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Packing density and filling effect of limestone fines

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Abstract. The use of limestone fines (LF) in mortar and concrete can in certain ways improve performance and thus has become more and more commonplace. However, although LF is generally regarded as a filler, it is up to now not clear how much filling effect it could have and how best the filling effect could be utilized. Herein, the packing density and filling effect of LF were studied by measuring the packing densities of LF, (LF + cement) blends and (LF + cement + fine aggregate) blends under dry and wet conditions, and measuring the performance of mortars made with various amounts of LF added. It was found that the addition of LF would not significantly increase the packing density of (LF + cement) blends but would fill into the paste to increase the paste volume and paste film thickness, and improve the flow spread and strength of mortar.

Keywords: fillers; limestone fines; mortar; packing density; paste film thickness

1. Introduction

In recent years, various kinds of fillers, such as limestone fines (LF), have been used in the production of concrete (Bonavetti *et al*. 2003; Mňahončáková *et al*. 2008; Craeye *et al*. 2010). Depending on the fineness of the fillers and how the fillers are added (whether replacing aggregate, cement or cement paste), the addition of fillers has significant effects on the fresh and hardened properties of concrete. Unlike supplementary cementitious materials, which take part in chemical reactions to produce gel for strength development, fillers are chemically inert and thus would not take part in any chemical reactions (Sprung and Siebel 1991). Nevertheless, it has been found that the incorporation of LF in certain ways can enhance the workability, stability and early strength of concrete (Kanazawa *et al*. 1992).

The use of LF in concrete has been a major research topic for many years. LF was first used as an aggregate to replace part of the sand. Malhotra and Carette (1985) observed that replacing part of the sand with LF could increase or decrease the compressive strength of concrete, depending on the water/cement ratio and LF content. Besides, they found that the incorporation of LF would increase the cohesiveness of the fresh concrete and the drying shrinkage of the hardened concrete but has little effect on the durability of the concrete structure.

Later, LF was used to replace part of the cement. Nehdi *et al*. (1996) showed that replacing part of the cement with LF up to 10% or 15% would not affect the early strength of mortar, but would

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reduce the strength at later ages. Bentz and Conway (2001) suggested that a portion of the coarse cement grains can be replaced by an inert filler with little reduction in strength. Bentz (2005) experimentally demonstrated 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 quality. However, Bentz *et al*. (2009) later pointed out that the effective water/cementitious materials (W/CM) ratio should not be taken as the water/(cement + LF) ratio because this would cause significant reduction in strength of the concrete and that the reduction in strength could be compensated for by a slight reduction of the water/(cement + LF) ratio.

More recently, LF was used to replace part of the cement paste. Chen and Kwan (2012) showed that the addition of LF to replace an equal volume of cement paste would allow the cement paste volume to be decreased to fairly small values without causing air entrapment due to incomplete filling of the voids between aggregate particles with cement paste. Using this strategy, they have substantially reduced the carbon footprint, heat generation (Chen and Kwan 2012) and drying shrinkage (Kwan *et al*. 2013) of the concrete produced.

Opoczky (1992) postulated that the main effects of LF are due to its physical nature and that LF would render a better packing of the cement granular skeleton and a larger dispersion of the cement grains. Actually, some years ago, Soroka and Setter (1977) already found that the addition of LF could produce an increase in strength of mortar and suggested that such increase in strength may be attributed to the increase in packing density of the solid particles. On the other hand, several more recent studies (Lee *et al*. 2003; Kwan and Wong 2008a; Nanthagopalan *et al*. 2008) revealed that the packing density of the cementitious materials is an important factor governing the flowability of the cement paste formed, especially at low W/CM ratio. However, due to the presence of inter-particle forces causing agglomeration, the packing density of cementitious materials or a mixture of cementitious materials and aggregate particles is not easy to measure. Moreover, although it is well known that the water and superplasticizer (SP) in the cement paste, mortar or concrete may have some effects on the packing density, these are usually ignored.

The conventional methods of packing density measurement, as stipulated in British Standard BS 812-2: 1995 (British Standards Institution 1995), and European Standard BS EN 1097-3: 1998 (British Standards Institution 1998) and BS EN 1097-4: 2008 (British Standards Institution 2008), measure the packing density of the solid particles under dry condition. These methods, which may be classified as dry packing methods, are not really applicable to materials containing fine particles, such as cementitious materials, LF and fine aggregate. This is because under dry condition, the fine particles tend to form agglomerates and the packing density so measured is very sensitive to the compaction applied (Svarovsky 1987). More importantly, the effects of water and SP in the concrete mix cannot be included.

To resolve these problems, the authors' research group has recently developed a new method, called the wet packing method, for measuring the packing densities of cementitious materials (Wong and Kwan 2008a), fine aggregate (Fung *et al*. 2009) and cementitious materials plus fine aggregate (Kwan and Fung 2009) with the effects of water and SP included. Basically, the test results revealed that the presence of water and SP would significantly increase the packing density and substantially decrease the voids ratio of materials containing fine particles, and therefore, the wet packing method is a more appropriate test method for the packing density measurement of solid particles in a paste or mortar. Diederich *et al*. (2012) have used this wet packing method to study the effects of LF on the excess water ratio, yield stress and apparent viscosity of cement based matrix containing LF.

For further in-depth study, an experimental program has been launched to evaluate the packing density and filling effect of LF, as reported herein. First, the packing densities of LF, (LF + cement) blends and (LF + cement + fine aggregate) blends were measured under the dry and wet conditions. Then, the effects of compaction and SP were studied by measuring the packing densities with different compaction applied or different SP dosages added, the effects of water were studied by comparing the wet packing density results with the respective dry packing density results, and the effects of blending and particle size ratio were investigated from the packing density results of the blended materials. Finally, the effects of LF on the packing density, flowability and strength of mortar were studied, from which the actual filling effect of LF was identified.

