CONSTRUCTION INDUSTRY COUNCIL
建造業議會

Research on River Sand Substitutes for Concrete Production and Cement Sand Mortar Production (Phase Two) Final Report

Version 1
March 2016

www.cic.hk

Executive Summary

Excessive dredging of river sand could cause adverse environmental impacts and instability of river banks. For this reason, there is a global trend to limit the dredging of river sand. Locally, due to limitation of river sand export from Mainland, there is an acute shortage of river sand, which has been commonly used as fine aggregate in concrete and mortar. In view of such situation, the Construction Industry Council has launched this research project to explore possible river sand substitutes for concrete and mortar production in two phases (Phase One and Phase Two). Phase One was completed in April 2013. This report is for Phase Two.

A thorough literature review of existing standards on aggregates for concrete and mortar had been carried out in the Phase One study. However, after completion of Phase One study, four new standards were published. These new standards have been reviewed in this Phase Two study. It is seen that the sieve sizes, demarcation between coarse and fine aggregates, and definition of fines vary from one standard to another. Since those in the British Standards and Chinese Standards are very similar and some quarries are supplying aggregates to both Hong Kong and Mainland markets, it is better to stay with the sieve sizes and demarcation between coarse and fine aggregates given in the British Standards. In fact, the Hong Kong Construction Standard CS3: 2013 on aggregates for concrete follows basically the British Standards.

The major issues in the various standards are the limits to be imposed on the fines content and the assessment of harmfulness of the fines content. Since there are still no established methods for assessing the harmfulness of fines, the usual practice is to impose limits on the fines content so as to reduce the risk of having harmful substances in the aggregate. In this regard, it should be noted that in general, river sand, which has been subjected to washing by flowing water, has lower fines content than crushed rock fine. Another major issue is that since the requirements are different, the standard CS3: 2013 on aggregates for concrete is not applicable to aggregates for mortar. A separate standard on aggregates for mortar is needed. Basically, since the high fines content in crushed rock fine has been causing problems in mortar works, lower fines content limits have to be imposed on aggregate for mortar.

From the Phase One study, it is evident that crushed rock fine has already substituted river sand as fine aggregate for concrete but crushed rock fine is not a suitable river sand substitute as aggregate for mortar because of its excessively high fines content. Even when used in concrete, the high fines content may cause problem.

It is better to process the crushed rock fine to reduce and control the fines content to suit different applications. The crushed rock fine may also be processed to improve particle shape and grading for enhanced performance. Such processed material, called manufactured sand, may be a better alternative to both river sand and crushed rock fine as aggregates for concrete and mortar.

In this Phase Two study, laboratory tests have been carried out to evaluate the effects of fines content on the performance of concrete and mortar. The laboratory tests on concrete revealed that (1) the fines content has significant adverse effect on the workability; (2) the fines content has little effect on the strength, except at very low W/C ratio due to difficulties in compaction; and (3) the fines content has certain beneficial effect on the cohesiveness and segregation resistance. Overall, it may be said that a fines content of up to 10% may be considered acceptable. A fines content of higher than 10% may still be considered acceptable if trial concrete mixing has demonstrated that the required workability can be achieved without using an excessively high dosage of superplasticizer. On the other hand, the laboratory tests on mortar revealed that (1) the trowelability of a mortar is best when the mortar is of the right wetness, which somehow is dependent more on the water content rather than the fines content; and (2) a fines content of up to 8% has no adverse effects on both trowelability and strength. Overall, there is no real necessity to impose a fines content limit of 3% in any fine aggregate for mortar. Nevertheless, it is still considered advisable to limit the fines content in aggregate for mortar at 5% in order to avoid large fluctuations in the fines content.

Laboratory tests have also been carried out to investigate the possible uses of crushed waste glass and recycled fine aggregate as river sand substitutes. The laboratory tests on crushed waste glass revealed that (1) it should be possible to use up to 50% crushed waste glass aggregate to make grade 45 precast paving blocks and up to 100% crushed waste glass aggregate to make grade 35 precast paving blocks; and (2) it should be possible to use up to 50% crushed waste glass aggregate in mortar for plastering. On the other hand, the laboratory tests on recycled fine aggregate revealed that (1) to use 100% recycled fine aggregate in concrete, there is a necessity to control the fines content at not higher than 5% when used to produce grade 30 concrete, and at not higher 10% when used to produce grade 20 concrete; and (2) it should be possible to use up to 50% recycled fine aggregate in mortar for plastering but the fines content needs to be controlled at not higher than 5%.

Field trials by experienced workers on the uses of manufactured sand and river sand as aggregate in mortar for plastering have been carried out. The field trials revealed that both the two manufactured sand samples tried are suitable as aggregate in mortar for plastering. Relatively, the manufactured sand sample with a smaller maximum size of aggregate of 2.36 mm was found to be easier to trowel and applicable to both vertical concrete walls and concrete slab ceilings. Overall, its trowelability was found to be very similar to that of river sand.

A preliminary draft of the Recommended Specifications for Aggregates for Mortar was produced at an early stage of this study. To be compatible with the Construction Standard CS3: 2013, the draft Recommended Specifications follows the general requirements and employs the same test methods given in CS3: 2013. It has been sent out to the stakeholders for consultation in 2013. After the consultation, it was slightly revised and then sent out for another round of consultation. No request for further revisions has been received and the revised Recommended Specifications is generally considered acceptable.

Lastly, three companies have been interviewed. One company has started the production of manufactured sand complying with the Recommended Specifications. The other two companies are interested in producing crushed waste glass and recycled fine aggregate as river sand substitutes but requested more government support.

CONTENTS

Page no.

1. Background 1

2. Objectives as Stated in the Brief 1

3. Overview of River Sand and River Sand Substitutes 2

4. Literature Review of Most Updated Standards 4

4.1 Hong Kong Construction Standard CS3: 2013 4

4.2 European Standard BS EN 12620: 2013 5

4.3 European Standard BS EN 13139: 2013 5

4.4 American Standard ASTM C33/C33M-13 7

4.5 Summary and Recommendations 7

5. Laboratory Tests on Effects of Fines Content in Fine Aggregate on Concrete and Mortar 9

5.1 Tests on Effects of Fines Content on Performance of Concrete 9

5.2 Tests on Effects of Fines Content on Performance of Mortar 12

6. Laboratory Tests on Possible Uses of Crushed Waste Glass and Recycled Fine Aggregate 17

6.1 Tests on Possible Use of Crushed Waste Glass 17

6.2 Tests on Possible Use of Recycled Fine Aggregate 20

7. Field Trials on Use of Manufactured Sand in Plastering 23

8. Interview with Stakeholders 25

8.1 Interview with Man Fai Tai 26

8.2 Interview with K. Wah 26

8.3 Interview with LVFAR 28

8.4 Summary 29

9. Discussions **29**

9.1 Manufactured Sand as River Sand Substitutes **29**

9.2 Possible Use of Crushed Waste Glass **31**

9.3 Possible Use of Recycled Fine Aggregate **32**

10. Recommended Specifications **34**

10.1 Drafting of the Recommended Specifications **34**

10.2 Consultation with Stakeholders **35**

11. Conclusions **36**

11.1 Conclusions from Literature Review **36**

11.2 Conclusions on Fine Aggregate for Concrete **37**

11.3 Conclusions on Fine Aggregate for Mortar **38**

11.4 Conclusions on Possible Use of Crushed Waste Glass **39**

11.5 Conclusions on Possible Use of Recycled Fine Aggregate **40**

11.6 Conclusions on Manufactured Sand as River Sand Substitute **41**

Appendix A	**Literature Review of Newest Standards Published in 2013 on Aggregates for Concrete and Mortar (Hong Kong CS3, BS EN 12620, BS EN 13139 and ASTM C33/33M)**	**42－56**
Appendix B	**Report on Laboratory Tests on Effects of Fines Content in Fine Aggregate and Possible Uses of Crushed Waste Glass and Recycled Fine Aggregate**	**57－98**
Appendix C	**Report on Field Trials on Use of Manufactured Sand in Plastering**	**99－105**
Appendix D	**Recommended Specifications for Aggregates for Mortar**	**106－114**
Appendix E	**Comments by Stakeholders on the Recommended Specifications for Aggregates for Mortar**	**115－125**

1. Background

River sand is a widely used construction material in many places, including Hong Kong. However, excessive dredging of river sand could cause adverse environmental impacts and instability of river banks. For this reason, there is a global trend to limit the dredging of river sand. Locally, due to limitation of river sand export from Mainland China, there is an acute shortage of river sand, which has been commonly used as fine aggregate in the production of concrete and cement-sand mortar.

In view of such situation, the Construction Industry Council of Hong Kong has launched a research project entitled "Research on River Sand Substitutes for Concrete Production and Cement Sand Mortar Production" to explore possible river sand substitutes as fine aggregate for local use. The ultimate aim of the research project was to identify suitable materials and products as river sand substitutes and establish a set of practical guidelines and specifications on the river sand substitutes for adoption in both public and non-public works projects in Hong Kong.

The research project was launched in two phases. The first phase (Phase One) of the research project aimed to identify natural and recycled materials, which may be processed to become suitable river sand substitutes for practical applications in the local construction industry. It was completed in April 2013. The second phase (Phase Two) of the research project was to conduct comprehensive laboratory tests by technicians and field trials by experienced workers in order to develop manufactured products as suitable river sand substitutes and to draft a Recommended Specifications for the river sand substitutes. This report is to present the research outcomes of Phase Two.

2. Objectives as Stated in the Brief

The objectives as stated in the Outline Brief of the "Research on River Sand Substitutes for Concrete Production and Cement Sand Mortar Production (Phase Two)" are:

(1) To draft a local construction standard on aggregates for mortar based on existing standards in Europe, UK and China;

(2) To study the effects of fines content on concrete to determine the optimum and allowable fines contents so as to draft general guidelines for fine aggregate for concrete;

(3) To study the effects of fines content on various types of mortar to determine the optimum and allowable fines contents so as to draft a set of specifications for aggregate for different types of mortar and a set of requirements for classification of manufactured sand;

(4) To study the feasibility of crushing and processing waste glass for recycling as aggregate for mortar; and

(5) To study the feasibility of crushing and processing old concrete for recycling as aggregate for concrete and mortar.

3. Overview of River Sand and River Sand Substitutes

River sand is used in the construction industry mainly for concrete production and cement-sand mortar production. In concrete production, it is used as the fine aggregate whereas in mortar production, it is used as the sole aggregate. Basically, river sand is obtained by dredging from river beds. It has the major characteristics that since it has been subjected to years of abrasion, its particle shape is more or less rounded and smooth, and since it has been subjected to years of washing, it has very low silt and clay contents.

Both these two characteristics of river sand would improve the workability of concrete and mortar compared to the use of alternatives such as crushed rock fine. For this reason, the use of river sand would, for a given workability requirement, reduce the water demand and/or superplasticizer demand, and thus allow a lower water content and a lower cement content to be adopted in the mix design. In addition, with lower silt and clay contents, the use of river sand would improve the quality control of the concrete/mortar production because the presence of too much silt and/or clay would adversely affect the workability and strength of the concrete/mortar produced.

However, there could be two major shortcomings with the use of river sand. First, since river sand is brought down by river water from upstream, it could be of widely different mineralogy and, as a result, it is generally difficult to ascertain whether its use would lead to any deleterious alkali-aggregate reaction. Second, river sand dredged from river estuaries close to the sea may be contaminated with salt thus causing the concrete/mortar produced to have high chloride content.

Nevertheless, the local construction industry in Hong Kong, like many other places, has been using river sand for many decades. In fact, the experience of most concrete/mortar producers in Hong Kong is based mainly on the use of river sand. With river sand changed to river sand substitutes, which may have very different characteristics, it takes time for the local construction industry to adapt. Hence, apart from identifying suitable river sand substitutes to supplement or even completely replace river sand, it is important also to evaluate the characteristics of the identified substitutes and the possible effects of using the identified substitutes on the performance of the concrete/mortar produced so that the potential users of the substitutes would better understand the major differences between river sand and river sand substitutes.

The opportunity may be taken to develop a river sand substitute that is not just a substitute but is actually a better material than river sand. For instance, by sieving and blending different sand-sized particles to control the particle size distribution, it should be possible to optimize the particle size distribution for best overall performance of the concrete/mortar produced. Moreover, by air classification or water washing, it should be possible to reduce and control the silt/clay content so as to reduce the water demand and/or superplasticizer demand of the concrete/mortar to be produced. In theory, it should also be possible to grind the aggregate particles so that they would become rounded and smooth for improving the packing density of the fine aggregate (a higher packing density would allow the use of a smaller cement paste volume for reducing the cement consumption and carbon footprint, and improving the dimensional stability) and for increasing the workability of the concrete and mortar produced. Such engineered fine aggregate, often called “manufactured sand” to distinguish it from ordinary unprocessed fine aggregate, would allow the production of much greener and higher performance concrete or mortar than with the use of ordinary river sand.

Quite obviously, the most suitable river sand substitute is crushed rock fine specifically processed to become a “manufactured sand” that complies with certain specification requirements. The specification requirements for the manufactured sand as a river sand substitute are dependent on the intended applications and there is a need to strike a balance between the cost of production and the expected performance of the manufactured sand. Since the river sand substitute is expected to be for general usage in the production of normal concrete (not including high-strength concrete or high-performance concrete), mortar for precast paving blocks and partition wall blocks, and mortar for plastering and rendering, the specification requirements to be established in this study would be the minimum requirements for general applications so as to keep the cost of production of the manufactured sand at a relatively low and affordable level. Prof. Albert K.H. Kwan has spoken to some quarry operators and was given to understand that the cost of production of manufactured sand in accordance with the Recommended Specifications draft as an outcome of this study would not be higher than the current price of river sand (at the time of writing this report, the price of river sand in Hong Kong is approximately HK$150 per ton).

