adiabatic curing test method developed previously by the authors (Ng *et al.*, 2008, 2009). As the test method has been published before, only the essential features are presented herein.

The test set-up consists of a mould provided with both internal

Mix no.	SP dosage: % by mass of powder	Slump: mm	Flow: mm	7-day cube strength: MPa	28-day cube strength: MPa
C-0·35-0	1·09	230	498	75·1	87·3
C-0·35-4	1·68	235	543	79·7	91·9
C-0·35-8	2·35	270	714	82·8	91·3
C-0·40-0	0·98	225	530	65·2	74·8
C-0·40-4	1·23	245	555	70·8	80·5
C-0·40-8	1·94	255	679	74·1	85·1
C-0·45-0	0·78	230	501	52·0	63·8
C-0·45-4	1·04	253	678	60·7	67·6
C-0·45-8	1·74	245	728	65·2	76·0
C-0·50-0	0·89	230	569	47·0	56·0
C-0·50-4	0·98	235	575	53·5	62·0
C-0·50-8	1·57	255	733	58·8	68·7
C-0·55-0	0·65	205	473	40·4	50·5
C-0·55-4	0·93	210	530	44·0	53·6
C-0·55-8	1·03	245	610	46·8	55·9
C-0·55-12	1·57	275	693	52·3	60·8
C-0·60-0	0·48	210	503	35·9	44·3
C-0·60-4	0·79	230	505	41·7	49·2
C-0·60-8	1·05	230	530	42·8	51·5
C-0·60-12	1·46	260	750	47·6	55·8

Table 2. Workability and strength results

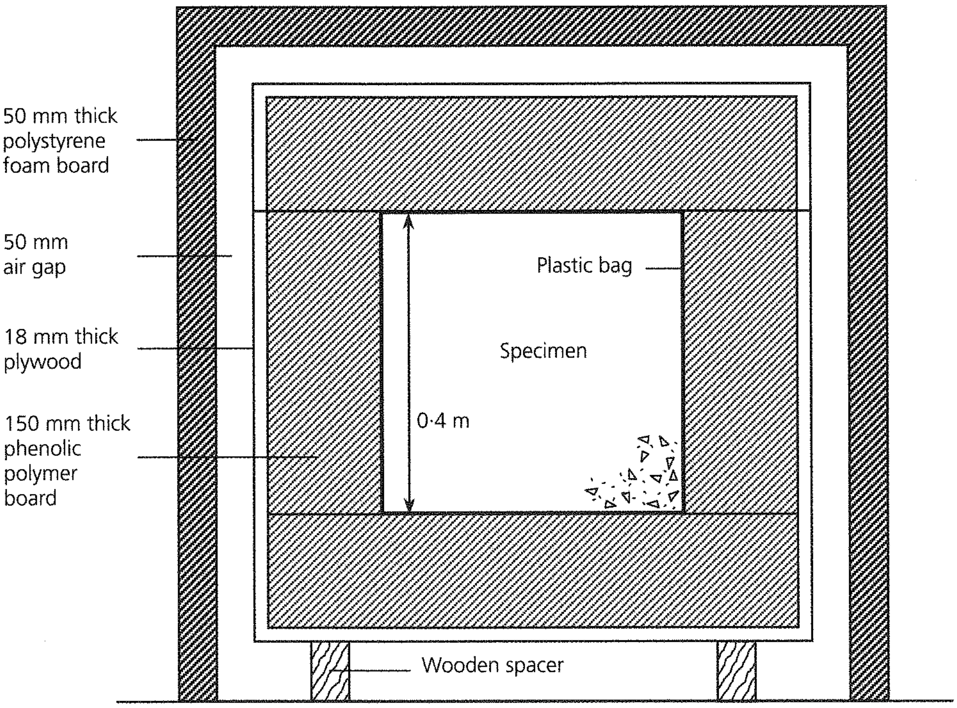

Figure 1. Set-up for semi-adiabatic curing test

and external heat insulation, as depicted in Figure 1. The mould itself is a cubic box made of 18 mm thick plywood. Inside the plywood box, a 150 mm thick phenolic polymer board is affixed onto each of the six faces to serve as internal insulation. The space surrounded by the internal insulation is where the 0·40 m concrete cube specimen is to be cast. As the phenolic polymer has lower specific heat capacity and heat conductivity than the plywood, this arrangement would minimise the amount of heat absorbed by the mould. To minimise heat conduction to the ground, the plywood box is lifted off the ground by wooden spacers. Furthermore, to avoid leakage, the concrete is cast inside a plastic bag, which is sealed after casting. On the outside, an external shell, made of 50 mm thick polystyrene foam boards, is mounted. Between the external shell and the plywood box, there is a 50 mm thick air gap. The external shell and the air gap together serve as external insulation of the mould. During the entire testing period, the ambient temperature around the test set-up is regulated within 22 to 24°C by air-conditioning.