2. Materials

An ordinary Portland cement (OPC) of strength class 52.5N complying with BS EN 197-1: 2000 (British Standards Institution 2000) and a finely ground limestone fines (LF) were used. The OPC has a Blaine fineness of 376 m^2/kg and a 28-day mortar cube strength of 59.0 MPa, as measured in accordance with BS EN 196-1: 2005 (British Standards Institution 2005). The fine aggregate (FA) used was a local crushed granite rock fine with a maximum size of 1.18 mm and a water absorption of 1.0% by mass. The relative densities of the OPC, LF and FA had been measured in accordance with BS EN 196-6: 2010 (British Standards Institution 2010) as 3.11, 2.64 and 2.61, respectively. A laser diffraction particle size analyzer was used to measure the particle size distributions of the materials and the results are plotted in Fig. 1. Based on these particle size

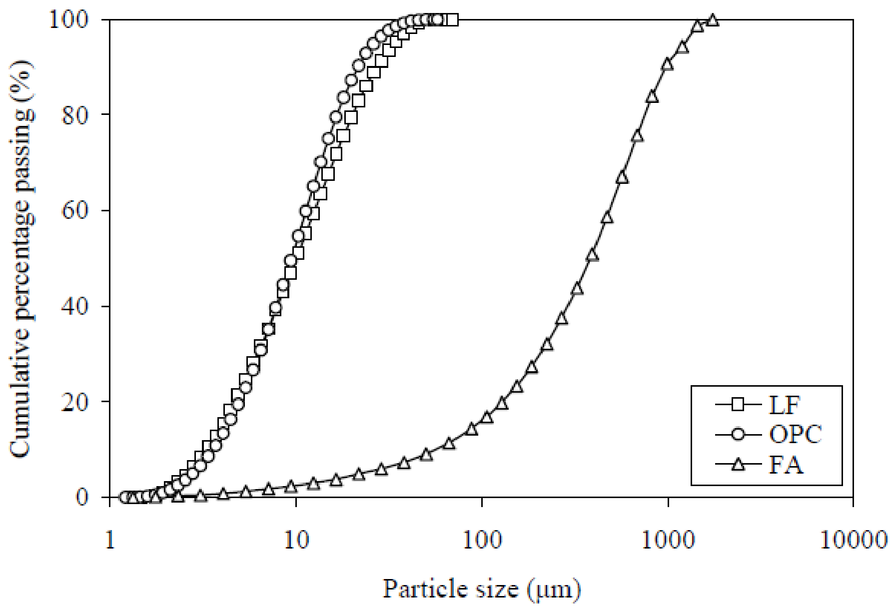

Fig. 1 Particle size distributions of LF, OPC and FA

distributions, the specific surface areas of the OPC, LF and FA were calculated using a shape factor of 6.0 as 1.12×10^6 m^2/m^3, 1.03×10^6 m^2/m^3 and 1.15×10^5 m^2/m^3, respectively, and the volumetric mean particle sizes of the OPC, LF and FA were calculated as 11.8 μm, 13.6 μm and 506 μm, respectively. The superplasticizer (SP) added was a polycarboxylate type supplied in the form of an aqueous solution with a solid mass content of 20% and a relative density of 1.03.

3. Experimental program

The experimental program consisted of two parts. Part A was to measure the packing densities of LF, OPC, (LF+OPC) blends, (LF+FA) blends, (OPC+FA) blends and (LF+OPC+FA) blends under dry condition with different compaction applied and under wet condition with different SP dosages added. Part B was to measure the packing density, flow spread, flow rate and cube compressive strength of mortar samples produced with different LF contents so as to study the effects of LF on the fresh and hardened properties of mortar.

3.1 Part A - Packing density tests

The testing conditions are depicted in Table 1. For measuring the dry packing densities, different degrees of compaction, each expressed in terms of the number of compactive blows, were applied to evaluate the effects of compaction on the dry packing density. For measuring the wet packing densities, no compaction was applied but different SP dosages, each expressed as a percentage by mass of the powder content (the powder content includes both the LF content and OPC content), were added to evaluate the effects of SP dosage on the wet packing density.

For the (LF+OPC) blends, the LF/OPC ratio by volume was varied from 0.0 to 1.0 in steps of 0.2. For the (LF+FA) blends and (OPC+FA) blends, the LF/FA and OPC/FA ratios by volume were each varied from 0.0 to 1.0 in steps of 0.1. For the (LF+OPC+FA) blends, the LF/OPC ratio by volume was fixed at 1.0 while the P/FA ratio by volume (P means powder and is equal to LF+OPC) was varied from 0.0 to 1.0 in steps of 0.1. The mix proportions were defined in terms of volumetric ratios because the packing densities of the particle systems are governed by the volumetric ratios of the ingredients rather than the mass ratios.

In total, 24 non-blended samples and 108 blended samples were produced for testing. The non-blended LF and OPC samples tested under the dry and wet conditions are depicted in Tables 2 and 3, respectively, while the (LF+OPC) blends, (LF+FA) blends, (OPC+FA) blends and (LF+OPC+FA) blends tested under both the dry and wet condition are depicted in Tables 4, 5, 6, and 7, respectively.

To measure the dry packing densities, the dry packing method stipulated in British Standard BS 812-2: 1995 (British Standards Institution 1995) for measuring the uncompacted and compacted packing densities of aggregate was adopted. Basically, the sample was filled into a steel container and the bulk density of the sample was measured to determine the packing density of the sample as the bulk density to solid density ratio. For testing under condition D0, the sample was filled into the container without applying any compaction. For testing under conditions D10, D20, D30, D40 and D50, the sample was filled into the container in three equal portions and each time after filling a one-third portion, the sample in the container was compacted by applying 10, 20, 30, 40 and 50

Table 1 Testing conditions

Designation of testing condition	Dry or wet condition	Number of compactive blows	SP dosage (%)
D0	Dry	0	Nil
D10		10	Nil
D20		20	Nil
D30		30	Nil
D40		40	Nil
D50		50	Nil
W0	Wet	Nil	0.0
W1		Nil	0.5
W2		Nil	1.0
W3		Nil	1.5
W4		Nil	2.0
W5		Nil	2.5

Table 2 Dry packing density results of non-blended LF and OPC

Material	Packing density under each testing condition					
	D0	D10	D20	D30	D40	D50
LF	0.461	0.479	0.492	0.502	0.512	0.514
OPC	0.448	0.460	0.475	0.484	0.498	0.505

Table 3 Wet packing density results of non-blended LF and OPC

Material	Packing density under each testing condition					
	W0	W1	W2	W3	W4	W5
LF	0.611	0.616	0.621	0.621	0.621	0.621
OPC	0.587	0.594	0.600	0.605	0.605	0.605

compactive blows respectively with a metal tamping rod. For non-blended samples, the sample was first used for measuring the uncompacted packing density under condition D0, and then remixed and reused for measuring the compacted packing density under condition D10, D20, D30, D40 and D50. This was to study the effect of compaction on the dry packing density. For blended samples, only the uncompacted packing density under condition D0 was measured because the tests on blended samples were mainly to study the effects of water and SP, not compaction.