If, somehow, the user wants to acquire better performance manufactured sand than those stipulated in the draft Recommended Specifications to produce high-strength concrete, high-performance concrete, long-distance pumping concrete, and self-levelling screeding etc, it is up to the user to negotiate with the aggregate supplier to produce manufactured sand with certain specific characteristics. In such case, the user and the aggregate supplier may have to conduct their own research to find out what specific characteristics of the manufactured sand are required. The development of manufactured sand for special applications is outside the scope of this study.

On the other hand, there are large quantities of inert solid waste materials, such as waste glass from used bottles and old concrete from construction and demolition wastes, being dumped to landfills, which would be filled up to their full capacities within a short time. Such waste materials, after careful selection and processing, may also be used as river sand substitutes for concrete and mortar production. The possible uses of recycled waste materials would help to reduce the amount of waste to be dumped to landfills and also reduce the consumption of river sand in Hong Kong. Hence, the possible uses of crushed waste glass and recycled fine aggregate as river sand substitutes have also been investigated in this study. However, as reported herein, there needs to be government policies to support the waste recycling industry.

4. Literature Review of Most Updated Standards

A detailed literature review of the various standards on aggregates for concrete or mortar has already been carried out in Phase One of this research project. However, subsequent to the completion of Phase One in April 2013, four new standards on aggregates for concrete or mortar have been published in 2013. These new standards are:

(1) Hong Kong Construction Standard CS3: 2013 Aggregates for concrete
(2) European Standard BS EN 12620: 2013 Aggregates for concrete
(3) European Standard BS EN 13139: 2013 Aggregates for mortar
(4) American Standard ASTM C33/C33M-13 Standard specification for concrete aggregates

These most updated standards, which are highly relevant to this research project, have been reviewed. For CS3: 2013, the focuses of the review were on the applicability of the various stipulations contained therein to aggregates for mortar and on how to maintain compatibility between the requirements for aggregates for concrete and the requirements for aggregates for mortar. For BS EN 12620: 2013 and ASTM C33/C33M-13, the focuses of the review were on the newest requirements on grading, fines content and fines quality in Europe and the US. For BS EN 13139: 2013, the focuses of the review were on the newest requirements on grading, fines content and fines quality, and the applicability of these requirements in Hong Kong.

A detailed literature review report is attached in Appendix A. For conciseness, only a brief summary is presented in the following.

4.1 Hong Kong Construction Standard CS3: 2013

This construction standard on aggregates for concrete is currently the only local standard on aggregates because there is, up to now, no local standard on aggregates for mortar. It is largely based on the British Standard BS 882: 1992, but is intended to replace this British Standard.

The standard sieve sizes and definitions of fine aggregate and fines are the same as those in the British Standard BS 882: 1992 but are totally different from those in the European Standards BS EN 12620: 2013 and BS EN 13139: 2013. There are, however, two major differences between CS3: 2013 and BS 882: 1992. Firstly, the BS 882: 1992 imposes limits on the fines content in fine aggregate as 9% for use in heavy duty floor finishes and 16% for general use. In contrast, the CS3: 2013 imposes limits on the fines content in fine aggregate as 10% for use in heavy duty floor finishes and 14% for general use. Secondly, the BS 882: 1992 does not require checking of the cleanliness of the fine aggregate. In contrast, the CS3: 2013 imposes the requirement that if the fines content > 10%, the methylene blue value shall be ≤ 1.4.

To be compatible with CS3: 2013, the same standard sieve sizes and the same definition of fines should be followed in any specifications or new standards for aggregates for mortar. Moreover, the same test methods should be adopted.

4.2 European Standard BS EN 12620: 2013

This is the newest European Standard on aggregates for concrete. It is an update of BS EN 12620: 2002, which has replaced the British Standard BS 882: 1992 in the UK.

Compared to the 2002 version of the standard, there are no changes in the standard sieve sizes, the demarcation between coarse aggregate and fine aggregate, and the definition of fines. However, compared to the British Standard and the local Construction Standard, the standard sieve sizes, the demarcation between coarse aggregate and fine aggregate, and the definition of fines are totally different.

As in the 2002 version, the aggregate producer is required to declare the typical grading of the fine aggregate produced but tolerance limits are applied to control the variability of the fine aggregate. However, the tolerance limits stipulated in BS EN 12620: 2013 are quite different from the respective tolerance limits stipulated in BS EN 12620: 2002.

As in the 2002 version, there are no limits imposed on the fines contents in the aggregate. The aggregate producer is allowed to declare the maximum fines content in accordance with specified categories. However, in the 2013 version, one more specified category, the category f_6 for a fines content of not more than 6%, has been added. Hence, the fines content categories in BS EN 12620: 2013 are more refined.

As in the 2002 version, no precise limits have been given for the fines content, sand equivalent value and methylene blue value for ensuring the cleanliness of the aggregate. These limits shall be established from experience of existing requirements of materials in local satisfactory use according to the provisions valid in the place of use of the aggregate.

4.3 European Standard BS EN 13139: 2013

This is the newest European Standard on aggregates for mortar. It is an update of BS EN 13139: 2002, which has replaced the British Standards BS 1199 and 1200: 1976 in the UK.

Compared to the 2002 version of the standard, there are no changes in the standard sieve sizes, the demarcation between coarse aggregate and fine aggregate, and the definition of fines. However, compared to the British Standard and the local Construction Standard, the standard sieve sizes, the demarcation between coarse aggregate and fine aggregate, and the definition of fines are totally different.

As in the 2002 version, the aggregate producer is required to declare the typical grading for each fine aggregate size produced but tolerance limits are applied to control the variability of the fine aggregate. However, the tolerance limits stipulated in BS EN 13139: 2013 are quite different from the respective tolerance limits stipulated in BS EN 13139: 2002.

As in the 2002 version, there are no limits imposed on the fines contents in the fine aggregate. The aggregate producer is allowed to declare the maximum fines content in accordance with specified categories. However, the specified categories in the 2013 version are not the same as the specified categories in the 2002 version, as summarized below.

In the 2002 version, the categories for maximum values of fines content are:
category 1 – fines content ≤ 3%;
category 2 – fines content ≤ 5%;
category 3 – fines content ≤ 8%; and
category 4 – fines content ≤ 30%.
Furthermore, examples of end uses for the different categories are given as:
category 1: floor screeds, sprayed, repair mortars, grouts (all aggregates)
category 2: rendering and plastering mortars (all aggregates)
category 3: masonry mortars (excluding crushed rock aggregate)
category 4: masonry mortars (crushed rock aggregate)

In the 2013 version, the categories for maximum values of fines content are:
category f_3 – fines content ≤ 3%;
category f_5 – fines content ≤ 5%;
category f_8 – fines content ≤ 8%; and
category f_{22} – fines content ≤ 22%.
No examples of end uses for the different categories are given anymore.

As in the 2002 version, no precise limits have been given for the fines content, sand equivalent value and methylene blue value for ensuring the cleanliness of the aggregate. These limits shall be established from experience of existing requirements of materials in local satisfactory use according to the provisions valid in the place of use of the aggregate. These requirements are exactly the same as those in BS EN 12620: 2013.

4.4 American Standard ASTM C33/C33M-13

This is the newest American Standard on aggregates for concrete published in 2013. In this standard, the standard sieve sizes are similar to those in the British Standard BS 882: 1992 and the Construction Standard CS3: 2013.

The demarcation between coarse aggregate and fine aggregate is a particle size of 4.75 mm. Moreover, the definition of fines is the particle size fraction finer than 75 µm. These are similar to those in the British Standard BS 882: 1992 and the Construction Standard CS3: 2013. Unlike BS 882: 1992 and CS3: 2013, however, only one type of grading is specified. If not stated, the fines content limit shall be 3.0%. For concrete not subjected to abrasion, the fines content limit shall be 5.0%.

For manufactured fine aggregate (i.e. crushed rock fine aggregate), if the fines content consists of dust of fracture, essentially free of clay or shale, the fines content limit shall be 5.0% for concrete subjected to abrasion and 7.0% for concrete not subjected to abrasion. These limits on the fines content are rather low and comparable to those in the Chinese Standards GB/T 14684: 2001 and JGJ 52: 2006.

For manufactured fine aggregate having elevated fines content, evaluation should be carried out to ensure that the fines content is essentially composed of dust of fracture derived from the parent rock and does not contain an appreciable level of clay mineral or other deleterious constituents. Methylene blue adsorption and hydrometer analyses are accepted as reliable tests for characterizing the fines content and determining the suitability of the fine aggregate for use in concrete. Manufactured fine aggregate with less than 4% by mass finer than 2 µm and with methylene blue adsorption value less than 5 mg/g is considered suitable for use in concrete. However, fine aggregate that exceeds these values also may be considered suitable for use provided that fresh and hardened concrete properties are shown to be acceptable.

4.5 Summary and Recommendations

From the above review, it is seen that the standard sieve sizes, demarcation between coarse and fine aggregates and definition of fines vary from one standard to another standard. As the standard sieve sizes, demarcation between coarse and fine aggregates and definition of fines in the British Standards that have been in use in Hong Kong for a long time are almost the same as those in the Chinese Standards and some of the quarries are supplying aggregate to both the Hong Kong market and the Mainland China market, it is better from the market operation point of view to stay with the standard sieve sizes, demarcation between coarse and fine aggregates and definition of fines in the British Standards. This will also avoid the trouble of changing from an established practice to a totally new practice, save the cost of buying new equipment and help to preserve our previous experience with aggregate for future use.

In general, different requirements are imposed on aggregates for concrete and aggregates for mortar. This is because concrete and mortar have different performance attributes and the quality of fine aggregate has different effects on concrete and mortar. Hence, aggregates for concrete and aggregates for mortar should be clearly differentiated.

For both aggregates for concrete and aggregates for mortar, the major issues seem to be the limits to be imposed on the fines content and the assessment of the harmfulness of the fines content. The fines content needs to be limited for the following reasons. In concrete, any harmful substances, such as clay, in the fines would adversely affect the abrasive resistance, maximum achievable strength, and durability of the concrete. Moreover, since the fines content has very large specific surface area, its quantity would affect the water and superplasticizer demands and thus also the workability of the concrete. The presence of high fines content in the concrete would render the concrete more cohesive, but this has little effect on the concreting operation. In mortar, the presence of clay or excessive fines would adversely affect the abrasive resistance, maximum achievable strength and workability of the mortar. Moreover, the increase in water demand due to higher fines content would force the worker to add more water to improve the workability of the mortar and thus cause the hardened mortar to have a relatively large drying shrinkage and a higher risk of shrinkage cracking. More importantly, the increase in cohesiveness and paste volume due to the presence of excessive fines would render the mortar too sticky and slippery to be properly trowelled because the mortar tends to stick to the trowel and slip downwards.

On the other hand, there are still no established methods for assessing the harmfulness of fines in aggregate and no established acceptance criteria for the non-harmfulness of fines. The BSI PD 6682-3 recommends that aggregates should better be assessed for harmful fines using either a fines content limit or evidence of satisfactory use. This seems to be a pragmatic way of avoiding the controversies regarding the methods of assessment and acceptance criteria. Hence, another reason for limiting the fines content is to reduce the risk of having harmful substance in the aggregate.

Lastly, whilst the fine aggregates stipulated in BS 1199: 1976, BS 1200: 1976, BS 882: 1992 and CS3: 2013 all have a maximum aggregate size of 5.0 mm, the fine aggregates in BS EN 13139: 2002 and BS EN 13139: 2013 may have a maximum aggregate size of 4.0 mm or 2.0 mm. Although we are not strictly following the European Standards, it seems prudent to follow the practice of having fine aggregates with different maximum aggregate sizes (of say, 5.0 mm and 2.36 mm) for different applications.

Based on the above, it is recommended that a separate local construction standard on aggregate for mortar should be produced. However, it should be compatible with CS3: 2013 so that the same terms would have the same meanings in the two standards, the same test methods may be used for both aggregates for concrete and aggregates for mortar, and some of the aggregate products may be used for both concrete and mortar. Moreover, unlike the previous standards on aggregates for concrete or mortar, which stipulate the maximum aggregate size of fine aggregate as 5.0 mm, the fine aggregate for mortar should be allowed to have a maximum aggregate size of 5.0 mm or 2.36 mm to suit different applications. Finally, although there are big differences in the maximum allowable limits on the fines content in the various standards, and the new European Standard BS EN 13139: 2013 does not impose any precise limits on the fines contents and no longer gives any examples of usage of the various categories of fine aggregates with different fines content limits, it is still considered prudent to impose fines content limits based on the fines content limits previously given in BS 1199: 1976, BS 1200: 1976, BS EN 13139: 2002, and BSI PD 6682-3: 2003 (a summary of these fines content limits has been given in Table 11 of the Literature Review Report attached in Appendix A).