The temperature of the concrete specimen is measured using thermocouples mounted at four locations, namely, the centre of mass, centre of one face, mid-point of an edge and one corner. Four additional thermocouples are attached at the outside faces of the external shell to measure the ambient temperature. All thermocouples are type K thermocouples. They are connected to a data-logger, which automatically records the temperature readings of the thermocouples at 5 min intervals.

Basically, this test method measures the temperature of the concrete specimen up to the age of 7 days, estimates the heat loss of the concrete specimen from the temperature drop after the age of 6 days when the heat generation has become insignificant, and then compensates for the heat loss to determine the adiabatic temperature rise of the concrete. The formulae for heat loss compensation are given in the following.

Let T_V be the volumetric mean temperature of the concrete, T_S be the surface mean temperature of the concrete and T_A be the ambient temperature. The rate of heat loss of the concrete should be proportional to $(T_S - T_A)$. After a certain period of time, when the heat generation of the concrete has become insignificant, the rate of heat loss, expressed in terms of the rate of temperature drop, is governed by

$$1. \quad \frac{\partial T_V}{\partial t} = -\lambda(T_S - T_A)$$

in which λ is the heat loss characteristic of the test set-up and t is the time after mixing. The actual value of λ may be estimated from the measured temperature–time curve of the concrete when the heat generation has become insignificant (say, after 6 days). Having estimated the value of λ, the adiabatic temperature rise of the concrete T_G may be obtained as

$$2. \quad T_G = (T_V - T_P) + \lambda \int_0^t (T_S - T_A)\mathrm{d}t$$

where T_P is the placing temperature of the concrete. The volumetric mean temperature T_V and surface mean temperature T_S can be evaluated from the readings of the four thermocouples mounted at the centre of mass, centre of one face, mid-point of an edge and one corner. Using the values of T_V and T_S so evaluated and performing numerical integration for Equation 2, the adiabatic temperature rise at any time t can be determined from the semi-adiabatic curing test results.

Results and discussion

Workability and strength

The SP dosage needed, the slump achieved and the flow achieved of each concrete mix are, respectively, presented in the second, third and fourth columns of Table 2. As the LF was added as cement paste replacement, the powder content (the cement plus LF content) increased and consequently the SP dosage needed to achieve the minimum required workability (in other words, the SP demand) also increased. To reflect the effect of such increase in powder content, the SP dosage is expressed herein as a percentage by mass of the powder content. From the SP dosage results, it can be seen that the SP demand increased quite substantially with the LF volume. Moreover, the increase in SP demand was proportionally larger than the increase in powder content, as indicated by the increase of SP dosage per powder content with the LF volume. The increase in SP demand may also be interpreted as a reduction in workability owing to the addition of LF as cement paste replacement. Nevertheless, from the slump and flow results, it can be seen that the reduction in workability can be more than restored by increasing the SP dosage, as indicated by the higher slump and flow values of the concrete mixes containing LF compared to the concrete mixes containing no LF.

It is noteworthy that for the concrete mixes C-0·35-0 and C-0·55-0, which contained no LF, the achieved flow values were marginally short of the required value of 500 mm. This was because at flow values close to 500 mm, these concrete mixes were already showing signs of slight segregation and thus to avoid serious segregation, the SP dosages of these concrete mixes were not further increased to increase the flow. In fact, although the other concrete mixes, which also contained no LF, were able to achieve the required flow values of 500 mm, they were at such flow values as to show certain signs of segregation. Hence, for the concrete mixes with no LF added, the flow values listed in the fourth column of Table 2 may be interpreted as the maximum achievable flow values without segregation. On the other hand, all the concrete mixes with LF added showed no sign of segregation. This may be taken to infer that the addition of LF to replace part of the cement paste would increase the cohesiveness of the concrete mix to avoid segregation.