To measure the wet packing densities, the wet packing method developed by the authors' research group (Wong and Kwan 2008a; Fung *et al*. 2009; Kwan and Fung 2009) was adopted. In this method, the packing density measurement was conducted under wet condition by mixing the solid particles with water and SP so that the effects of both water and SP could be incorporated. Basically, the wet packing density was determined as the maximum solid concentration of the solid particles that can be achieved at varying water content ranging from insufficient to fill the voids to

Table 4 Packing density results of (LF+OPC) blends

Mix no.	LF/OPC ratio	Packing density under each testing condition			Increase in packing density due to presence of water (%)	Increase in packing density due to addition of SP (%)
		D0	W0	W5		
LF+OPC-0.0	0.0	0.448	0.587	0.605	31.0	3.1
LF+OPC-0.2	0.2	0.449	0.592	0.609	31.8	2.9
LF+OPC-0.4	0.4	0.451	0.595	0.612	31.9	2.9
LF+OPC-0.6	0.6	0.454	0.598	0.614	31.7	2.7
LF+OPC-0.8	0.8	0.455	0.600	0.615	31.9	2.5
LF+OPC-1.0	1.0	0.456	0.601	0.617	31.8	2.7

Table 5 Packing density results of (LF+FA) blends

Mix no.	LF/FA ratio	Packing density under each testing condition			Increase in packing density due to presence of water (%)	Increase in packing density due to addition of SP (%)
		D0	W0	W5		
LF+FA-0.0	0.0	0.517	0.619	0.627	19.7	1.3
LF+FA-0.1	0.1	0.536	0.653	0.683	21.8	4.6
LF+FA-0.2	0.2	0.555	0.676	0.708	21.8	4.7
LF+FA-0.3	0.3	0.564	0.688	0.722	22.0	4.9
LF+FA-0.4	0.4	0.569	0.685	0.721	20.4	5.3
LF+FA-0.5	0.5	0.563	0.679	0.719	20.6	5.9
LF+FA-0.6	0.6	0.552	0.673	0.711	21.9	5.6
LF+FA-0.7	0.7	0.547	0.667	0.706	21.9	5.8
LF+FA-0.8	0.8	0.540	0.661	0.701	22.4	6.1
LF+FA-0.9	0.9	0.536	0.657	0.698	22.6	6.2
LF+FA-1.0	1.0	0.533	0.654	0.692	22.7	5.8

Table 6 Packing density results of (OPC+FA) blends

Mix no.	OPC/FA ratio	Packing density under each testing condition			Increase in packing density due to presence of water (%)	Increase in packing density due to addition of SP (%)
		D0	W0	W5		
OPC+FA-0.0	0.0	0.517	0.619	0.627	19.7	1.3
OPC+FA-0.1	0.1	0.531	0.644	0.678	21.3	5.3
OPC+FA-0.2	0.2	0.540	0.661	0.697	22.4	5.4
OPC+FA-0.3	0.3	0.548	0.672	0.709	22.6	5.5
OPC+FA-0.4	0.4	0.552	0.675	0.716	22.3	6.1
OPC+FA-0.5	0.5	0.556	0.667	0.709	20.0	6.3
OPC+FA-0.6	0.6	0.549	0.661	0.702	20.4	6.2
OPC+FA-0.7	0.7	0.541	0.656	0.696	21.3	6.1
OPC+FA-0.8	0.8	0.535	0.654	0.693	22.2	6.0
OPC+FA-0.9	0.9	0.529	0.651	0.691	23.1	6.1
OPC+FA-1.0	1.0	0.524	0.649	0.688	23.9	6.0

Table 7 Packing density results of (LF+OPC+FA) blends

Mix no.	P/FA ratio	Packing density under each testing condition			Increase in packing density due to presence of water (%)	Increase in packing density due to addition of SP (%)
		D0	W0	W5		
P+FA-0.0	0.0	0.517	0.619	0.627	19.7	1.3
P+FA-0.1	0.1	0.534	0.650	0.681	21.8	4.8
P+FA-0.2	0.2	0.548	0.671	0.703	22.6	4.8
P+FA-0.3	0.3	0.556	0.683	0.719	22.8	5.3
P+FA-0.4	0.4	0.561	0.682	0.717	21.7	5.1
P+FA-0.5	0.5	0.560	0.674	0.715	20.5	6.1
P+FA-0.6	0.6	0.551	0.669	0.707	21.5	5.7
P+FA-0.7	0.7	0.544	0.663	0.702	21.9	5.9
P+FA-0.8	0.8	0.538	0.660	0.698	22.8	5.8
P+FA-0.9	0.9	0.533	0.655	0.696	23.0	6.3
P+FA-1.0	1.0	0.529	0.651	0.691	23.2	6.1

more than sufficient to fill the voids. For testing under condition W0, no SP was added while for testing under conditions W1, W2, W3, W4 and W5, SP was added at dosages of 0.5%. 1.0%, 1.5%, 2.0% and 2.5% respectively by mass of the powder content. No compaction was applied because the wet packing tests were mainly to study the effects of water and SP, not compaction. For non-blended samples, each sample was tested under all the six conditions W0, W1, W2, W3, W4 and W5. This was to study the effects of SP on the wet packing density. For blended samples, each sample was tested under the conditions W0 and W5 only because these tests were mainly to study the effects of blending, not SP dosage.