5. Laboratory Tests on Effects of Fines Content in Fine Aggregate on Concrete and Mortar

Laboratory tests are required to fulfil Objectives (2) and (3), which for easy reference, are listed below:
Objective (2) is to study the effects of fines content on concrete to determine the optimum and allowable fines contents so as to draft a general guideline for fine aggregate for concrete.
Objective (3) is to study the effects of fines content on various types of mortar to determine the optimum and allowable fines contents so as to draft a set of specifications for aggregate for different types of mortar and a set of requirements for classification of manufactured sand.

For the above objectives, a comprehensive laboratory testing program was launched. The details of the testing program and the test results are presented in Appendix B. For conciseness, only a brief summary is presented in the following.

5.1 Tests on Effects of Fines Content on Performance of Concrete

From the literature review, it has been found that the maximum limits imposed on the fines content in aggregate for concrete vary from one standard to another. Whilst no limits are imposed in the European Standards, the limits imposed in the Chinese Standards and American Standards are rather stringent. Up to now, there is no general consensus regarding the effects of the fines content on the performance of the concrete produced and therefore the allowable fines content in fine aggregate for concrete has remained a controversial issue.

To study the effects of the fines content in fine aggregate on the overall performance of the concrete produced, a testing program has been worked out. In the testing program, there are four combinations of water/cement (W/C) ratio ranging from 0.30 to 0.60, three combinations of paste volume (PV) ranging from 25% to 35%, four combinations of fines content ranging from 6% to 15% (the specific fines content values are 6%, 9%, 12% and 15%), and two combinations of superplasticizer (SP) dosage ranging from no SP added to SP added (however, the SP dosage when added varied from 1.0 litre/m^3 of concrete at a W/C ratio of 0.60 to 4.0 litre/m^3 of concrete at a W/C ratio of 0.30). During the course of the testing program, some of the concrete mixes were found to be too dry to be mixed and therefore not tested. For this reason, the actual number of concrete mixes produced for testing was 80.

The fine aggregate (FA) and coarse aggregate (CA) used in the tests were crushed granite rock aggregates obtained from the local market. These aggregates are the same as those being used by some concrete producers in Hong Kong. Samples of the fine aggregate have been sent to Anderson Concrete Ltd and Gammon Construction Ltd for methylene blue tests. The MB value obtained by Anderson Concrete Ltd was 0.8 while the MB value obtained by Gammon Construction Ltd was 1.0. Hence, the fines content in the fine aggregate may be regarded as of good quality containing little deleterious materials.

To produce fine aggregates with the prescribed fines contents of 6%, 9%, 12% or 15%, the fines content in the fine aggregate was first removed by mechanical sieving so that the fine aggregate contained a fines content of exactly 0%. Then, the right amount of fines was put back into the fine aggregate so that the fine aggregate contained the prescribed fines content.

Regarding the cement used, it was an ordinary Portland cement (OPC) of strength class 52.5 N complying with BS EN 197-1: 2000. The relative density of the cement has been measured in accordance with BS EN 196-6: 2010 as 3.11. Regarding the superplasticizer (SP) used, it was a polycarboxylate-based SP commonly used in Hong Kong. It has a solid content of 20% and a relative density of 1.03.

A pan mixer was used to mix the ingredients in the trial concrete mix. Electronic balances were used to weigh the correct quantities of ingredients to be added to the mixer. During mixing, all the solid ingredients were added at the same time to the mixer. After about one minute of dry mixing, water was added to the mixer and the concrete mix was further mixed for two minutes. If SP was to be added, it was added last and after adding, the concrete mix was further mixed for another two minutes.

Upon completion of mixing, a fresh sample was taken from the mixer for the slump-flow test. The slump-flow test was carried out using the standard slump cone in accordance with BS EN 12350-8: 2010 (in this European Standard, the slump measurement is the same as that in CS1: 2010, but the flow spread measurement is very different from that in CS1: 2010). After placing the fresh concrete into the slump cone and lifting the slump cone vertically upwards, the drop in height of the concrete was taken as the slump (a measure of deformability) and the average value of two perpendicular diameters of the concrete patty formed was taken as the flow spread (a measure of flowability). It should be noted that since the base diameter of the slump cone is 200 mm, a flow spread of 200 mm actually means no flowability.

After the slump-flow test, the edge of the concrete patty was observed for any sign of segregation. If there was a strip of cement paste/mortar with no coarse aggregate at the edge, the average width of the strip of cement paste/mortar was measured and recorded as the segregation width. A segregation width of not more than 10 mm should be considered acceptable but a segregation width of larger than 10 mm indicates unacceptable segregation.

Meanwhile, another fresh sample was taken from the mixer for sieve segregation test. The sieve segregation test was carried out using a 5 mm test sieve in accordance with BS EN 12350-11: 2010 (this test has become a standard test for self-consolidating concrete). The weight of concrete mix dripped through the sieve and collected by a base receiver was measured and expressed as a percentage of the weight of concrete mix poured onto the sieve. The result so obtained is recorded as the sieve segregation index of the concrete mix. A sieve segregation index of not higher than 10% should be considered acceptable but a sieve segregation index of higher than 10% indicates unacceptable segregation.

Finally, after completion of the slump-flow and sieve segregation tests, all the concrete samples were put back into the mixer and remixed. Then, six 100 mm concrete cubes were cast from the remixed fresh concrete. After casting, the concrete cubes, together with their moulds, were covered and stored in the laboratory. At 24 hours after casting, the cubes were demoulded and put into a lime-saturated water curing tank controlled at a temperature of 27 ± 2 ℃. Three of the cubes were tested at the age of 7 days and the remaining three of the cubes were tested at the age of 28 days. The average value of the measured strengths of the three cubes tested at the age of 7 days was taken as the 7-day cube strength while the average value of the measured strengths of the three cubes tested at the age of 28 days was taken as the 28-day cube strength.

The test results of the concrete mixes, without or with superplasticizer added, reveal the following effects of the fines content on the performance of concrete:

(1) The fines content has significant adverse effect on the workability of concrete, except at very low slump or flow spread, in which case, the effect of fines content on workability is not revealed.

(2) The fines content has little effect on the strength, except at W/C = 0.3, in which case, a fines content of 12% or higher has significant adverse effect on the strength due to difficulties in compaction caused by the high fines content.

(3) Although the segregation width and sieve segregation index results indicate no segregation and high cohesiveness for all the concrete

mixes tested, hands on experience with the concrete mixes reveals that generally, a concrete mix with a higher fines content is more sticky, or in other words has a higher cohesiveness or a higher segregation resistance. Hence, the fines content has certain beneficial effect on the cohesiveness and segregation resistance of concrete.

Overall, a higher fines content in the fine aggregate would lead to a lower workability of the concrete produced but if the fines content does not exceed 10%, the decrease in workability can be more than compensated by adding more superplasticizer. Hence, it may be said that provided the fines content in the fine aggregate is of good quality and contains little deleterious materials, a fines content of up to 10% may be considered acceptable.

A fines content of higher than 10% may still be considered acceptable if trial concrete mixing has demonstrated that the required workability can still be achieved without using an excessively high dosage of superplasticizer. Even then, it is still considered advisable to set a certain maximum limit to the fines content. In CS3: 2013, the fine content is limit to 14% for general use (with the additional requirement that if the fines content > 10%, the methylene blue value shall be ≤ 1.4) and to 10% for use in heavy duty floor finishes. These are very reasonable maximum limits to be imposed. Another reason of setting a maximum limit to the fines content is that in practice, the fines content could fluctuate quite substantially within the specified limit and if the fluctuation in fines content is too large, the workability of the concrete produced would vary from time to time and the concrete producer might find it difficult to adjust the superplasticizer dosage to compensate for the variation in workability. In this regard, the concrete producer is advised to check regularly the actual fines content in the fine aggregate (perhaps for each consignment).

Moreover, it has been found from this study that at a low W/C ratio of 0.3, a fines content of 12% or higher has significant adverse effect on the strength due to difficulties in compaction caused by the high fines content. Since the W/C ratio of high-strength concrete tends to be low, it is recommended that for the production of high-strength concrete, the fines content should be limited to not higher than 10%. In other words, the fines content should be limited to 10% not only for use in heavy duty floor finishes, but also for use in high-strength concrete.

5.2 Tests on Effects of Fines Content on Performance of Mortar

Unprocessed crushed rock fine is not really suitable as aggregate for mortar works. There are two major issues in the use of crushed rock fine as aggregate for mortar works. Firstly, the fines content would greatly affect the water demand of the mortar. Secondly, the use of a smaller size aggregate would improve the trowelabilty of the mortar. However, there has been little research on the effects of the fines content and maximum size of the fine aggregate on the performance of mortar.

From the literature review, it has been found that the maximum limits imposed on the fines content in aggregate for mortar vary from one standard to another. In the British Standards BS 1199: 1976 and BS 1200: 1976, the fines content in crushed rock sand for mortar is limited to 5% for rendering and plastering and to 10% for type S sand for masonry mortar and 12% for type G sand for masonry mortar. In the European Standard BS EN 13139: 2002, it is stipulated that fine aggregates for mortar are to be classified into four categories: category 1 (fines content ≤ 3%), category 2 (fines content ≤ 5%), category 3 (fines content ≤ 8%), and category 4 (fines content ≤ 30%), which are for the following recommended uses: category 1: floor screeds, sprayed, repair mortars, grout; category 2: rendering and plastering; category 3: masonry mortar not using crushed rock aggregate; and category 4; masonry mortar using crushed rock aggregate. In the Chinese Standards GB/T 14684 and JGJ 52, there is no distinction between aggregate for concrete and aggregate for mortar and very stringent limits are imposed on the fines content in fine aggregate, depending on the source of aggregate. Up to now, there is no general consensus regarding the effects of the fines content on the performance of the mortar produced and therefore the allowable fines content in fine aggregate for mortar has remained a controversial issue.

To study the effects of fines content and maximum size of aggregate on the overall performance of mortar, a testing program has been worked out. In the testing program, there are four combinations of water/cement (W/C) ratio ranging from 0.30 to 0.60, two combinations of paste volume (PV) ranging from 42% to 48%, two combinations of maximum size of aggregate (MSA) ranging from 2.36 mm to 5.0 mm, and four combinations of fines content ranging from 2% to 10% (the specific fines content values are 2%, 5%, 8% and 10%). No superplasticizer was added to any of the mortar mixes. During the course of the testing program, some of the mortar mixes were found to be too dry to be mixed and therefore not produced for testing. Moreover, it was found that a PV of 42% was a bit too small for trowelling and a MSA of 5.0 mm tended to produce fairly rough trowelled surfaces. Hence, the mortar mixes originally designed to have a PV of 42% and a MSA of 5.0 mm were not tested. For these reasons, the actual number of mortar mixes produced for testing was 36.

The fine aggregate (FA) used in the tests was crushed granite rock fine aggregate obtained from the local market. This fine aggregate is the same as those being used by some concrete producers in Hong Kong. The fine aggregate originally has a MSA of 5.0 mm. To produce fine aggregate with a MSA of 2.36 mm, the fine aggregate was mechanically sieved to remove the particles coarser than 2.36 mm. The relative density of the fine aggregate was measured as 2.54. The water absorption of the fine aggregate was measured as 1.81%. From time to time, the moisture content of the fine aggregate was measured and the water absorption of the fine aggregate was allowed for in determining the amount of water to be added to the trial mortar mixes.

Samples of the fine aggregate have been sent to Anderson Concrete Ltd and Gammon Construction Ltd for methylene blue tests. The MB value obtained by

Anderson Concrete Ltd was 0.8 while the MB value obtained by Gammon Construction Ltd was 1.0. Hence, the fines content in the fine aggregate may be regarded as of good quality containing little deleterious materials.

To produce fine aggregates with the prescribed fines contents of 2%, 5%, 8% or 10%, the fines content in the fine aggregate was first removed by mechanical sieving so that the fine aggregate contained a fines content of exactly 0%. Then, the right amount of fines was put back into the fine aggregate so that the fine aggregate contained the prescribed fines content. Such fine aggregates with the fines content controlled at certain maximum levels may be regarded as manufactured sand (processed crushed rock fine).

Regarding the cement used, it was an ordinary Portland cement (OPC) of strength class 52.5 N complying with BS EN 197-1: 2000. The relative density of the cement has been measured in accordance with BS EN 196-6: 2010 as 3.11.

A Hobart mixer was used to mix the ingredients in the trial mortar mix. Electronic balances were used to weigh the correct quantities of ingredients to be added to the mixer. During mixing, all the solid ingredients were added at the same time to the mixer. After about one minute of dry mixing, water was added to the mixer and the mortar mix was further mixed for two minutes.

Upon completion of mixing, a fresh sample was taken from the mixer for the mini slump-flow test. The mini slump-flow test for mortar was similar to the slump-flow test for concrete, except that a mini slump cone was used instead. The mini slump cone used was the same as the one developed by Okamura and Ouchi (H. Okamura and M. Ouchi, Self-compacting concrete, Journal of Advanced Concrete Technology, Vol.1, No.1, 2003, 5-15). It has a base diameter of 100 mm, a top diameter of 70 mm and a height of 60 mm. The test procedures were similar to those of the slump-flow test. The drop in height of mortar was taken as the slump (a measure of deformability) whereas the average value of two perpendicular diameters of the mortar patty formed minus the base diameter of the mini slump cone was taken as the flow spread (a measure of flowability). It should be noted that a flow spread of zero means no flowability and a flow spread of 100 mm is a very good flowability.