The 7-day and 28-day cube strengths of each concrete mix are, respectively, presented in the fifth and sixth columns of Table 2. Each cube strength value given therein is the average value of the three cubes cast from the same concrete mix and tested at the same time. From the strength results, it is apparent that the addition of LF as cement paste replacement had significantly increased the 7-day and 28-day cube strengths, even though the W/C ratio was kept constant. For better illustration, the variations of the 7-day and 28-day cube strengths with the W/C ratio for LF volumes of 0%, 4%, 8% and 12% are shown graphically in Figure 2. The different curves plotted for different LF volumes clearly show that at the same W/C ratio, the cube strength was generally higher at higher LF volume, as indicated by the steady upwards shifting of the curve with increasing LF volume. For instance, with 4% LF added as cement paste replacement, the 28-day cube strength was increased by 7·6%, 10·7% and 11·1%, respectively, at W/C ratios of 0·40, 0·50 and 0·60. With 8% LF added as cement paste replacement, the 28-day cube strength was increased by 13·8%, 22·7% and 16·3%, respectively, at W/C ratios of 0·40, 0·50 and 0·60.

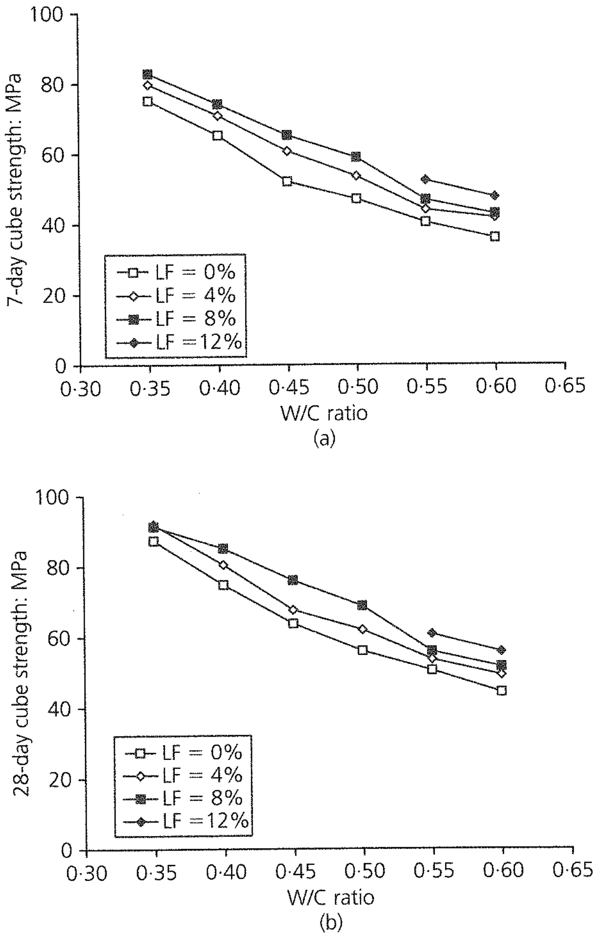

Figure 2. Cube strengths: (a) 7-day cube strength; (b) 28-day cube strength

The increase in strength at constant W/C ratio owing to the addition of LF as cement paste replacement is an interesting phenomenon. As the LF added is chemically inert and therefore not cementitious, the increase in strength should not be attributed to any increase in the cementitious materials content or lowering of the W/CM ratio. One possible contributing factor is that the LF might have acted as nuclei for precipitation of CH and thus increased the degree of cement hydration, as postulated by Soroka and Setter (1977). Another possible contributing factor is that the increase in powder content and decrease in water/powder ratio caused by the addition of LF might have reduced the bleeding of the concrete mix. According to Mehta and Aïtcin (1990), a reduction in bleeding would decrease the amount of bleeding water trapped underneath the aggregate particles and thus improve the bond strength of the interfacial transition zones at the surfaces of the aggregate particles. Further in-depth study on this phenomenon is recommended.