3.2 Part B - Mortar tests

Four mortar mixes were produced for testing. Their cement paste volume (volume of cement plus volume of water) was set constant at 50% while their LF volume was varied among 0%, 4%, 8% and 12% of the mortar volume so as to study the filling effects of LF. The remaining volume of the mortar was the FA volume. In other words, the LF was added to replace an equal volume of FA without changing the cement paste volume. For every mortar mix, the water/cement (W/C) ratio by mass was fixed at 0.50. In terms of quantity per volume of mortar, the OPC content was constant at 609 kg/m^3, the LF content varied from 0 to 317 kg/m^3, the FA content varied from 993 to 1307 kg/m^3 and the water content (not including the water in the SP) varied from 291 to 294 kg/m^3. Details of the mix proportions are presented in Table 8. Each mortar mix was assigned an identification code of M-X-Y, in which M denotes mortar, X denotes the cement paste volume and Y denotes the LF volume.

SP was added to each mortar sample. Since SP is a surface reactant and it is the SP dosage per solid surface area that actually governs the effectiveness of the SP (Wong and Kwan 2008b; Kwan *et al*. 2012), the SP dosage was determined according to the total surface area of the solid particles in the mortar. Before setting the SP dosage to be used, trial cement paste mixing using different SP dosages was carried out and it was found that the saturation dosage (the dosage beyond which further addition of the SP yields little further increase in flowability) was 3.7×10^{-5} kg/m^2 of the solid surface area. Hence, the SP dosage in terms of liquid mass of SP per solid surface area was set as 3.7×10^{-5} kg/m^2 for all the mortar samples. Converted to dosage per volume of mortar, the SP dosage varied from 11 kg/m^3 for the mortar mix containing no LF to 14 kg/m^3 for the mortar mix containing a LF volume of 12%.

The packing density of the particles in each mortar sample was measured using the wet packing method (Wong and Kwan 2008a; Fung *et al*. 2009; Kwan and Fung 2009), as explained before. In this particular study, the 4 mortar samples tested for their rheological and hardened properties were actually made from 4 different mix proportions of LF, OPC and FA. Hence, the 4 mix proportions of LF, OPC and FA were separately tested for their wet packing densities.

After mixing, each mortar sample was subjected to the mini slump cone test and mini V-funnel test for evaluation of its flow ability in terms of flow spread and flow rate. Both the mini slump cone and mini V-funnel tests for mortar may be regarded as reduced scale versions of the slump and V-funnel tests for concrete. There are several versions of mini slump cone and mini V-funnel with different dimensions. The versions adopted here are the same as those used by Okamura and Ouchi (2003). The detailed test procedures have been given before and are therefore not repeated here (Kwan *et al*. 2010).

After the above flow ability tests, the mortar sample was remixed in the mixer and then used to cast six 100 mm cubes, three of which were for testing of 7-day compressive strength and the other three were for testing of 28-day compressive strength. The cubes were cast in steel moulds, covered with a plastic sheet on each top surface and then stored in the laboratory at a temperature of 24 ± 2°C. At one day after casting, the moulds were removed and the cubes were cured in a lime-saturated water tank controlled at a temperature of 27 ± 2°C until the ages of 7 days and 28 days for cube compression tests.

Table 8 Mix proportions, packing density, WFT and PFT results of mortar samples

Mix no.	Materials content in the mortar (kg/m^3)					Packing density	WFT (μm)	PFT (μm)
	OPC	LF	FA	Water	SP			
M-50-0	609	0	1307	294	11	0.720	0.111	32.7
M-50-4	609	106	1202	293	12	0.717	0.087	42.7
M-50-8	609	211	1098	292	13	0.710	0.054	54.6
M-50-12	609	317	993	291	14	0.705	0.032	69.0

Table 9 Flowability and strength results of mortar samples

Mix no.	Flow spread (mm)	Flow rate (ml/s)	7-day cube strength (MPa)	28-day cube strength (MPa)
M-50-0	60	98	50.5	58.7
M-50-4	75	73	51.2	59.5
M-50-8	65	38	52.9	61.3
M-50-12	50	40	56.5	62.7

4. Experimental results

4.1 Packing densities of non-blended LF and OPC

Table 2 presents the dry packing density results of the non-blended LF and OPC under the testing conditions D0, D10, D20, D30, D40 and D50 while Table 3 presents the wet packing density results of the non-blended LF and OPC under the testing conditions W0, W1, W2, W3, W4 and W5. From these results, it is obvious that the packing density of the LF was generally within 0.461 to 0.621 whereas the packing density of OPC was generally within 0.448 to 0.605. On the whole, the packing density of LF was higher than the packing density of OPC under any testing condition. This was because the LF has a wider size range than OPC. It is also obvious that for both LF and OPC, the effects of compaction, water and SP are significant.

Comparing the packing density results under the dry conditions D0, D10, D20, D30, D40 and D50, it is evident that under dry condition, the packing density was quite sensitive to the compaction applied. With compaction applied, the dry packing density of LF increased by 3.9%, 6.7%, 8.9%, 11.1% and 11.5% whereas the dry packing density of OPC increased by 2.7%, 6.0%, 8.0%, 11.2% and 12.7%, as the number of compactive blows increased from 0 to 10, 20, 30, 40 and 50, respectively.

Comparing the packing density results under the wet conditions to those under the dry conditions, it is clear that for both LF and OPC, the wet packing density was substantially higher than the dry packing density. With no compaction applied and no SP added, the wet packing densities of LF and OPC were 32.5% and 31.0% higher than the respective dry packing densities. In fact, for both LF and OPC, the wet packing density with no compaction applied and no SP added was at least 16% higher than the respective dry packing density with 50 compactive blows applied.

Comparing the packing density results under the wet conditions W0, W1, W2, W3, W4 and W5, it can be seen that the wet packing density increased slightly with the SP dosage. For LF, the wet packing density increased by up to 1.6% when the SP dosage was increased to 1.0% and thereafter remained the same when the SP dosage was further increased. For OPC, the wet packing density increased by up to 3.1% when the SP dosage was increased to 1.5% and thereafter remained the same when the SP dosage was further increased. Hence, for each material, there was a saturation SP dosage beyond which further increase in SP dosage has little effect. From the above results, the saturation SP dosages for LF and OPC may be determined as 1.0% and 1.5% by mass of the powder content, respectively.