Meanwhile, another fresh sample was taken from the mixer for the stone rod adhesion test, which was developed by Li and Kwan (L.G. Li and A.K.H. Kwan, Mortar design based on water film thickness, Construction and Building Materials, Vol.25, No.5, 2011, 2381-2390). The test setup consisted of a handle with six granite stone rods vertically fixed underneath and a container. Each stone rod has a diameter of 10 mm and an exposed length of 110 mm. To perform the test, the six stone rods were immersed into the mortar until the immersion depth was 100 mm and then slowly extracted. The weight of mortar adhering to the stone rods was taken as a measure of the adhesion of the mortar.

After completion of the mini slump-flow and stone rod adhesion tests, all the mortar samples were put back into the mixer and remixed. Then, three 70.7 mm mortar cubes were cast from the remixed fresh mortar. After casting, the mortar cubes, together with their moulds, were covered and stored in the laboratory. At 24 hours after casting, the cubes were demoulded and put into a lime-saturated water curing tank controlled at a temperature of 27 ± 2 ℃. The cubes were tested at the age of 7 days and the average value of the measured strengths of the three cubes was taken as the 7-day cube strength.

For testing of the trowelability and pull-out strength of the mortar plastered onto a vertical concrete surface, another sample of the fresh mortar was taken from the mixer and plastered onto the moulded surface of a 300 mm width × 300 mm width × 70 mm thick precast concrete panel in vertical position. The plaster was applied in two layers, each 10 mm thick, with the first layer applied in the first day and the second layer applied in the second day. Each time a layer of plaster was applied, the surface to be plastered was pre-wetted by spraying water onto the surface at about 15 minutes before plastering. No primer was used in the plastering. After plastering, the plastered specimen was kept in the laboratory with no specific curing applied, as in real practice. At the age of 7 days after application of the second layer of plaster, the pull-out strength of the mortar layer was measured in accordance with BS EN 1015-12: 2000 as the 7-day pull-out strength. In general, a pull-out strength of at least 0.5 MPa is regarded as acceptable whereas a pull-out strength of lower than 0.5 MPa is regarded as unacceptable.

During plastering onto the vertical concrete surface, the trowelability of the mortar was judged visually and manually into one of the following ratings:

Too dry – the mortar appears to be very dry and un-cohesive; it does not adhere to the concrete surface at all

Dry – the mortar appears to be dry and un-cohesive; it adheres to the concrete surface if pressed very hard against the concrete surface

Slight dry – the mortar appears to be slightly dry; it adheres well to the concrete surface if pressed hard against the concrete surface

Optimum – the mortar appears to have good consistence and cohesiveness; it adheres well to the concrete surface without the need of pressing hard against the concrete surface and would not drip downwards after plastering

Slight wet – the mortar appears to be slightly wet; it adheres well to the concrete surface but tends to drip downwards after plastering

Wet – the mortar appears to be wet and un-cohesive; it adheres to the concrete surface but drips downwards with time after plastering

Too wet – the mortar appears to be very wet and un-cohesive; it does not adhere to the concrete surface at all due to continuous dripping

Summarizing, the test results of the mortar mixes with a maximum aggregate size of 2.36 mm reveal the following effects of the fines content on the performance of mortar:

(1) At PV = 42%, the mortar is too dry for trowelling when W/C ≤ 0.50 and the suitable W/C ratio for trowelling is about 0.60. Generally, a PV of 42% appears to be a bit too small for trowelling.
(2) At PV = 42%, a fines content of up to 8% has no adverse effects on trowelability and strength.
(3) At PV = 48%, the mortar is too dry for trowelling when W/C ≤ 0.40 and the suitable W/C ratio for trowelling is about 0.50. Generally, a PV of 48% is better than 42% for trowelling.
(4) At PV = 48%, a fines content of up to 8% has no adverse effects on trowelability and strength.

Summarizing, the test results of the mortar mixes with a maximum aggregate size of 5.0 mm reveal the following effects of the fines content on the performance of mortar:
(1) At PV = 48%, the mortar is too dry for trowelling when W/C ≤ 0.30 and too wet for trowelling when W/C ≥ 0.50, and the suitable W/C ratio for trowelling is about 0.40. Generally, at MSA = 5.0 mm, a PV of 48% is suitable for trowelling. However, even at such PV, the trowelled surfaces tend to be quite rough.
(2) At PV=48%, a fines content of up to 8% has no adverse effects on trowelability and strength.

Overall, it may be concluded that the trowelability of a mortar is best when the mortar is neither too dry nor too wet. However, this seems to be dependent more on the W/C ratio or the water content of the mortar mix, rather than the fines content in the fine aggregate. The suitable W/C ratios for trowelling are as follows:
(1) At MSA = 2.36 mm and PV = 42%, suitable W/C = 0.60;
(2) At MSA = 2.36 mm and PV = 48%, suitable W/C = 0.50; and
(3) At MSA = 5.0 mm and PV = 48%, suitable W/C = 0.40.
The suitable W/C for trowelling varies with the MSA and PV, and for each given mortar mix, the acceptable range of W/C or water content for trowelling is very narrow and thus the W/C ratio or the water content has to be controlled carefully. Nevertheless, within the ranges of MSA and PV covered in this study, a fines content of up to 8% has no adverse effects on trowelability and strength. Lastly, at a suitable W/C for trowelling and with the fines content limited to not more than 8%, a pull-out strength of at least 0.7 MPa can be achieved, which should be sufficiently high because the required pull-out strength is only 0.5 MPa.

From the above test results, it appears that there is no real necessity to impose a fines content limit of 3% in any fine aggregate for mortar. In other words, the class F3 fine aggregate (fines content ≤ 3%) is not really necessary, and it may be simpler to remove the class F3 fine aggregate and just allow the use of class F5 fine aggregate (fines content ≤ 5%) in all kinds of plastering and screeding works.

Moreover, from the above test results, it appears that a paste volume of 48% is better for plastering. A slightly smaller paste volume of 45% may also be acceptable. Converting to cement to sand ratio, which is more commonly used for batching on site, a paste volume of PV = 48% is equivalent to a cement to sand ratio of 1:2.36, and a paste volume of PV = 45% is equivalent to a cement to sand ratio of 1:2.66. Hence, the cement to sand ratio of mortar for plastering should be set at around 1:2.5.

In conventional practice, the water content of the mortar mix is not explicitly specified and the workers are left to themselves to judge the appropriate amount of water to be added to give the optimum trowelability. This requires the workers to have proper training and good experience. From the present study, a general guideline has been produced as a slump of 10 ± 3 mm, as measured by the mini slump-flow test. So, to overcome the common workmanship problem of often putting in too little or too much water, the workers should be encouraged and trained to perform the mini slump-flow test. Alternatively, pre-packed dry plastering mortar can be used. The use of pre-packed materials can ensure that the fine aggregate is of the right quality and the cement to sand ratio has been accurately controlled. Moreover, the mortar supplier should know by tests and experience the appropriate amount of water to be added and thus should be able to explicitly specify the amount of water to be added to the dry mortar so that the workers need only add the specified amount of water without having to determine the appropriate amount of water to be added by trial and error on site.

6. Laboratory Tests on Possible Uses of Crushed Waste Glass and Recycled Fine Aggregate

Laboratory tests are required to fulfil Objectives (4) and (5), which for easy reference, are listed below:
Objective (4) is to study the feasibility of crushing and processing waste glass for recycling as aggregate for mortar.
Objective (5) is to study the feasibility of crushing and processing old concrete for recycling as aggregate for concrete and mortar.

For the above objectives, a comprehensive laboratory testing program was launched. The details of the testing program and the test results are presented in Appendix B. For conciseness, only a brief summary is presented in the following.

6.1 Tests on Possible Use of Crushed Waste Glass

Currently, only about 4% to 5% of waste glass is being recycled as aggregate in precast concrete paving blocks. The Hong Kong SAR Government is very keen in increasing the recycling rate so as to avoid dumping waste glass to landfills. Crushing the waste glass to sand size for use as river sand substitute could be one good way of using up the waste glass.

There are two possible ways of increasing the consumption of crushed waste glass. First, the proportion of crushed waste glass aggregate in precast concrete paving blocks may be increased. At present, the crushed waste glass aggregate in eco-glass paving blocks constitutes only 20 to 25% by weight of the total aggregate. It is felt that the crushed waste glass aggregate content in eco-glass blocks may be increased to 70% or even 100% of the total aggregate. Second, crushed waste glass may also be used as aggregate in mortar for plastering, rendering, screeding and masonry. Since the consumption of river sand as aggregate for mortar is more than 1,000,000 tons per year and there is a shortage of river sand in Hong Kong, the use of crushed waste glass as aggregate in mortar would resolve not only the waste glass recycling problem but also the river sand shortage problem.

Two materials suppliers have helped to produce some crushed waste glass for testing. From the samples obtained, it does appear that the fines content in the crushed waste glass is quite low and the glass particles are fairly un-cohesive (probably because glass is hydrophobic). Moreover, the glass particles are angular in shape, having many sharp edges and corners. This is probably due to the high brittleness of glass which causes the formation of cleavage planes during crushing. In theory, a rounded particle shape should be better than an angular particle shape. However, according to the suppliers, although it is possible to grind the waste glass to make the glass particles rounded in shape, the production cost is very high and thus such grinding is not really practical. Nevertheless, it appears at first sight that it may be necessary to crush the waste glass to a higher fineness than the usual fine aggregate (so that the grading is F instead of C) so as to improve the cohesiveness and adhesiveness of the mortar made from the crushed waste glass.

It was originally proposed to study the above possible uses of crushed waste glass as river sand substitute by producing mortar mixes with 70% crushed waste glass + 30% crushed rock fine or 100% crushed waste glass used as fine aggregate for the making of precast paving blocks and mortars for plastering, rendering, screeding and masonry. Later, when the testing program was half completed, it was found that the use of a high percentage of crushed waste glass as aggregate in plastering and rendering works would lead to lack of adhesion and difficulties in trowelling. It was therefore suggested and agreed at a meeting between Prof. Albert K.H. Kwan and Construction Industry Council held on April 15, 2014 that instead of continuing to study the possible use of 70% crushed waste glass as aggregate in plastering and rendering works, it should be more worthwhile to study the possible use of 50% crushed waste glass as aggregate in plastering and rendering works. Hence, in the further tests, the 70% crushed waste glass was changed to 50% crushed waste glass.

The fine aggregate (FA) used in the tests was crushed granite rock fine aggregate obtained from the local market. This FA is actually the same as that used in the previous tests on concrete and mortar. Its maximum size of aggregate (MSA) was 5.0 mm. Its fines content was measured by mechanical sieving as 5.0%. The fines content was not removed from the FA but rather was retained in the FA to mimic manufactured sand with similar fines content. Samples of the fine aggregate have been sent to Anderson Concrete Ltd and Gammon Construction Ltd for methylene blue tests. The MB value obtained by Anderson Concrete Ltd was 0.8 while the MB value obtained by Gammon Construction Ltd was 1.0. Hence, the fines content in the fine aggregate may be regarded as of good quality containing little deleterious materials.

The crushed waste glass (CWG) was obtained from a material supplier in Mainland China. It was crushed from white colour glass bottles bought from the market. The glass bottles were first cleaned and then crushed to become a sand sized material. To control its particle size distribution, the CWG was first sieved into different size fractions and then the different size fractions were blended together according to certain mix proportions to produce CWG with a grading of C and CWG with a grading of F. The relative density and water absorption of the CWG were measured as 2.33 and 0%, respectively.

Regarding the cement used, it was an ordinary Portland cement (OPC) of strength class 52.5 N complying with BS EN 197-1: 2000. The relative density of the cement has been measured in accordance with BS EN 196-6: 2010 as 3.11.

Summarizing, the test results of the mortar mixes containing 100% crushed waste glass as aggregate reveal that:

(1) Regardless of the CWG grading and the PV, the mortar is often either too dry or too wet for trowelling and the suitable range of W/C ratio for trowelling is rather narrow.

(2) For CWG grading = C, the suitable W/C ratios for trowelling are 0.45 at PV = 45%, 0.40 at PV = 50% and 0.35 at PV = 55%.

(3) For CWG grading = F, the suitable W/C ratios for trowelling are 0.55 at PV = 45%, 0.45 at PV = 50% and 0.40 at PV = 55%.

(4) For trowelling, the CWG grading of F and the CWG grading of C perform similarly. Hence, there is no need to crush the waste glass to a higher fineness than usual.

(5) At W/C = 0.30, a 7-day cube strength of at least 55.0 MPa can be achieved. Hence, crushed waste glass aggregate may be used up to 100% for precast blocks up to a mean cube strength of 55 MPa (good enough for production of grade 35 precast paving blocks).

Summarizing, the test results of the mortar mixes containing 50% crushed waste glass as aggregate reveal that:

(1) Regardless of the CWG grading and the PV, the mortar is often either too dry or too wet for trowelling and the suitable range of W/C ratio for trowelling is rather narrow.

(2) For CWG grading = C, the suitable W/C ratios for trowelling are 0.50 at PV = 45%, 0.45 at PV = 50% and 0.40 at PV = 55%.

(3) For CWG grading = F, the suitable W/C ratios for trowelling are 0.60 at PV = 45%, 0.55 at PV = 50% and 0.50 at PV = 55%.

(4) For trowelling, the CWG grading of F and the CWG grading of C perform similarly. Hence, there is no need to crush the waste glass to a higher fineness than usual.

(5) At W/C = 0.30, a 7-day cube strength of at least 65.0 MPa can be achieved. Hence, crushed waste glass aggregate may be used up to 50% for precast blocks up to a mean cube strength of 65 MPa (good enough for production of grade 45 precast paving blocks).