Adiabatic temperature rise

From the thermocouple readings, the placing temperature T_P and volumetric mean temperature T_V of each concrete specimen during the semi-adiabatic curing test were determined and the temperature rise of the concrete specimen at any time t was then evaluated as $(T_V - T_P)$. The measured temperature rise so obtained is plotted against time for the typical concrete mix C-0·50-4 in Figure 3 as a solid line. From the temperature rise–time curves, it can be seen that generally the temperature of the concrete started to rise at an age of a few hours and reached a certain peak value at an age of within 20 to 40 h. After reaching the peak, owing to heat loss arising from imperfect heat insulation being larger than heat generation, the temperature of the concrete dropped. From these results, the measured temperature rise was taken as the maximum value of $(T_V - T_P)$. The placing temperature and measured temperature rise of each concrete mix before heat loss compensation are presented in the second and third columns of Table 3.

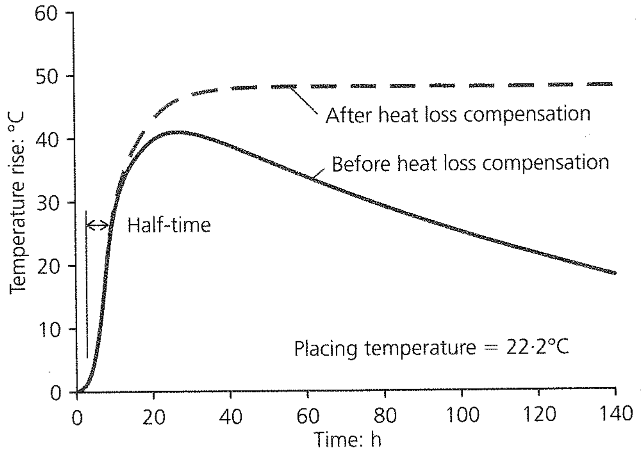

Figure 3. Temperature rise–time curves of concrete mix C-0·50-4

Mix no.	Placing temperature: °C	Measured temperature rise (before heat loss compensation): °C	Adiabatic temperature rise (after heat loss compensation):°C	Adiabatic temperature rise per cement content: °C/(100 kg/m^3)
C-0·35-0	21·4	51·4	58·6	11·6
C-0·35-4	21·4	46·4	53·6	12·0
C-0·35-8	25·1	39·0	47·1	12·2
C-0·40-0	25·2	47·3	54·5	11·6
C-0·40-4	23·3	44·9	52·0	12·5
C-0·40-8	23·8	38·9	46·6	13·0
C-0·45-0	22·5	47·1	56·9	12·9
C-0·45-4	26·4	43·9	52·7	13·6
C-0·45-8	23·3	37·7	45·5	13·6
C-0·50-0	24·4	41·7	50·6	12·2
C-0·50-4	22·2	41·0	48·1	13·2
C-0·50-8	20·5	37·1	44·9	14·2
C-0·55-0	25·7	39·8	49·0	12·6
C-0·55-4	21·0	38·0	46·6	13·6
C-0·55-8	26·2	32·0	40·4	13·6
C-0·55-12	25·5	27·2	34·7	13·8
C-0·60-0	25·3	36·2	44·6	12·1
C-0·60-4	25·2	35·1	43·3	13·3
C-0·60-8	19·7	31·6	39·0	13·9
C-0·60-12	26·1	26·4	33·4	14·0

Table 3. Temperature measurement results

To account for the effect of heat loss, heat loss compensation was applied to each concrete specimen. The adiabatic temperature rise so obtained is plotted against time for the typical concrete mix C-0·50-4 in Figure 3, as a dotted line. Comparing the measured temperature rise–time curves before heat loss compensation with the adiabatic temperature rise–time curves after heat loss compensation, it is evident that the maximum temperature rise of each concrete mix would become significantly higher after heat loss compensation. The adiabatic temperature rise of each concrete mix so determined by applying heat loss compensation is presented in the fourth column of Table 3. It can be seen from these results that the adiabatic temperature rise of the concrete mixes tested was generally within 33·4 to 58·6°C.

The variations of the adiabatic temperature rise with the W/C ratio at different LF volumes are plotted in Figure 4. This figure reveals that at all W/C ratios, the adiabatic temperature rise decreased steadily and quite substantially as the LF volume increased from 0% to 8% or even 12%. Such decrease in adiabatic temperature rise can be attributed to the decreases in cement content and water content when part of the cement paste was replaced by the LF added. Furthermore, at all LF volumes, the adiabatic temperature rise generally decreased with increasing W/C ratio. When interpreting these results, it should be borne in mind that the change of adiabatic temperature rise with increasing W/C ratio was the net effect of the decrease in cement content (as shown in Table 1), increase in degree of hydration (the degree of hydration should be higher at a higher W/C ratio), and slight increase in specific heat capacity (owing to increase in water content).