4.2 Packing densities of LF+OPC, LF+FA, OPC+FA and LF+OPC+FA blends

Tables 4, 5, 6 and 7 present the packing density results of the (LF+OPC) blends, (LF+FA) blends, (OPC+FA) blends and (LF+OPC+FA) blends under the testing conditions D0, W0 and W5. These results reveal that under the dry condition D0, the packing densities of the LF+OPC, LF+FA, OPC+FA and LF+OPC+FA blends were generally within 0.448 to 0.456, 0.517 to 0.569, 0.517 to 0.556 and 0.517 to 0.561, respectively. Under the wet condition W0 with no SP added, the packing densities of the LF+OPC, LF+FA, OPC+FA and LF+OPC+FA blends were generally within 0.587 to 0.601, 0.619 to 0.688, 0.619 to 0.675 and 0.619 to 0.683, respectively. Under the wet condition W5 with SP added, the packing densities of the LF+OPC, LF+FA, OPC+FA and LF+OPC+FA blends were generally within 0.605 to 0.617, 0.627 to 0.722, 0.627 to 0.716 and

0.627 to 0.719, respectively.

Comparing the packing density results under the wet condition W0 to those under the dry condition D0, it can be seen that for all the blended samples, regardless of the LF/OPC ratio and P/FA ratio, the wet packing density was substantially higher than the corresponding dry packing density. Such effect of water may be evaluated in terms of the increase in packing density due to the presence of water, as tabulated in the respective sixth column in Tables 4, 5, 6 and 7. From the tabulated values, it is evident that the increase in packing density due to the presence of water varied from 19.7% when there was only FA to 31.9% when there was only powder (LF+OPC).

Comparing the packing density results under the condition W5 with SP added to those under the condition W0 with no SP added, it can be seen that for all the blended samples, regardless of the LF/OPC ratio and P/FA ratio, the wet packing density was slightly higher with SP added. Such effect of SP may be evaluated in terms of the increase in packing density due to the addition of SP, as tabulated in the respective seventh column of Tables 4, 5, 6 and 7. As can be seen from the tabulated values, the increase in packing density due to the addition of SP varied from 1.3% to 6.3%. It should be noted that the SP dosage under condition W5 was higher than the saturation SP dosage and thus these increases in packing density are already the best results that could be obtained by the type of SP used.

In theory, blending of different size particles together so that the smaller size particles would fill into the voids between the larger size particles would increase the packing density. However, the actual increase in packing density due to blending is dependent on several factors, including the mix proportions and size ratios of the different size particles blended together. In this research, the opportunity was taken to study the effects of blending under the dry and wet conditions. For this purpose, the packing densities of LF+OPC are plotted against the LF/OPC ratio in Fig. 2 and the packing densities of LF+FA, OPC+FA and LF+OPC+FA are plotted against the P/FA ratio (P = LF+OPC) in Fig. 3.

The curves plotted in Figure 2 reveal that as the LF/OPC ratio increased, the packing density increased only marginally, indicating that blending of OPC with LF has little effect on the packing density. This was because the OPC and LF have similar particle sizes and thus very little filling effect could take place. The marginal increase in packing density with the LF/OPC ratio was due to the slight higher packing density of LF rather than any filling effect of LF.

The curves plotted in Figure 3 reveal that as the P/FA ratio increased from 0 to 1.0, the packing density first increased from the packing density of FA to a maximum packing density at an optimum P/FA ratio and then decreased to the packing density of the powder P (P could be LF, OPC or LF+OPC). The increase in packing density as the P/FA ratio increased from zero to an optimum value was caused by the smaller size P particles filling into the voids between the larger size FA particles (this is exactly the filling effect). The decrease in packing density as the P/FA ratio further increased to beyond the optimum value was caused by the excess P (the portion of P in excess of that needed to fill the voids between the FA particles) pushing the FA particles apart to reduce the solid concentration of FA.

More importantly, the maximum packing density was always higher than both the packing density of FA and the packing density of P, indicating that blending of FA with P could increase the packing density. For instance, under the condition W0, blending of FA with LF, OPC and LF+OPC had increased the packing density by 11.1%, 9.0% and 10.3%, respectively. Comparing the effect of blending on the packing density of LF+OPC and the effect of blending on the packing density of P+FA, it is obvious that the blending of FA with P has a much larger effect than the blending of