Overall, the test results obtained so far are generally positive. Firstly, it should be possible to use up to 50% crushed waste glass aggregate to make grade 45 precast paving blocks and up to 100% crushed waste glass aggregate to make grade 35 precast paving blocks. Secondly, it should be possible to use up to 50% crushed waste glass aggregate in mortar for plastering. The use of 100% crushed waste glass aggregate in mortar for plastering is not recommended because the mortar produced tends to be less cohesive than usual and thus more difficult to apply. Thirdly, since CWG grading of F and CWG grading of C perform similarly, there is no particular advantage and no real necessity of crushing the waste glass to higher fineness than usual.

Regarding the PV of mortar for plastering, a PV of 45% to 50% should be appropriate. The suitable W/C ratio is dependent on the PV and the CWG grading and content. With suitable W/C ratio adopted to ensure optimum trowelability, a pull-out strength of at least 0.6 MPa can be achieved.

However, there remains the problem of how the workers can determine the right amount of water to be added to the mortar mix to give the optimum trowelability. This requires the workers to have proper training and good experience. From the results obtained herein, a general guideline may be worked out as a slump of 10 ± 5 mm, as measured by the mini slump-flow test. Apart from judging by experience, the workers should be encouraged and trained to perform the mini slump-flow test of the mortar to determine the appropriate amount of water to be added to the mortar mix. Alternatively, the CWG aggregate may be pre-blended with manufactured sand and cement, and then supplied in the form of pre-packed dry plastering mortar. In general, the quality control of using pre-packed dry mortar materials is better than batching the various ingredients on site. Moreover, the mortar supplier should know by tests and experience the appropriate amount of water to be added and thus should be able to explicitly specify the amount of water to be added. With the amount of water to be added explicitly specified, the workers need only add the specified amount of water without having to determine the appropriate amount of water to be added by trial and error on site.

6.2 Tests on Possible Use of Recycled Fine Aggregate

Millions of tonnes of old concrete are generated as inert solid waste every year in Hong Kong. The Hong Kong SAR Government has been promoting the crushing of old concrete to produce recycled aggregate for reuse in new construction. However, the recycled aggregate, especially the fine portion, tends to have old cement paste adhered onto the particle surfaces that may adversely affect the quality of the concrete or mortar produced. Hence, most engineers hesitate to use recycled aggregate. Currently, the usage of recycled aggregate (mainly in the production of precast paving blocks) is very low and most of the old concrete is just dumped as waste in landfills or shipped to outside Hong Kong.

To increase the recycling rate of old concrete, we need to make better use of crushed old concrete, which is available as grade 200 recycled rockfill from government fill banks. The cheapest way is to use the crushed old concrete as a filling material in reclamation works, earth works, road works and pipe laying works.

To allow greater use of recycled coarse aggregate in concrete works other than precast concrete paving blocks, there is a need to increase the allowable percentage replacement of fresh natural coarse aggregate by recycled coarse aggregate in concrete up to 35 MPa. But first of all, we need to improve the quality of the recycled coarse aggregate by removing the old cement paste on the surfaces of the aggregate particles. It is envisaged that the old cement paste can be removed by grinding the coarse aggregate particles using the grinding technology being adopted in the production of manufactured sand to improve particle roundness. However, since recycled coarse aggregate is not really a river sand substitute, research on improving the quality of recycled coarse aggregate for greater use of recycled coarse aggregate is outside the scope of the present study on river sand substitutes.

The present research should focus more on the possible use of recycled fine aggregate as river sand substitute in mortar. At the beginning, it was suggested to seek help from the quarry operators and manufactured sand suppliers to produce the following two types of recycled fine aggregate for testing:

CRFA – crushed recycled fine aggregate with only crushing for size reduction applied and no grinding applied.

GRFA – ground recycled fine aggregate with grinding applied after crushing to remove old cement paste adhered onto particle surfaces.

However, none of the quarry operators and manufactured sand suppliers contacted is interested in producing recycled concrete aggregate for testing. In fact, they are rather pessimistic about the future of the old concrete recycling industry in Hong Kong. Nevertheless, Prof. Albert K.H. Kwan has recently contacted LVFAR Green Technology Corp (LVFAR), who have a factory in Shenzhen crushing and recycling about one million tons of construction and demolition waste per year. They have sent some samples of their recycled fine aggregate, which belongs to the CRFA type, to The University of Hong Kong for testing. They are not producing any recycled fine aggregate of the GRFA type, which to them is much too expensive to produce. Nevertheless, they are using 100% recycled fine aggregate in some of their building products, such as precast paving blocks and pre-packed dry mortar.

In theory, the recycled fine aggregate should be air classified to control its fines content. However, the recycled fine aggregate samples sent to The

University of Hong Kong have not been processed by any means to control their fines contents. On receipt, the recycled fine aggregate samples have been tested to have fines contents of about 12%. To control the fines contents of these recycled fine aggregate samples, the recycled fine aggregate samples were first mechanically sieved to remove all the fines contained therein and then the right amounts of fines were put back to produce recycled fine aggregate samples with different prescribed fines contents for testing. It is envisaged that with the fines content controlled, even recycled fine aggregate of the CRFA type may be good enough to be used up to 100% in low grade concrete and mortar for plastering, rendering, screeding and masonry.

To study the possible use of recycled fine aggregate up to 100% in concrete and mortar, a testing program has been worked out. In the testing program, there are four combinations of W/C ratio ranging from 0.30 to 0.60, two combinations of PV ranging from 42% to 48%, two combinations of fines content ranging from 5% to 10%, but only one type of recycled fine aggregate, namely the CRFA type (no recycled fine aggregate of the GRFA type was available for testing). The tests carried out were the same as in the previous testing programs.

The recycled fine aggregate has a maximum size of 5.0 mm. It has been processed by mechanical sieving to have a fines content of either 5.0% or 10%. The particle size distributions of the CRFA with 5% fines and the CRFA with 10% fines, as determined by mechanical sieving, are presented in Figure 16. The CRFA with 5% fines and the CRFA with 10% fines were measured to have the same relative density of 2.29 but different water absorptions of 9.0% and 12.0%, respectively. In determining the amount of water to be added to the trial mortar mixes, the water absorption of the CRFA was allowed for.

The cement used was an ordinary Portland cement (OPC) of strength class 52.5 N complying with BS EN 197-1: 2000. The relative density of the cement has been measured as 3.11.

Summarizing, the test results of the mortar mixes made with CRFA reveal that:

(1) The fines content has significant adverse effect on the strength. Hence, there is a necessity to control the fines content in the recycled fine aggregate at not higher than 10% and preferably at not higher than 5%.

(2) At a fines content of 5%, a maximum 7-day cube strength of at least 45 MPa can be achieved, whereas at a fines content of 10%, a maximum 7-day cube strength of 38 MPa can be achieved. Such 7-day strengths should be high enough for the production of grade 30 concrete (good for precast paving blocks in footpaths) and grade 20 concrete (good for blinding layers and non-structural concrete), respectively.

(3) Regardless of the PV, the suitable range of W/C ratio for trowelling is rather narrow. At a PV of 42%, the suitable W/C ratio for trowelling is around 0.45, whereas at a PV of 48%, the suitable W/C ratio for trowelling is around 0.40.

(4) A higher fines content of up to 10% does not necessary cause problem in trowelling. At a fines content of not more than 10%, a pull-out strength of 0.5 MPa can be achieved.

Overall, the test results obtained so far are generally positive. Firstly, it should be possible to use 100% recycled fine aggregate in concrete. However, there is a necessity to control the fines content in the recycled fine aggregate at not higher than 5% when used to produce grade 30 concrete, and at not higher 10% when used to produce grade 20 concrete. Secondly, it should be possible to use 100% recycled fine aggregate in mortar for plastering. The suitable range of W/C ratio for trowelling is in general rather narrow but at the right W/C ratio, a pull-out strength of at least 0.5 MPa can be achieved. Although a fines content of up to 10% is still acceptable, it is considered advisable to limit the fines content at not higher than 5% because a larger variation in fines content would lead to a larger variation in water absorption and eventually difficulty on site in determining the right amount of water to be added to the mortar mix.

Only a small quantity of recycled fine aggregate has been tested in this study. Hence, the possible variation in quality of the recycled fine aggregate has not been reflected in the test results. It is expected that the quality of recycled fine aggregate can be quite variable. To render the quality of fine aggregate more consistent, one possible way is to blend 50% recycled fine aggregate with 50% manufactured sand (processed crushed rock fine) so that the quality variation would become smaller. However, such usage of recycled fine aggregate only up to 50% would reduce the recycling rate of old concrete. Nevertheless, even with only 50% recycled fine aggregate used in various kinds of mortar works, the recycling rate of construction and demolition waste in Hong Kong can be substantially increased and the demand of river sand as fine aggregate for mortar works can be greatly decreased.

7. Field Trials on Use of Manufactured Sand in Plastering

As a part of the research project, field trials on the use of manufactured sand in plastering have been carried out. The field trials were to invite experienced workers to evaluate the trowelability of cement sand mortar made with manufactured sand.

Two manufactured sand samples were obtained for testing. The first sample was provided by Man Fai Tai Holdings Ltd, who is currently the only supplier of manufactured sand for cement sand mortar in Hong Kong. The second sample was provided by Alliance Concrete Ltd, who currently has no interest in supplying manufactured sand for cement sand mortar in Hong Kong and is producing manufactured sand solely for use in concrete production. According to Man Fai Tai and Alliance, both the two manufactured sand samples were obtained from crushed rock fine processed by air classification to have the fines content controlled at relatively low levels.

The first sample provided by Man Fai Tai is herein named as MS1 whereas the second sample provided by Alliance is herein named as MS2. For comparison, a river sand sample obtained from the market was also used in the trial; it is herein named as RS.

The details of the field trials and the test results are presented in Appendix C. For conciseness, only a brief summary is presented in the following.

It was found by mechanical sieving that MS1 has 2.8% coarser than 2.36 mm and 0.6% finer than 75 μm, and that MS2 has 16.0% coarser than 2.36 mm and 2.5% finer than 75 μm. Comparatively, MS1 is on average finer and has a lower fines content of 0.6% whereas MS2 is on average coarser and has a higher fines content of 2.5%. MS1 may be regarded as a fine aggregate with a maximum particle size of 2.36 mm whereas MS2 may be regarded as a fine aggregate with a maximum particle size of 5.0 mm.

Thanks to the arrangements made by Mr. Ho Wai Wah, Construction Industry Council and Hop Yuen Building Materials Ltd, two field trials on the use of manufactured sand in plastering have been carried out.

First plastering trial: The first plastering trial was carried out at the Kowloon Bay Training Centre of Construction Industry Centre on March 24, 2015. During the trial, a total of 5 mortar mixes were produced for testing. All plastering trials were conducted on vertical concrete surfaces, which were pre-wetted with water for about 10 minutes and then wiped dry before the plastering. After hardening, the plastered concrete panels were sent back to the laboratory of The University of Hong Kong for pull-out tests at the age of 7 days. For each plastered concrete panel, three pull-out tests were carried out.

Second plastering trial: The second plastering trial was carried out at the Training Centre of Hop Yuen Building Materials Ltd in Kowloon Bay on April 2, 2015. During the trial, a total of 5 mortar mixes were produced for testing. The plastering trials were conducted on vertical concrete surfaces and where possible also on the ceiling of a concrete slab, which were pre-wetted with water for about 10 minutes and then wiped dry before the plastering. After hardening, the plastered concrete panels were sent back to the laboratory of The University of Hong Kong for pull-out tests at the age of 7 days. For each plastered concrete panel, three pull-out tests were carried out.

Summing up, the following conclusions may be drawn:

(1) The manufactured sand MS1, which has a fines content of 0.6% and a maximum particle size of 2.36 mm, is suitable for use as fine aggregate in mortar for plastering works. With MS1 used as fine aggregate, the mortar mix should be designed to have a cement:sand ratio of 1:2.5 and a water/cement ratio of around 0.50. At a water/cement ratio of 0.50 (or any water/cement ratio giving the right consistence), the mortar could be applied to both vertical concrete walls and concrete slab ceilings, and an average pull-out strength of higher than 0.5 MPa could be achieved. At a water/cement ratio of lower than or higher than

0.50, the mortar might become too dry or too wet and could be applied only to vertical concrete walls but not concrete slab ceilings. Hence, the suitable range of water/cement ratio is rather narrow and, therefore, careful control of the water content and good judgement of consistence are needed.

(2) The manufactured sand MS2, which has a fines content of 2.5% and a maximum particle size of 5.0 mm, is also suitable for use as fine aggregate in mortar for plastering works, although it was originally intended for use as fine aggregate in concrete production. With MS2 used as fine aggregate, the mortar mix should be designed to have a cement: sand ratio of 1:2.5 and a water/cement ratio of around 0.50. At a water/cement ratio of 0.50 (or any water/cement ratio giving the right consistence), the mortar could be applied to vertical concrete walls and concrete slab ceilings (the plastering trial in phase one of this research had demonstrated that this same manufactured sand could be applied to concrete slab ceilings). Due to the presence of some relatively coarse particles (particles larger than 2.36 mm), the troweling tended to be slightly more difficult, although the mortar surfaces could still be troweled smooth. Hence, it might be better to limit the maximum particle size of manufactured sand to 2.36 mm.