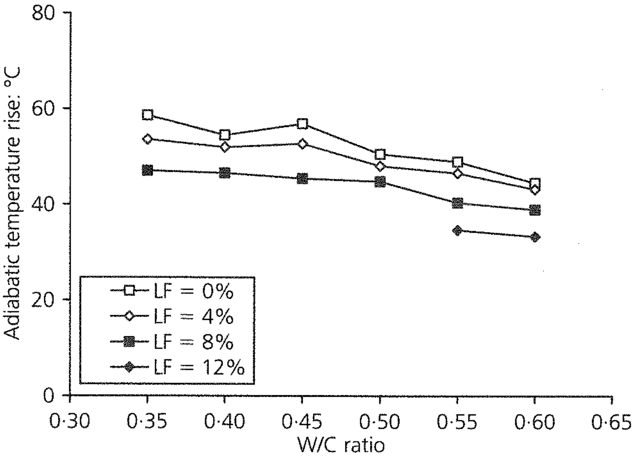

Figure 4. Adiabatic temperature rise

Dividing the adiabatic temperature rise by the cement content, the adiabatic temperature rise per cement content of each concrete mix is obtained, as presented in the last column of Table 3. It can be seen from these results that the adiabatic temperature rise per cement content was generally within 11·6 to 14·2°C per 100 kg/m^3. This range of temperature rise per cement content agrees quite well with the suggested value by Fitz Gibbon (1976) of 12°C per 100 kg/m^3 and the recommended value by Bamforth (1978) of 14°C per 100 kg/m^3.

The variations of the adiabatic temperature rise per cement content with the W/C ratio at different LF volumes are plotted in Figure 5. This figure clearly shows that at all W/C ratios, the adiabatic temperature rise per cement content increased significantly as the LF volume increased from 0% to 4% and marginally as the LF volume further increased from 4% onwards. These increases in adiabatic temperature rise per cement content at constant W/C ratio reveal that the addition of LF as cement paste replacement would slightly increase the degree of hydration. A possible reason is that the LF added might have acted as nuclei for precipitation of CH, as postulated by Soroka and Setter (1977). Furthermore, at all LF volumes, the adiabatic temperature rise per cement content increased with the W/C ratio. This is expected because a higher W/C ratio would generally increase the degree of hydration (Ng *et al.*, 2009).

Amount of heat generation

The heat generation of each concrete mix may be calculated by multiplying the adiabatic temperature rise with the specific heat capacity of the concrete. As the gradual reduction in specific heat capacity owing to reduction of the water content by cement hydration (the water content has the highest specific heat capacity) and the gradual increase in specific heat capacity due to temperature rise tend to offset each other, de Larrard (1999) suggested that the specific heat capacity of curing concrete may be assumed to be constant and taken simply as that of the fresh concrete. Following his suggestion, the specific heat capacity of curing concrete may be calculated as the sum of those of the constituents. Assuming the specific heat capacities of water, cement, LF and aggregate to be 4·19, 0·86, 0·83 and 0·82 kJ/kg/°C, respectively, as given in the references by de Schutter and Taerwe (1995), Holman (2010) and Lide (2010), the specific heat capacity of curing concrete ψ may be calculated as

$$3. \quad \psi = 4{\cdot}19W + 0{\cdot}86C + 0{\cdot}83L + 0{\cdot}82A$$

in which ψ is in kJ/m^3/°C, and W, C, L and A are the water, cement, LF and aggregate contents, respectively, in kg/m^3. It is noteworthy that since water has the highest heat capacity, the specific heat capacity of concrete increases slightly with the W/C ratio.