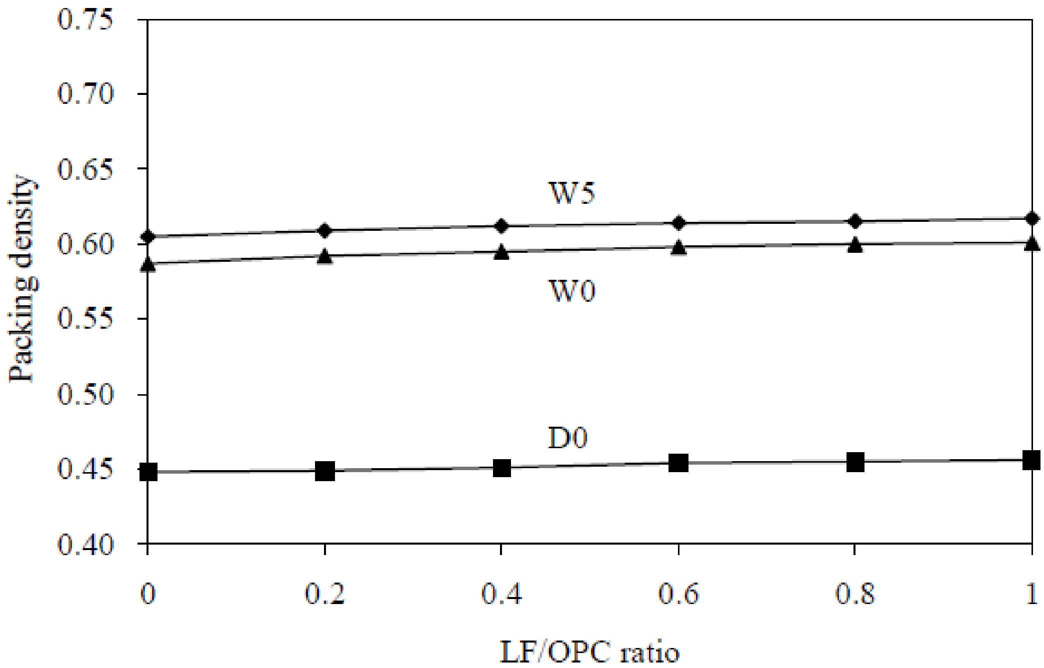

Fig. 2 Packing densities of (LF+OPC) blends

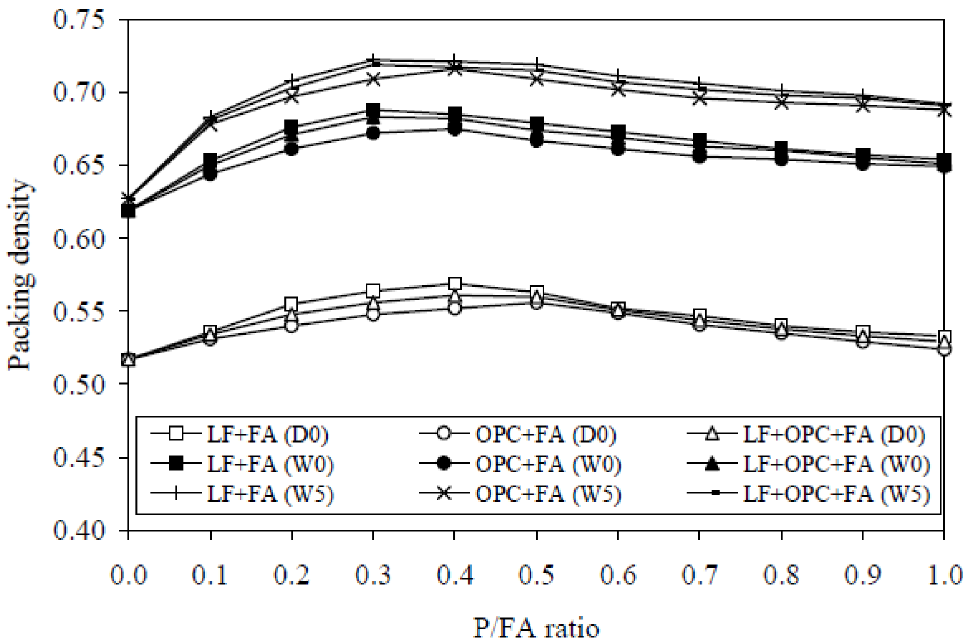

Fig. 3 Packing densities of (LF+FA), (OPC+FA) and (LF+OPC+FA) blends

OPC with LF. This was because of the difference in size ratio (ratio of the size of smaller particles to the size of larger particles). LF and OPC have similar particle sizes and thus the size ratio is close to 1 whereas P is much smaller than FA and thus the size ratio is relatively small. As explained by De Larrard (1999), a smaller size ratio would lead to a larger beneficial effect of blending whereas a larger size ratio would lead to a smaller beneficial effect of blending. This agrees with the general observation that a larger size range would yield a higher packing density.

The curves in Figure 3 also reveal that the optimum P/FA ratio at which the maximum packing density would be achieved was different under different testing conditions. For instance, for the OPC+FA blends, the optimum P/FA ratios under conditions D0, W0 and W5 were 0.5, 0.4 and 0.4, respectively. Hence, the presence of water could affect the optimum P/FA ratio for maximum packing density. Generally, the optimum P/FA ratio was slightly lower under wet condition than dry condition.

4.3 Packing density, water film thickness and paste film thickness of mortar

The packing density results of the 4 mortar mixes tested are tabulated in the seventh column of Table 8. These results show that the packing density decreased slightly from 0.720 to 0.705 as the LF volume increased from 0% to 12%. This phenomenon can be explained using the packing theory (De Larrard 1999). When the powder volume is small, the powder would fill into the voids between the aggregate particles to increase the packing density, but when the powder volume is large, the powder would become more than enough to fill the voids and the excess powder (the powder in excess of that needed to fill the voids between the aggregate particles) would push the aggregate particles apart thus causing the packing density to decrease. The maximum packing density occurs when the powder is just enough to fill the voids. From Tables 6 and 7, it can be seen that under condition W5, the maximum packing densities of OPC+FA and LF+OPC+FA blends were 0.716 and 0.719, respectively, but in the case of mortar mix M-50-0 with only OPC added and no LF added, the packing density was already as high as 0.720. With the packing density already at maximum, the addition of LF to the mortar would increase the powder content to more than enough to fill the voids, and thus cause the packing density to decrease.

Apart from changing the packing density of the particle system, the addition of a filler like LF would also change the characteristics of the water-solid mixture because of the corresponding changes in voids volume and solid surface area. From previous research (Kwan and Wong 2008b; Fung and Kwan 2010; Kwan and Li 2012), it has been found that the two major characteristics of cement paste and cement-sand mortar governing their fresh and hardened properties are the water film thickness (WFT) and paste film thickness (PFT). The WFT, which has the physical mean of average thickness of water films coating the solid particles, may be determined as the ratio of the excess water (water in excess of that needed to fill the voids between solid particles) to the solid surface area of all solid particles. Likewise, the PFT, which has the physical meaning of average thickness of paste films coating the aggregate particles, may be determined as the ratio of the excess paste to (paste in excess of that needed to fill the voids between aggregate particles) to the solid surface area of aggregate particles.

The WFT was obtained by first measuring the packing density of all solid particles, from which the voids volume (bulk volume minus solid volume) and the excess water volume (water volume minus voids volume) could be evaluated, and then determining the WFT as the excess water to solid surface area of all solid particles ratio. Likewise, the PFT was obtained by first measuring the packing density of the aggregate particles and then determining the PFT as the excess paste to solid surface area of aggregate particles ratio. However, the FA contained a significant portion of fines (particles smaller than 75 μm), which tends to intermix with the OPC, LF and water to form part of the paste. Hence, the paste volume was taken as the total volume of OPC, LF, fines in the FA and water, and the packing density and solid surface area were taken as those of the FA with the fines content excluded by sieving.