(3) The river sand RS, which is quite commonly used in the construction industry, is also suitable for use as fine aggregate in mortar for plastering works. With RS used, the mortar mix should be designed to have a cement:sand ratio of 1:2.5 and a water/cement ratio of around 0.50. With a suitable water/cement ratio adopted, the mortar could be applied to both vertical concrete walls and concrete slab ceilings. However, it should be borne in mind that the characteristics (mainly the fineness and moisture content) of river sand could fluctuate a lot (depending on where it was dredged) and thus the exact amount of water to be added has to be judged during mixing and good experience and skill are needed to produce a mortar mix with right consistence for application onto vertical concrete walls and concrete slab ceilings.

8. Interview with Stakeholders

During the Phase One study, the Investigator Ir. Prof. Albert K.H. Kwan (AKHK) had already interviewed a number of stakeholders, who are mainly users of river sand and crushed rock fine aggregate for concrete production and mortar works. In this Phase Two study, AKHK had interviewed three more companies, who may be interested in producing manufactured sand, crushed waste glass and recycled fine aggregate as river sand substitutes for the Hong Kong market. These interviews are reported below.

8.1 Interview with Man Fai Tai

Man Fai Tai Holdings Ltd. has been supplying river sand and manufactured sand for mortar works in Hong Kong for many years. Currently, they are the only manufactured sand supplier in Hong Kong.

AKHK has met or telephone interviewed with Mr. Jason To of Man Fai Tai several times on 18/2/2014, 14/4/2014, 11/5/2014, 28/7/2014, 24/9/2014, 26/12/2014 and 10/3/2015. Mr. Jason To advised that their manufactured sand production plant in She Kou was moved to another quarry in Xin Hui in 2013 (AKHK visited the production plant in She Kou several months before the plant was dismantled). However, they encountered land matter problems and certain difficulties in the setting up of a new and more advanced production plant in Xin Hui and therefore their supply of manufactured sand to Hong Kong had been suspended for more than a year. That is why they had not been able to deliver manufactured sand samples to AKHK as promised for testing. Finally, their production plant in Xin Hui started operation in March 2015. Mr. Jason To advised that they are still fine tuning the production plant and will resume supplying manufactured sand to Hong Kong if the trial production is satisfactory. Their production capacity will be around 600,000 tons per year but if there is a good market, they can install another plant to double their production capacity.

On 10/3/2015, Mr. Jason To delivered some manufactured sand samples to AKHK for the field trials in this study.

During the several interviews, Mr. Jason To expressed his appreciation of the Construction Industry Council for launching this research project, which will help the industry adapt to the use of manufactured sand as river sand substitute. He also added that they are quite happy to produce manufactured sand in full compliance with the Recommended Specifications.

8.2 Interview with K. Wah

K. Wah Construction Materials Ltd. has been producing precast concrete blocks using crushed waste glass as part of the aggregate. They have a production plant in Anderson Quarry and another one in Tuen Mun Eco Park.

AKHK has met with Mr. Alfred Ho, Mr. Andy Kwok and Mr. Alex Lam of K. Wah several times. He visited K. Wah’s office on 13/12/2013 and K. Wah’s factory in Eco Park on 16/5/2014.

A summary of their discussions during the factory visit is given below:

(1) K. Wah’s factory has the capacity to produce more recycled glass paving blocks and partition wall blocks should more waste glass be delivered to the factory for recycling. So the recycling rate of waste glass in Hong Kong can be increased by delivering more waste glass to the factory. It is only that the cost of recycled glass paving blocks and partition wall blocks is substantially higher than conventional products and users are not willing to pay for the higher cost if there is not sufficient incentive given to them.

(2) At the moment, the amount of recycled waste glass aggregate in the paving blocks is only 20-25% of the total aggregate. It may be possible to increase the recycled waste glass aggregate to 50% of the total aggregate. AKHK has tested mortar with 100% recycled waste glass aggregate and achieved a sufficiently high strength for the production of grade 45 paving blocks. Hence, in theory, it should be possible to increase the recycled waste glass aggregate to 50% so as to increase the recycling rate of waste glass in Hong Kong. K. Wah agreed to such possibility but emphasized that trial production is needed to study how the mix design should be adjusted. K. Wah also emphasized that the increase in recycled waste glass aggregate in the paving blocks would lead to a significant increase in production cost. Incentives should be provided to the users for them to pay for the higher cost. Alternatively, some kind of subsidy should be provided to the producer to keep the price at an affordable level.

(3) No recycled waste glass aggregate has been added in the partition wall blocks. In Hong Kong, the consumption of partition wall blocks is much larger (~10 times larger) than the consumption of paving blocks. Moreover, the strength requirement of partition wall blocks is much lower than that of paving blocks. Hence, it is almost certain that at least 50% recycled waste glass aggregate can be used in partition wall blocks. Again, the cost of production would be significantly higher. But, if there is incentive for users to use partition wall blocks made with at least 50% recycled waste glass aggregate, the recycling rate of waste glass in Hong Kong could be dramatically increased.

(4) The use of recycled waste glass aggregate as river sand substitute for mortar rendering works would surely increase the recycling rate of waste glass in Hong Kong. But crushing waste glass to a relatively high fineness for mortar rendering works is quite costly. K. Wah was of the opinion that greater use of crushed waste glass in paving blocks and partition wall blocks may be more economical. Nevertheless, if there is a market, K. Wah may consider producing crushed waste glass as river sand substitute for mortar rendering works.

8.3 Interview with LVFAR

As per the request of Construction Industry Council, AKHK has contacted Mr. Steven Wong of LVFAR Green Technology Corp, paid a visit to LVFAR's construction and demolition waste recycling factory in Shenzhen, and met with the senior management of LVFAR both in Shenzhen and in Hong Kong.

A brief report of AKHK's interaction with LVFAR is presented below.

(1) On 10/7/2014, AKHK visited LVFAR's recycling factory in Longgang, Shenzhen. According to LVFAR, this recycling factory is the biggest in China. It is processing about one million tons of construction and demolition waste and producing various types of precast concrete blocks (paving blocks, partition wall blocks, pervious blocks and grass planting blocks etc) and pre-packed dry mortar for plastering using 100% recycled fine and coarse aggregates. One unique feature of their production process is that no virgin rock aggregate or river sand is needed to produce their precast concrete blocks or dry mortar. Hence, their production process may be one possible way of reducing rock aggregate or river sand consumption.

(2) LVFAR is planning to enter into Hong Kong market. In fact, they have a representative in Hong Kong. AKHK attended the opening ceremony of their Hong Kong office on 18/7/2014. AKHK told them that the performance standards for precast concrete blocks and dry mortar in Hong Kong are higher than those in Mainland. Therefore, they need to have their products tested in Hong Kong to find out whether their products comply with the General Specification for Civil Engineering Works in Hong Kong.

(3) AKHK also discussed with them about whether Hong Kong would welcome products made with construction and demolition waste generated from outside Hong Kong. The use of products made with construction and demolition waste generated from outside Hong Kong would not help to recycle the construction and demolition waste in Hong Kong. To help recycle the construction and demolition waste in Hong Kong, the only way is to use the construction and demolition waste generated from inside Hong Kong as the raw materials. For this purpose, LVFAR may need to set up a factory in Hong Kong to recycle the construction and demolition waste generated from inside Hong Kong. To set up a recycling factory in Hong Kong, land would be the major difficulty.

(4) On 30/12/2014, AKHK interviewed with LVFAR again to find out their progress in the setting up of a recycling factory in Hong Kong. LVFAR advised that they are still looking for suitable land to set up a recycling factory in Hong Kong. They said that their recycling factory in Shenzhen have already developed several building products (paving blocks, pervious paving blocks, partition wall blocks, and TiO_2 added

air purifying blocks) using recycled construction and demolition waste specifically for the Hong Kong market. They have also received enquires on the collection of construction and demolition waste in Hong Kong but could not take up the job because at the moment, they have no land to process construction and demolition waste in Hong Kong.

8.4 Summary

From the interviews, the following points are noted:

(1) There should be no particular technical difficulties in the production of manufactured sand complying with the Recommended Specifications. Informally, AKHK was given to understand that the cost of production of manufactured sand would not be higher than the current price of river sand (at the time of writing this report, the price of river sand in Hong Kong is approximately HK$150 per ton).

(2) In the production of precast paving blocks and partition wall blocks, it should be possible to increase the recycled waste glass aggregate to at least 50% of the total aggregate. It is only that the increase in recycled waste glass aggregate content would lead to a significant increase in production cost. Incentives should be provided to the users for them to pay for the higher cost. Alternatively, some kind of subsidy should be provided to the producer to keep the price at an affordable level.

(3) As LVFAR have been doing for many years in Shenzhen, there should be no particular difficulties in the production of recycled fine aggregate for precast concrete block construction and mortar works. The major difficulty in the setting up of a recycling plant in Hong Kong for the sorting, crushing and processing of construction and demolition waste into recycled fine aggregate is the shortage of suitable land. In order to promote recycling of construction and demolition waste and increase the currently very low recycling rate of inert solid waste in Hong Kong, the Government should consider providing low cost and suitable land for the solid waste recycling industry.

9. Discussions

9.1 Manufactured Sand as River Sand Substitutes

There is no doubt that processed crushed rock fine (often called manufactured sand to distinguish it from unprocessed crushed rock fine) is the most suitable river sand substitute for concrete and mortar production. River sand, which has been in use for decades, has the major characteristics that since it has been subjected to years of washing, it has a rather low fines content, and since it has been subjected to years of abrasion, it has a more or less rounded and smooth shape. Comparatively, crushed rock fine, if unprocessed, has a relatively high fines content and an angular and rough shape. Nevertheless, there are nowadays quarrying technologies for processing crushed rock aggregate to control the fines content and improve the particle shape. Basically, the fines content can be reduced by water washing or air classification and the particle shape can be improved by grinding the aggregate particles in addition to crushing for size reduction.

In fact, the use of manufactured sand as river sand substitute can help to overcome three major shortcomings with river sand. First, since river sand is brought down by river water from upstream, it could have a very complex mineralogy and, as a result, it is generally difficult to ascertain whether its use would lead to any deleterious alkali-aggregate reaction. Second, since river sand is a natural material with no quality control applied, its characteristics could vary widely (in fact river sands dredged from different locations could have different characteristics) whereas manufactured sand is an engineered material with quality control applied to ensure compliance with standards and specifications. Third, river sand dredged from river estuaries close to the sea might have been contaminated with salt, thus causing the concrete/mortar produced to have high chloride content.

For crushed rock fine to be used as river sand substitute for concrete production, the concrete producers in Hong Kong have already adapted by changing their concrete mix designs to suit. There has been no major problem with the use of crushed rock fine as fine aggregate in normal-strength concrete. The use of crushed rock fine in place of river sand has some effects on the workability and strength of the concrete produced but these can be dealt with by adding a bit more cement and water or by increasing the superplasticizer dosage. Some concrete producers commented that for the production of high-strength concrete or pumpable concrete, river sand, which has lower fines content and better particle shape, is still a better fine aggregate than crushed rock fine. Recently, a study on the possible use of manufactured sand in concrete production has been carried out locally (R.K.K. Chow, S.W.S. Yip and A.K.H. Kwan, Processing crushed rock fine to produce manufactured sand for improving overall performance of concrete, HKIE Transactions, Vol.20, No.4, 2013, 240-249). It was found that the use of manufactured sand with the fines content controlled at lower than 5% and the particle shape improved would increase the packing density of the aggregate and reduce the amount of cement needed for concrete production.

However, manufactured sand is more costly to produce than unprocessed crushed rock fine and whether it should be used is dependent on the performance requirement of the concrete to be produced. For the production of high-strength concrete or pumpable concrete, manufactured sand, which is of higher standard than stipulated in CS3: 2013, should be used. Actually, the standard stipulated in CS3: 2013 is a minimum standard for general applications. The fines content limits set in this standard are quite reasonable, as verified by the test results obtained from this study. However, for the production of high-strength concrete, high-performance concrete and low carbon footprint concrete, a higher standard may have to be imposed on the fine aggregate to be used. In such case, the concrete producers are advised to make prior arrangements with the aggregate producers on the possibility of producing manufactured sand of higher standard than stipulated in CS3: 2013 for special applications.

For crushed rock fine to be used as river sand substitute for mortar works, interviews with practitioners and trial plastering in Phase One of this study have already established that unprocessed crushed rock fine, which generally has a relatively high fines content, is not a suitable river sand substitute for mortar works. The test results obtained from this study reveal that a fines content of up to 8% has no adverse effects on trowelability and strength, and that there is no real necessity to impose a fines content limit of 3%. Moreover, a maximum aggregate size of 2.36 mm is better than a maximum aggregate size of 5.0 mm. Hence, a suitable river sand substitute for mortar to be used in plastering and screeding is manufactured sand with a fines content of not higher than 5% and a maximum size of aggregate of 2.36 mm. For mortar to be used in masonry, there is no trowelability problem and the fines content limit may be raised to 10% (no MB requirement) or even 14% (if MB $\leq$ 1.4), as for fine aggregate to be used in concrete. Based on these findings, a Recommended Specifications for Aggregate for Mortar has been produced. It is hoped that with a standard to follow, the aggregate producers would be able to adjust their manufacturing process to suit and market their products as having complied with a recognized standard.