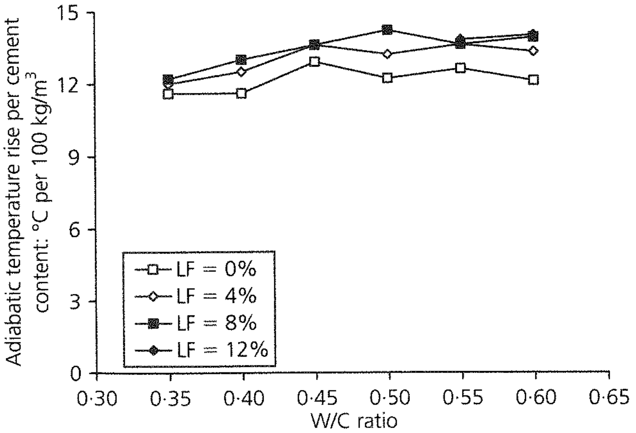

Figure 5. Adiabatic temperature rise per cement content

The heat generation of each concrete mix so calculated is presented in the second column of Table 4. It can be seen from these results that the heat generation per volume of concrete was generally within 82 to 150 MJ/m^3. The variations of the heat generation per volume of concrete with the W/C ratio at different LF volumes are shown in Figure 6. Evidently, at all W/C ratios, the heat generation per volume of concrete reduced greatly as the LF volume increased. As explained before, such reduction in heat generation with increasing LF volume can be attributed to the decreases in cement content and water content when part of the cement paste was replaced by the LF added.

The percentage reductions in heat generation at different LF volumes are plotted against the W/C ratio in Figure 7, where dotted horizontal lines representing 11·8%, 23·5% and 35·3% decreases in cement paste volume at LF volumes of 4%, 8% and 12%, respectively, are also plotted for reference. The curves plotted reveal that the reductions in heat generation are somewhat smaller than the corresponding decreases in cement paste volume. Nevertheless, the addition of a LF volume of 4% to decrease the cement paste volume by 11·8% would reduce the heat generation by about 5% to 10% while the addition of a LF volume of 8% to decrease the cement paste volume by 23·5% would reduce the heat generation by about 15% to 23%.

Dividing the heat generation by the cement content, the heat generation per weight of cement of each concrete mix is also evaluated, as presented in the fourth column of Table 4. It can be seen from these results that the heat generation per weight of cement was generally within 29·6 to 35·4 MJ per 100 kg. The variations of the heat generation per weight of cement with the W/C ratio at different LF volumes are shown in Figure 8. It is evident that unlike the case of adiabatic temperature rise per cement content, at all W/C ratios, the heat generation per cement content increased slightly as the LF volume increased from 0% to 4% and then remained more or less constant as the LF volume further increased from 4% onwards. The increase in heat generation per cement content with the LF volume was smaller than the respective increase in adiabatic temperature rise per cement content because the specific heat capacity of the concrete was lower at a higher LF volume owing to the lower water content at higher LF volume. Furthermore, at all LF volumes, the heat generation per cement content increased slightly with the W/C ratio because of gradual increase in degree of hydration with the W/C ratio.

Mix no.	Heat generation per volume of concrete: MJ/m^3	Reduction in heat generation per volume of concrete: %	Heat generation per weight of cement: MJ/(100 kg)	Heat generation half-time: h
C-0·35-0	150	0·0	29·6	3·84
C-0·35-4	134	10·4	30·1	3·90
C-0·35-8	115	22·9	29·9	3·46
C-0·40-0	140	0·0	29·8	3·68
C-0·40-4	131	6·7	31·5	3·88
C-0·40-8	115	18·1	32·0	3·98
C-0·45-0	147	0·0	33·4	4·36
C-0·45-4	133	9·3	34·4	4·26
C-0·45-8	113	23·4	33·5	4·73
C-0·50-0	131	0·0	31·8	4·46
C-0·50-4	122	7·0	33·5	4·36
C-0·50-8	112	15·1	35·4	4·90
C-0·55-0	128	0·0	32·9	4·92
C-0·55-4	119	7·0	34·7	5·28
C-0·55-8	101	21·4	33·8	4·84
C-0·55-12	85	33·9	33·7	4·94
C-0·60-0	117	0·0	31·7	5·00
C-0·60-4	111	5·2	34·1	4·69
C-0·60-8	97	16·6	34·7	5·96
C-0·60-12	82	30·3	34·3	4·78