The WFT and PFT of the 4 mortar mixes, which all had a constant cement paste volume of 50% and a constant W/C ratio of 0.50, are listed in the last two columns of Table 8 and plotted against the LF volume in Figs. 4 and 5. The WFT results reveal that for the mortar samples tested, the WFT decreased steadily from 0.111 μm to 0.032 μm as the LF volume increased from 0% to 12%. This was because the addition of LF had slightly decreased the packing density and significantly increased the solid surface area of the mortar mixes. On the other hand, the PFT results reveal that for the mortar samples tested, the PFT increased steadily from 32.7 μm to 69.0 μm as the LF volume increased from 0% to 12%. This was because the addition of LF had significantly increased the paste volume (the paste volume includes the LF volume), had not changed the packing density of the aggregate and had decreased the solid surface area of the aggregate (due to decrease in aggregate content as part of the aggregate had been replaced by the LF added).

Summarizing, the addition of LF without changing the cement paste volume and W/C ratio would slightly decrease the packing density, significantly decrease the WFT and significantly increase the PFT. These are due to the corresponding changes in powder content, paste volume, aggregate content, solid surface area of all solid particles and solid surface area of aggregate particles. The filling effect of limestone fines is now clear. Although limestone fines has been regarded as a filler and even called limestone filler for many years, the actual filling effect of LF has never been thoroughly investigated. For the particular type of LF used herein, which has similar fineness as OPC, it has no filling effect when added to OPC to form a (LF+OPC) blend but has some filling effect when added to FA to form a (LF+FA) blend. When added to OPC and FA to form a (LF+OPC+FA) blend, it would increase the packing density if the OPC/FA ratio is less than the optimum for maximum packing density but would decrease the packing density if the OPC/FA

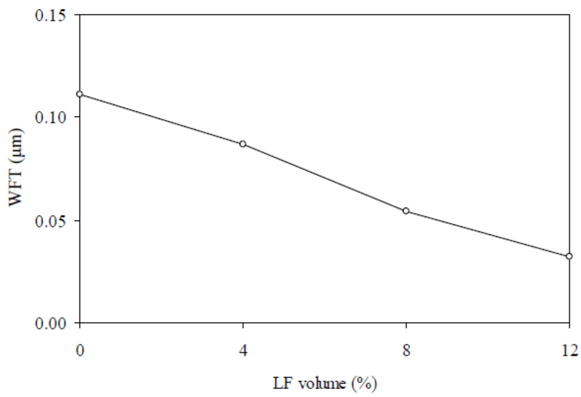

Fig. 4 Effect of LF on WFT of mortar

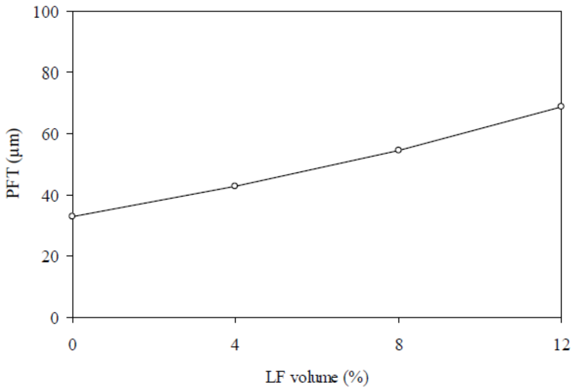

Fig. 5 Effect of LF on PFT of mortar

ratio is higher than the optimum for maximum packing density. When added to a mortar without changing the cement paste volume and W/C ratio, it would decrease the WFT and increase the PFT. Overall, it may be said that the filling effect of LF is contributed main by the LF filling into the paste to increase the paste volume and PFT.

4.4 Flowabilty of mortar

The flow spread and flow rate results are listed in Table 9 and plotted against the LF volume in Figs. 6 and 7. These results indicate very clearly that the addition of LF has significant effects on the flowability of mortar.

From the flow spread results, it can be seen that the flow spread first increased as the LF volume increased and then after reaching a maximum value at a LF volume of 4%, started to decrease as the LF volume further increased. Among the 4 mortar mixes tested, the mortar mixes with LF volumes of 4% and 8% have larger flow spread than the mortar mix with no LF added whereas the mortar mix with a LF volume of 12% has a smaller flow spread than the mortar mix