In the future, a product certification scheme may be worked out so that the aggregate producers may have incentives to improve their production and quality control so as to have their products certified. More importantly, the contractors and mortar workers would have a river sand substitute of known and consistent quality to use. Nevertheless, there is still the workmanship problem of adding the appropriate water content for optimum trowelability. Different workers have different ways of determining the amount of water to be added and such subjective determination of the water content for optimum trowelability has led to large variations in plaster/render work quality. A simple site test for objective determination of the water content for optimum trowelability is needed. The mini slump-flow test tried in this study does give some rough guidelines but judgement by the workers on site is still needed. To resolve this problem, further research is recommended. Finally, it is suggested to provide training to the workers to help them adapt to the use of manufactured sand instead of river sand in their mortar works.

9.2 Possible Use of Crushed Waste Glass

At present, the crushed waste glass aggregate in eco-glass paving blocks constitutes only 20 to 25% by weight of the total aggregate. If the crushed waste glass aggregate in precast paving blocks can be increased to 50% or higher, the consumption and recycling rate of waste glass in Hong Kong can be substantially increased and the amount of waste glass to be dumped to landfills can be substantially decreased. The test results obtained from this study reveal that it should be possible to use up to 100% crushed waste glass aggregate to make grade 35 precast paving blocks (for footpaths) and up to 50% crushed waste glass aggregate to make grade 45 precast paving blocks (for vehicle access and EVA).

In this study, all the mortar cubes for measurement of cube compressive strength were made by wet moulding with the moulds removed 24 hours after casting. However, in actual production, the precast paving blocks are generally made by dry moulding with the moulds removed right after casting for faster production. A supplier in Mainland China, upon Prof. Albert Kwan's request and advice, has tried the use of 100% crushed waste glass aggregate in the production of precast paving blocks by dry moulding and achieved a mean 28-day cube strength of about 50 MPa (good enough for the production of precast paving blocks of grade 30). Further trial using 70% crushed waste glass aggregate indicated that a mean 28-day cube strength of about 55 MPa can be achieved (good enough for the production of precast paving blocks of grade 35). Hence, it should be possible to use up to 100% crushed waste glass aggregate in the dry moulding production of grade 30 precast paving blocks. For the possible use of crushed waste glass aggregate up to, say, 50% in the dry moulding production of grade 45 precast paving blocks, further research is still needed.

Another possible use of crushed waste glass is in mortar works. At present, crushed waste glass has never been used in any mortar works. The test results from this study reveal that it should be possible to use up to 50% crushed waste glass aggregate in mortar for plastering. The use of 100% crushed waste glass aggregate in mortar for plastering is not recommended because the mortar produced tends to be less cohesive than usual and thus more difficult to apply. Since the consumption of river sand as aggregate for mortar is more than 1,000,000 tons per year and there is a shortage of river sand in Hong Kong, the use of crushed waste glass as aggregate in mortar would resolve not only the waste glass recycling problem but also the river sand shortage problem. However, it appears that the crushed waste glass to be used as river sand substitute in mortar has to have a tightly controlled particle size distribution and the mix proportions of the mortar have to be well controlled. Site batching and mixing could lead to a lot of workmanship problems. Perhaps, the best solution is to use 50% crushed waste glass aggregate as a constituent in pre-packed mortar for plastering and rendering. In addition, the pre-packed mortar has to be used with an accurate water dosage.

9.3 Possible Use of Recycled Fine Aggregate

Two quarry operators, who are supplying rock aggregate to Hong Kong, have Barmac grinding machines, which may be used to grind away the old cement paste on the surfaces of aggregate particles to produce higher quality recycled concrete aggregate. Prof. Albert Kwan has contacted them several times to see if they would be interested in producing ground recycled concrete aggregate for increasing the recycling rate of old concrete in Hong Kong. So far, no formal response has been received from them. Prof. Kwan has the feeling that at the moment, they have no interest in producing any ground recycled concrete aggregate. This is probably because right now, there is no obvious market demand and the government policy on recycling of old concrete is not clear. Hence, without clear government policy promoting greater use of recycled concrete aggregate, little progress in greater use of recycled concrete aggregate could be made.

Nevertheless, the company LVFAR Green Technology Corp is interested in entering into the Hong Kong market. This company is producing recycled fine aggregate from construction and demolition waste in Shenzhen and using 100% recycled fine aggregate in some of their building products. They are more optimistic and would investigate various possible means of improving the quality of recycled fine aggregate for greater use of recycled fine aggregate in both concrete and mortar.

The test results obtained from this study using the recycled fine aggregate samples provided by LVFAR are generally positive. Firstly, it should be possible to use 100% recycled fine aggregate to make grade 30 precast paving blocks and grade 20 non-structural concrete. However, there is a necessity to control the fines content in the recycled fine aggregate at not higher than 5% when used to produce grade 30 concrete, and at not higher 10% when used to produce grade 20 concrete. Secondly, it should be possible to use 100% recycled fine aggregate in mortar for plastering. The suitable range of W/C ratio for trowelling is rather narrow but at the right W/C ratio, a pull-out strength of at least 0.5 MPa can be achieved. Although a fines content of up to 10% is still acceptable, it is considered advisable to limit the fines content at not higher than 5% so as to reduce the variation in water absorption and improve the trowelability of the mortar mix produced.

The control of the fines content in the recycled fine aggregate can be done by applying air classification to the recycled fine aggregate so as to remove the excessive fines content. This would increase the cost of production but would significantly improve the quality of the recycled fine aggregate for greater use in concrete for precast and in-situ non-structural applications and in mortar for plastering, screeding and masonry. It is suggested to classify recycled fine aggregate for mortar into classes F5, F10 and F14, as for natural aggregate for mortar. In fact, like CS3: 2013, which is to be applied to both natural and recycled aggregates for concrete, the Recommended Specifications for Aggregate for Mortar draft based on this study is also supposed to be applied to both natural and recycled aggregates for mortar.

In any case, crushed rock fine and manufactured sand are much better river sand substitutes than recycled concrete aggregate. Greater use of recycled concrete aggregate is to reduce the amount of solid waste to be dumped to the landfills, rather than to reduce the consumption of river sand. The control of the quality of recycled concrete aggregate is not easy and therefore recycled concrete aggregate may only be used in low quality building products such as partition wall blocks, paving blocks and mortar works.

10. Recommended Specifications

10.1 Drafting of the Recommended Specifications

As stated in the Outline Brief of the "Research on River Sand Substitutes for Concrete Production and Cement Sand Mortar Production (Phase Two)", Objective (1) is to draft a local construction standard on aggregates for mortar based on existing standards in Europe, UK and China.

Based on the Phase One study and the literature review of the relevant existing standards, a preliminary draft of the Recommended Specifications entitled "Recommended Specifications for Aggregates for Mortar (Version 1.0)" has been prepared at the start of this Phase Two study. The draft Recommended Specifications is written in such a way that wherever applicable, the requirements stipulated in BS EN 13139 are followed. Where the requirements stipulated in BS EN 13139 cannot be followed, the requirements in the Recommended Specifications are stipulated based on considerations of the local conditions. Moreover, to be compatible with the Construction Standard CS3: 2013 and to make good use of the stipulations given therein, this draft Recommended Specifications follows the general requirements and employs the same test methods given in CS3: 2013.

It is envisaged that the most important issue is the allowable fines content in the aggregate. Since the maximum allowable fines contents are quite different in the various existing standards in different countries, this issue could be quite controversial. On the other hand, there is the general concern on the presence of harmful substances (such as clay and dirt) in the fines and the high water demand of the mortar produced due to the large surface area of the fines (finer materials have larger specific surface area). Hence, certain limits on the fines content in the aggregate have to be imposed. It is just a matter of what limits should be imposed and whether the stakeholders could come to any agreement on any proposed limits.

The preliminary draft Recommended Specifications entitled "Recommended Specifications for Aggregates for Mortar (Version 1.0)" was submitted together with the Inception Report and Progress Report No. 1 in September 2013. It was then sent out to the stakeholders for consultation. After the first round of consultation, the preliminary draft Recommended Specification was revised to become the revised draft Recommended Specifications entitled "Recommended Specifications for Aggregates for Mortar: 2015". It was submitted together with Progress Report No. 7 in January 2015 and then sent out to the stakeholders for another round of consultation. In this another round of consultation, there was no request for further revisions.

The revised draft Recommended Specifications is attached in Appendix D.

10.2 Consultation with Stakeholders

The preliminary draft Recommended Specifications entitled "Recommended Specifications for Aggregates for Mortar (Version 1.0)" submitted together with the Inception Report and Progress Report No. 1 in September 2013 was sent to the following stakeholders for consultation:

(1) Standing Committee on Concrete Technology of HKSAR Government;
(2) Public Works Central Laboratory of HKSAR Government;
(3) Hong Kong Construction Association;
(4) General Building Contractors Association;
(5) Hong Kong Concrete Producers Association;
(6) Institute of Quarrying Hong Kong Branch;
(7) Import Aggregates Suppliers Association Ltd.;
(8) Hong Kong Construction Sub-contractors Association;
(9) Plastering Sub-contractors Association;
(10) Brick-laying & Construction Trade Workers Union;
(11) Hong Kong Institution of Engineers Materials Division;
(12) Hong Kong Concrete Institute;
(13) Buildings Department of HKSAR Government; and
(14) Contractor's Authorized Signatory Association.

A detailed report of the consultation and the comments received is presented in Appendix E. The comments received were mainly on the possibilities of (1) waiving the durability requirements for non-structural applications and (2) removing class F3 fine aggregate (fines content $\leq$ 3%) and just allowing the use of class F5 fine aggregate (fines content $\leq$ 5%) in plastering and screeding works.

In response to the above comments and since the mortar test results reveal that there is no real necessity to impose a fines content limit of 3% in any fine aggregate for mortar, the draft Recommended Specifications was revised to address the above comments by waiving the durability requirements for non-structural applications and removing class F3 fine aggregate, and the revised draft Recommended Specifications, entitled "Recommended Specifications for Aggregates for Mortar: 2015", was submitted together with Progress Report No. 7 in January 2015.

The revised draft Recommended Specifications was then sent out to the stakeholders for another round of consultation. A detailed report of the consultation and the comments received is presented in Appendix E. The comments received were generally supportive and there was no request for further revisions of the draft Recommended Specifications. Many of the stakeholders thanked the Construction Industry Council for undertaking the task of drafting a local standard for aggregate for mortar, which would ensure that the manufactured sand to be used as a river sand substitute would be a suitable aggregate for mortar works and would enable the manufactured sand suppliers to have a recognized standard to follow.

11. Conclusions

11.1 Conclusions from Literature Review

The standard sieve sizes, demarcation between coarse and fine aggregates and definition of fines vary from one standard to another standard. As the standard sieve sizes, demarcation between coarse and fine aggregates and definition of fines in the British Standards that have been in use in Hong Kong for a long time are almost the same as those in the Chinese Standards and some of the quarries are supplying aggregate to both the Hong Kong market and the Mainland China market, it is better from the market operation point of view to stay with the standard sieve sizes, demarcation between coarse and fine aggregates and definition of fines in the British Standards.

In general, different requirements are imposed on aggregates for concrete and aggregates for mortar. This is because concrete and mortar have different performance attributes and the quality of fine aggregate has different effects on concrete and mortar. Hence, aggregates for concrete and aggregates for mortar should be clearly differentiated.

For both aggregates for concrete and aggregates for mortar, the major issues seem to be the limits to be imposed on the fines content and the assessment of the harmfulness of the fines content. The fines content needs to be limited because (1) the presence of any harmful substances in the fines content would adversely affect the abrasive resistance, strength and durability; (2) the fines content would increase the water and superplasticizer demands of the concrete or mortar mix; (3) the increase in water demand due to higher fines content would force the worker to add more water to improve the trowelability of the mortar and thus cause the hardened mortar to have a relatively large drying shrinkage; and (4) the presence of excessive fines would render the mortar too sticky and slippery to be properly trowelled.

On the other hand, there are still no established methods for assessing the harmfulness of fines in aggregate and no established acceptance criteria for the non-harmfulness of fines. The BSI PD 6682-3 recommends that aggregates should better be assessed for harmful fines using either a fines content limit or evidence of satisfactory use. This seems to be a pragmatic way of avoiding the controversies regarding the methods of assessment and acceptance criteria. Hence, another reason for limiting the fines content is to reduce the risk of having harmful substance in the aggregate.

Lastly, whilst the fine aggregates stipulated in BS 1199: 1976, BS 1200: 1976, BS 882: 1992 and CS3: 2013 all have a maximum aggregate size of 5.0 mm, the fine aggregates in BS EN 13139: 2002 and BS EN 13139: 2013 may have a maximum aggregate size of 4.0 mm or 2.0 mm. Although we are not strictly following the European Standards, it seems prudent to follow the practice of having fine aggregates with different maximum aggregate sizes (of say, 5.0 mm and 2.36 mm) for different applications.

Based on the above, it is recommended that a separate local construction standard on aggregate for mortar should be produced. However, it should be compatible with CS3: 2013 so that the same terms would have the same meanings in the two standards, the same test methods may be used for both aggregates for concrete and aggregates for mortar, and some of the aggregate products may be used for both concrete and mortar. Moreover, unlike the previous standards on aggregates for concrete or mortar, which stipulate the maximum aggregate size of fine aggregate as 5.0 mm, the fine aggregate for mortar should be allowed to have a maximum aggregate size of 5.0 mm or 2.36 mm to suit different applications. Finally, although there are big differences in the maximum allowable limits on the fines content in the various standards, and the new European Standard BS EN 13139: 2013 does not impose any precise limits on the fines contents and no longer gives any examples of usage of the various categories of fine aggregates with different fines content limits, it is still considered prudent to impose fines content limits based on the fines content limits previously given in BS 1199: 1976, BS 1200: 1976, BS EN 13139: 2002, and BSI PD 6682-3: 2003.