Table 4. Heat generation and heat generation half-time results

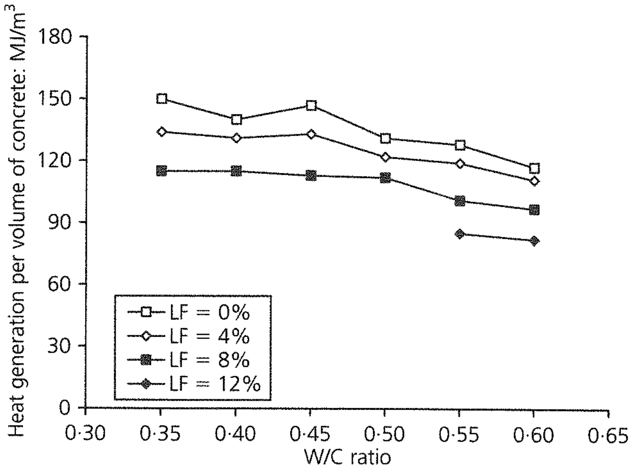

Figure 6. Heat generation per volume of concrete

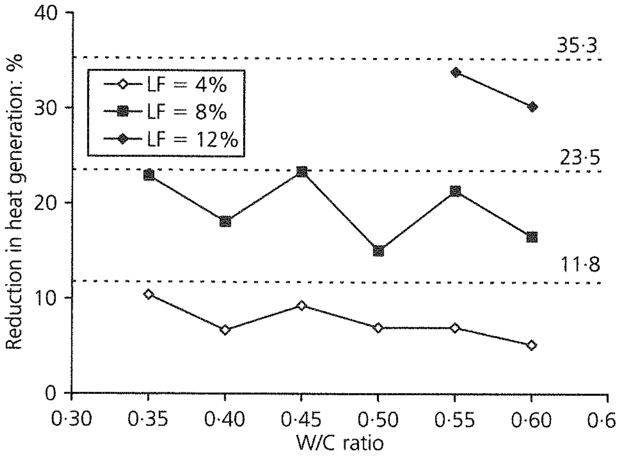

Figure 7. Percentage reduction in heat generation

Rate of heat generation

Besides the amount of heat generation, the rate of heat generation is also an important factor affecting the actual temperature rise of the concrete because at a given rate of heat dissipation, a faster rate of heat generation would lead to a higher peak temperature to be reached whereas a slower rate of heat generation would lead to a lower peak temperature to be reached. It is suggested herein to measure the rate of adiabatic temperature rise or heat generation in terms of the half-time of adiabatic temperature rise or heat generation, which is defined as the length of time after the start of temperature rise or heat generation for half of the adiabatic temperature rise or heat generation to take place, as illustrated in Figure 3. A shorter half-time indicates a faster rate of heat generation whereas a longer half-time indicates a slower rate of heat generation.

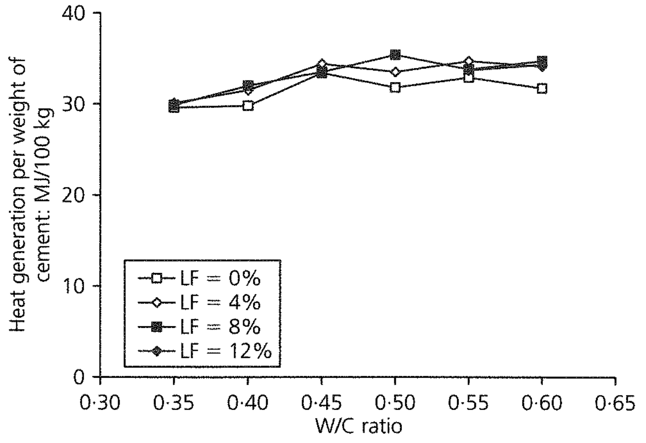

Figure 8. Heat generation per weight of cement

The heat generation half-time (same as adiabatic temperature rise half-time) of each concrete mix is listed in the last column of Table 4. From the values listed therein, it can be seen that the heat generation half-time was generally within 3·46 to 5·96 hours. At a constant W/C ratio, the heat generation half-time remained very much the same despite variation of the LF volume from 0% to 8% or 12% (the slight fluctuations in half-time were attributed to experimental errors), indicating that the addition of LF as cement paste replacement without changing the W/C ratio would not affect the heat generation half-time. On the other hand, as expected, the heat generation half-time increased significantly with the W/C ratio.

Heat generation and strength

The addition of LF as cement paste replacement without changing the W/C ratio not only reduces the heat generation, but also increases the strength of the concrete. If a higher strength is not really required, the opportunity may be taken to adjust the W/C ratio upwards to decrease the cement content further so as to reduce the heat generation further. Hence, the effectiveness of LF in reducing heat generation should not be assessed on an equal W/C ratio basis but should rather be assessed on an equal strength basis.