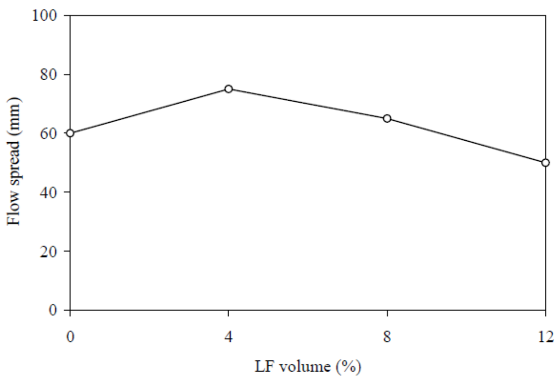

Fig. 6 Effect of LF on flow spread of mortar

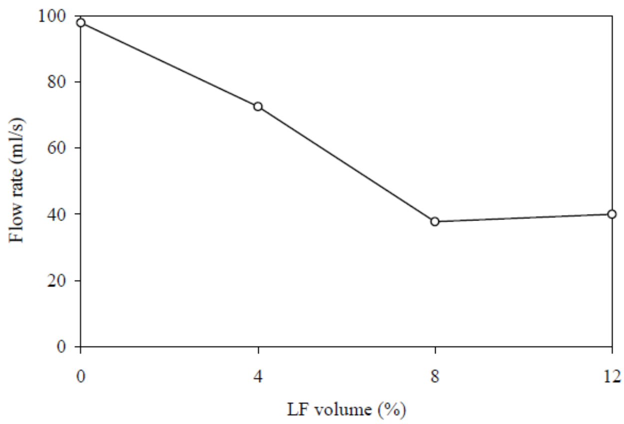

Fig. 7 Effect of LF on flow rate of mortar

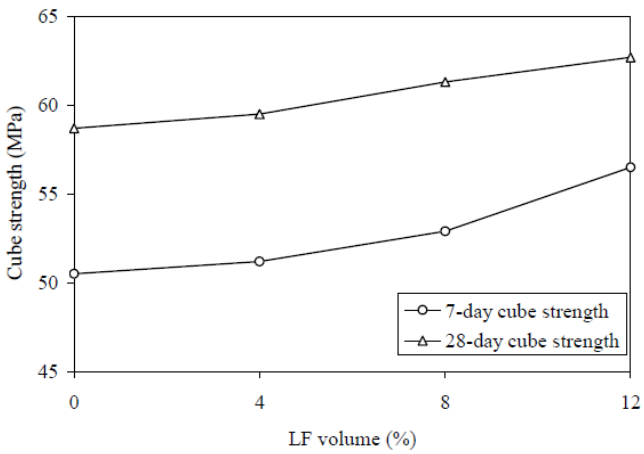

Fig. 8 Effect of LF on cube strength of mortar

with no LF added. Such variation of the flow spread with the LF volume may be attributed to the combined effects of the corresponding changes in WFT and PFT. Whilst the decrease in WFT due to addition of LF should have caused the flow spread to decrease, the concurrent increase in PFT due to addition of LF should have caused the flow spread to increase. It is quite likely that the effect of WFT is larger when the WFT is relatively small and smaller when the WFT is relatively large. Likewise, it is likely that the effect of PFT is larger when the PFT is relatively small and smaller when the PFT is relatively large. While the LF volume was smaller than 4%, the WFT was relatively large and the PFT was relatively small; in such situation, the PFT should have larger effect than the WFT and as a result, the flow spread increased as the LF volume increased. While the LF volume was larger than 4%, the WFT was relatively small and the PFT was relatively large; in such situation, the WFT should have larger effect than the PFT and as a result, the flow spread decreased as the LF volume further increased.

From the flow rate results, it can be seen that the flow rate decreased as the LF volume increased and then after reaching a certain value at a LF volume of 8%, remained more or less constant as the LF volume further increased. All the mortar mixes containing LF have smaller flow rate than the mortar mix containing no LF. In other words, the addition of LF would in general decrease the flow rate of mortar. Again, such variation of the flow rate with the LF volume may be attributed to the combined effects of the corresponding changes in WFT and PFT. Previous research (Kwan and Li 2012) has shown that for the flow rate of mortar, the WFT generally has larger effect than the PFT. So, it was the decrease in WFT as the LF volume increased that caused the flow rate to decrease with increase in LF volume.

4.5 Cube strength of mortar

The 7-day and 28-day cube strength results are tabulated in the last two columns of Table 9 and plotted against the LF volume in Fig. 8. Each cube strength result presented therein is the average of the three cubes cast from the same batch and tested at the same time. These results show that the cube strength increased slightly as the LF volume increased. With no LF added, the 7-day and 28-day cube strengths attained were 50.5 MPa and 58.7 MPa, respectively. With 12% LF added, the 7-day and 28-day cube strengths increased to 56.5 MPa (an increase of 11.9%) and 62.7 MPa (an increase of 6.8%), respectively. Hence, although the LF is chemically inert and would not react with the cement and water to produce gel, its addition to mortar can increase the early strength by up to 12% and the long term strength by up to 7%. This may be attributed to the decrease in the WFT, which reduces bleeding and thus improves the bond between aggregate particles and hardened cement paste, and the nucleation effect of the fine LF particles, which promotes precipitation of gel products and thus enhances the hydration of cement. The increase in PFT may also have certain positive effect because a larger PFT would allow easier compaction of the mortar mix during casting.

5. Conclusions

To study the effects of LF on the packing densities of the powder content and the whole particle system in mortar, the wet packing method has been applied to measure the packing densities of non-blended LF, and (LF + cement), (LF + fine aggregate) and (LF + cement + fine aggregate) blends. For comparison, the materials were also tested by the dry packing method with and without compaction applied. From the test results, it is evident that the wet packing density even with no compaction applied is generally much higher than the respective dry packing density with compaction applied and that the addition of superplasticizer could significantly increase the wet packing density. The test results of the (LF + cement) blends revealed that blending of cement with LF would not significantly increase the packing density because the LF has similar particle size as the cement whereas the test results of the (LF + fine aggregate) and (LF + cement + fine aggregate) blends revealed that blending of fine aggregate with LF or with both LF and cement could significantly increase the packing density because the LF and cement particles are much smaller than the aggregate particles and are thus able to fill into the voids between the aggregate particles. However, the effects of blending revealed by the wet packing test are not the same as those revealed by the dry packing test. Since the particles in mortar are actually under wet condition when freshly mixed, the wet packing test should be more appropriate for studying the effects of LF.

On the other hand, the mortar test results showed that for the particular mortar mixes tested with a constant cement paste volume of 50% and a constant W/C ratio of 0.5, the addition of LF would slightly decrease the packing density, significantly decrease the water film thickness (WFT) and significantly increase the paste film thickness (PFT). The slight decrease in packing density was because the addition of LF had caused the powder content to be more than enough to fill the voids between aggregate particles and the aggregate particles to be pushed apart. The decrease in WFT was caused by the slight decrease in packing density and the increase in solid surface area of all solid particles due to the addition of LF. The increase in PFT was caused by the increase in paste volume and the decrease in solid surface area of aggregate particles. The filling effect of LF is now clear. For a LF, which has similar fineness as cement, it has no filling effect when added to cement to form a (LF + cement) blend. It also has no filling effect when added to a mortar mix in which the powder content is already enough to fill the voids between aggregate particles. Its filling effect is contributed main by the LF filling into the paste to increase the paste volume and PFT.

Lastly, the flow spread and flow rate results revealed that the addition of LF could increase the flow spread but would decrease the flow rate of mortar. These were due to the corresponding changes in WFT and PFT. Hence, it is incorrect to simply say whether the addition of LF would improve or impair the flowability of mortar or concrete. Under static or near static condition such as ordinary placing of concrete, the flow spread is more important and thus the addition of LF may be advantageous. But under dynamic condition such as concrete pumping, the flow rate is more important and thus the addition of LF is not considered advisable. Regarding the cube strength results, the addition of LF without changing the W/C ratio could increase the 7-day and 28-day cube strengths by about 12% and 7%, respectively. It should be noted however that the LF added was not cementitious and thus should not have chemically reacted with the cement or water. The increases in strength may be attributed to the decrease in the WFT, which reduces bleeding and thus improves the bond between aggregate particles and hardened cement paste, and the nucleation effect of the fine LF particles, which promotes precipitation of gel products and thus enhances the hydration of cement. The increase in PFT may also have certain positive effect because a larger PFT would allow easier compaction of the mortar mix during casting.

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