For assessing the effectiveness in reducing heat generation on an equal strength basis, the heat generation is plotted against the 28-day cube strength for different LF volumes in Figure 9. The figure clearly shows that the heat generation–strength curve is generally lower at higher LF volume, indicating that at the same strength requirement, the addition of LF to replace part of the cement paste together with a slight increase of the W/C ratio to keep the strength constant is effective in reducing the heat generation. Interpolating from the curves plotted, the heat generation at a 28-day cube strength of 60 MPa may be worked out as 139 MJ/m^3 when LF volume is 0%, 121 MJ/m^3 when LF volume is 4%, 105 MJ/m^3 when LF volume is 8%, and 85 MJ/m^3 when LF volume is 12%. From these values, the reduction in heat generation on an equal strength basis owing to the addition of 4%, 8% and 12% LF volume may be calculated as 12·9%, 24·5% and 38·8%, respectively. As the powder paste volume was fixed at 34%, the addition of 4%, 8% and 12% LF volume had caused the cement paste volume to be reduced by 11·8%, 23·5% and 35·3%, respectively. Comparing the reduction in heat generation on an equal strength basis with the reduction in cement paste volume, it may be said that the percentage reduction in heat generation on equal strength basis was slightly larger than the percentage reduction in cement paste volume.

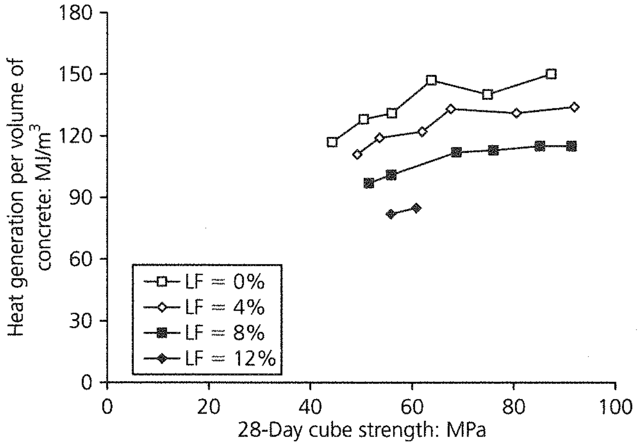

Figure 9. Heat generation per volume of concrete and cube strength

Conclusions

The effects of adding LF as cement paste replacement on the workability, strength and heat generation of concrete have been studied by testing a total of 20 concrete mixes with different W/C ratios and LF volumes. Based on the test results, the following conclusions are drawn.

(*a*) The addition of LF as cement paste replacement would reduce the workability of the concrete, but such reduction in workability can be more than restored by increasing the SP dosage.
(*b*) The addition of LF as cement paste replacement would significantly increase the strength of the concrete, even though the LF is chemically inert and therefore not cementitious.
(*c*) The addition of LF as cement paste replacement would substantially reduce the adiabatic temperature rise and heat generation of the concrete but would not affect the heat generation half-time.
(*d*) On an equal W/C ratio basis, the percentage reduction in heat generation would be smaller than the percentage reduction in cement paste volume. For instance, the addition of 4% LF volume to decrease the cement paste volume by 11·8% would reduce the heat generation by about 5% to 10% while the addition of 8% LF volume to decrease the cement paste volume by 23·5% would reduce the heat generation by about 15% to 23%.
(*e*) On an equal strength basis, the percentage reduction in heat

generation would be slightly larger than the percentage reduction in cement paste volume. For example, at required 28-day cube strength of 60 MPa, the addition of 4%, 8% and 12% LF volume to reduce the cement paste volume by 11·8%, 23·5% and 35·3%, respectively, would reduce the heat generation by 12·9%, 24·5% and 38·8%, respectively.

More importantly, the addition of an inert filler, such as LF, to reduce the cement paste volume while keeping the powder paste volume at more than sufficient to fill the voids between aggregate particles would allow the cement paste volume to be reduced to much lower than possible in conventional concrete with no filler added. Such reduction in cement paste volume should help to reduce the carbon footprint and improve the dimensional stability of the concrete. Further research along this line for the development of green and high-performance concrete is recommended.

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