11.2 Conclusions on Fine Aggregate for Concrete

The laboratory test results of the concrete mixes reveal the following effects of the fines content on the performance of concrete:

(1) The fines content has significant adverse effect on the workability of concrete, except at very low slump or flow spread, in which case, the effect of fines content on workability is not revealed.

(2) The fines content has little effect on the strength, except at W/C = 0.3, in which case, a fines content of 12% or higher has significant adverse effect on the strength due to difficulties in compaction caused by the high fines content.

(3) The fines content has certain beneficial effect on the cohesiveness and segregation resistance of concrete.

Overall, a higher fines content in the fine aggregate would lead to a lower workability of the concrete produced but if the fines content does not exceed 10%, the decrease in workability can be more than compensated by adding more superplasticizer. Hence, it may be said that provided the fines content in the fine aggregate is of good quality and contains little deleterious materials, a fines content of up to 10% may be considered acceptable.

A fines content of higher than 10% may still be considered acceptable if trial concrete mixing has demonstrated that the required workability can still be achieved without using an excessively high dosage of superplasticizer. Even then, it is still considered advisable to set a certain maximum limit to the fines content. In CS3: 2013, the fine content is limit to 14% for general use (with the additional requirement that if the fines content > 10%, the methylene blue value shall be ≤ 1.4) and to 10% for use in heavy duty floor finishes. These are very reasonable maximum limits to be imposed. Another reason of setting a maximum limit to the fines content is that in practice, the fines content could fluctuate quite substantially within the specified limit and if the fluctuation in fines content is too large, the workability of the concrete produced would vary from time to time and the concrete producer might find it difficult to adjust the superplasticizer dosage to compensate for the variation in workability.

Moreover, it has been found from this study that at a low W/C ratio of 0.3, a fines content of 12% or higher has significant adverse effect on the strength due to difficulties in compaction caused by the high fines content. Since the W/C ratio of high-strength concrete tends to be low, it is recommended that for the production of high-strength concrete, the fines content should be limited to not higher than 10%. In other words, the fines content should be limited to 10% not only for use in heavy duty floor finishes, but also for use in high-strength concrete.

11.3 Conclusions on Fine Aggregate for Mortar

From the laboratory test results of the mortar mixes, it may be concluded that the trowelability of a mortar is best when the mortar is neither too dry nor too wet. However, this seems to be dependent more on the W/C ratio or the water content of the mortar mix, rather than the fines content in the fine aggregate. The suitable W/C ratios for trowelling are as follows (note: MSA = maximum size of aggregate; and PV = paste volume):

(1) At MSA = 2.36 mm and PV = 42%, suitable W/C = 0.60;
(2) At MSA = 2.36 mm and PV = 48%, suitable W/C = 0.50; and
(3) At MSA = 5.0 mm and PV = 48%, suitable W/C = 0.40.

The suitable W/C for trowelling varies with the MSA and PV, and for each given mortar mix, the acceptable range of W/C or water content for trowelling is very narrow and thus the W/C ratio or the water content has to be controlled carefully. Nevertheless, within the ranges of MSA and PV covered in this study, a fines content of up to 8% has no adverse effects on trowelability and strength. Lastly, at a suitable W/C for trowelling and with the fines content limited to not more than 8%, a pull-out strength of at least 0.7 MPa can be achieved, which should be sufficiently high because the required pull-out strength is only 0.5 MPa.

Overall, it appears that there is no real necessity to impose a fines content limit of 3% in any fine aggregate for mortar. In other words, the class F3 fine aggregate (fines content ≤ 3%) is not really necessary, and it may be simpler to remove the class F3 fine aggregate and just allow the use of class F5 fine aggregate (fines content ≤ 5%) in all kinds of plastering and screeding works.

Moreover, it appears that a paste volume of 48% is better for plastering. A slightly smaller paste volume of 45% may also be acceptable. Converting to cement to sand ratio, which is more commonly used for batching on site, a paste volume of PV = 48% is equivalent to a cement to sand ratio of 1:2.36, and a paste volume of PV = 45% is equivalent to a cement to sand ratio of 1:2.66. Hence, the cement to sand ratio of mortar for plastering should be set at around 1:2.5.

In conventional practice, the water content of the mortar mix is not explicitly specified and the workers are left to themselves to judge the appropriate amount of water to be added to give the optimum trowelability. This requires the workers to have proper training and good experience. From the present study, a general guideline has been produced as a slump of 10 ± 3 mm, as measured by the mini slump-flow test. So, to overcome the common workmanship problem of often putting in too little or too much water, the workers should be encouraged and trained to perform the mini slump-flow test. Alternatively, pre-packed dry plastering mortar can be used. The use of pre-packed materials can ensure that the fine aggregate is of the right quality and the cement to sand ratio has been accurately controlled. Moreover, the mortar supplier should know by tests and experience the appropriate amount of water to be added and thus should be able to explicitly specify the amount of water to be added to the dry mortar so that the workers need only add the specified amount of water without having to determine the appropriate amount of water to be added by trial and error on site.

11.4 Conclusions on Possible Use of Crushed Waste Glass

The laboratory test results on possible use of crushed waste glass are generally positive. Firstly, it should be possible to use up to 50% crushed waste glass aggregate to make grade 45 precast paving blocks and up to 100% crushed waste glass aggregate to make grade 35 precast paving blocks. Secondly, it should be possible to use up to 50% crushed waste glass aggregate in mortar for plastering. The use of 100% crushed waste glass aggregate in mortar for plastering is not recommended because the mortar produced tends to be less cohesive than usual and thus more difficult to apply. Thirdly, since crushed waste glass with a grading of F and crushed waste glass with a grading of C perform similarly, there is no particular advantage and no real necessity of crushing the waste glass to higher fineness than usual.

Regarding the paste volume (PV) of mortar for plastering, a PV of 45% to 50% should be appropriate. The suitable W/C ratio is dependent on the PV and the crushed waste glass grading and content. With a suitable W/C ratio adopted to ensure optimum trowelability, a pull-out strength of at least 0.6 MPa can be achieved.

However, there remains the problem of how the workers can determine the right amount of water to be added to the mortar mix to give the optimum trowelability. This requires the workers to have proper training and good experience. From the results obtained herein, a general guideline may be worked out as a slump of 10 ± 5 mm, as measured by the mini slump-flow test. Apart from judging by experience, the workers should be encouraged and trained to perform the mini slump-flow test of the mortar to determine the appropriate amount of water to be added to the mortar mix. Alternatively, the crushed waste glass aggregate may be pre-blended with manufactured sand and cement, and then supplied in the form of pre-packed dry plastering mortar. In general, the quality control of using pre-packed dry mortar materials is better than batching the various ingredients on site. Moreover, the mortar supplier should know by tests and experience the appropriate amount of water to be added and thus should be able to explicitly specify the amount of water to be added. With the amount of water to be added explicitly specified, the workers need only add the specified amount of water without having to determine the appropriate amount of water to be added by trial and error on site.

11.5 Conclusions on Possible Use of Recycled Fine Aggregate

The laboratory test results on possible use of recycled fine aggregate are generally positive. Firstly, it should be possible to use 100% recycled fine aggregate in concrete. However, there is a necessity to control the fines content in the recycled fine aggregate at not higher than 5% when used to produce grade 30 concrete, and at not higher 10% when used to produce grade 20 concrete. Secondly, it should be possible to use 100% recycled fine aggregate in mortar for plastering. The suitable range of W/C ratio for trowelling is in general rather narrow but at the right W/C ratio, a pull-out strength of at least 0.5 MPa can be achieved. Although a fines content of up to 10% is still acceptable, it is considered advisable to limit the fines content at not higher than 5% because a larger variation in fines content would lead to a larger variation in water absorption and eventually difficulty on site in determining the right amount of water to be added to the mortar mix.

Only a small quantity of recycled fine aggregate has been tested in this study. Hence, the possible variation in quality of the recycled fine aggregate has not been reflected in the test results. It is expected that the quality of recycled fine aggregate can be quite variable. To render the quality of fine aggregate more consistent, one possible way is to blend 50% recycled fine aggregate with 50% manufactured sand (processed crushed rock fine) so that the quality variation would become smaller. However, such usage of recycled fine aggregate only up to 50% would reduce the recycling rate of old concrete. Nevertheless, even with only 50% recycled fine aggregate used in various kinds of mortar works, the recycling rate of construction and demolition waste in Hong Kong can be substantially increased and the demand of river sand as fine aggregate for mortar works can be greatly decreased.

11.6 Conclusions on Manufactured Sand as River Sand Substitute

In this research, the effects of fines content in the fine aggregate on the performance of concrete and mortar have been studied. For fine aggregate to be used in concrete, a fines content of up to 10% may be considered acceptable. A fines content of higher than 10% may still be considered acceptable if there is little deleterious materials in the fines content and trial concrete mixing has demonstrated that the required workability can still be achieved without using an excessively high dosage of superplasticizer. On the other hand, for fine aggregate to be used in mortar, a fines content of up to 8% has been found to have no adverse effects on trowelability and strength. Hence, a fines content of up to 8% may be considered acceptable. Nevertheless, to avoid large fluctuations in fines content, it is still considered advisable to limit the fines content at not higher than 5%.

Depending on the mineralogy of the rock from which the aggregate is obtained and the method of crushing, raw crushed rock fine (i.e. unprocessed crushed rock fine) may have a fines content of 6% to 16% (i.e. lower than or higher than 10%). Hence, for use as fine aggregate in concrete, which is required to comply with CS3: 2013, the crushed rock fine does not always need to be processed to control the fines content. However, for use as fine aggregate in mortar, which is required to have a fines content of not higher than 5%, the crushed rock fine needs to be processed to reduce its fines content. Moreover, since a maximum size of aggregate of 2.36 mm is generally preferred, the crushed rock fine needs to be mechanically sieved to remove most of the particles coarser than 2.36 mm. In other words, crushed rock fine to be used as fine aggregate in mortar has to be processed to become a manufactured sand. Some manufactured sand samples have been tested in field trials. It was found that the manufactured sand samples were suitable for trowelling onto vertical concrete walls and concrete slab ceilings.

Based on this research, a Recommended Specifications for Aggregates for Mortar has been draft. The contents of the draft Recommended Specifications have been emailed and explained to various stakeholders to seek their advice and comments. The comments received were duly considered and the draft Recommended Specifications has been revised accordingly. The revised draft has been sent out to the stakeholders for another round of consultation. The comments received were generally positive and there was no request for further revisions.

- End of Report -

Appendix A

Literature Review of Newest Standards Published in 2013 on Aggregates for Concrete and Mortar (Hong Kong CS3, BS EN 12620, BS EN 13139 and ASTM C33/33M)

1. Newest Standards Published in 2013 on Aggregates

Subsequent to the completion of Phase One of this research project on river sand substitutes, four new standards on aggregates for concrete or mortar have been published in 2013. These new standards are:

(1) Hong Kong Construction Standard CS3: 2013 Aggregates for concrete
(2) European Standard BS EN 12620: 2013 Aggregates for concrete
(3) European Standard BS EN 13139: 2013 Aggregates for mortar
(4) American Standard ASTM C33/C33M-13 Standard specification for concrete aggregates

These standards, which are highly relevant to Phase Two of this research project, are reviewed herein. For CS3: 2013, the focuses of the review are on the applicability of the various stipulations contained therein to aggregates for mortar and on how to maintain compatibility between the requirements for aggregates for concrete and the requirements for aggregates for mortar. For BS EN 12620: 2013 and ASTM C33/C33M-13, the focuses of the review are on the newest standard on grading, fines content and fines quality requirements in Europe and the US. For BS EN 13139: 2013, the focuses of the review are on the newest standard on grading, fines content and fines quality requirements, and the applicability of these requirements in Hong Kong.

2. Hong Kong Construction Standard CS3: 2013 – Aggregates for Concrete

This construction standard on aggregates for concrete is currently the only local standard on aggregates because there is, up to now, no local standard on aggregates for mortar. It is largely based on the British Standard BS 882: 1992, which has been in use for a long time in Hong Kong, but is intended to replace this British Standard.

The standard sieve sizes are: 75 µm, 150 µm, 300 µm, 600 µm, 1.18 mm, 2.36 mm, 5.0 mm, 10.0 mm, 20.0 mm, 37.5 mm and 50.0 mm. Particles finer than 5.0 mm (passing the 5.0 mm sieve) are regarded as fine aggregate and particles finer than 75 µm (passing the 75 µm sieve) are regarded as fines. These standard sieve sizes and definitions of fine aggregate and fines are the same as those in the British Standard BS 882: 1992 but are totally different from those in the European Standards BS EN 12620: 2013 and BS EN 13139: 2013.

There are, however, two major differences between CS3: 2013 and the British Standard BS 882: 1992. Firstly, the BS 882: 1992 imposes limits on the fines content in fine aggregate as: for use in heavy duty floor finishes, 9%; and for general use, 16%. In contrast, the CS3: 2013 imposes limits on the fines content in fine aggregate as: for Class I (use in heavy duty floor finishes), 10%; and for Class II (general use), 14%. Secondly, the BS 882: 1992 does not require checking of the cleanliness of the fine aggregate. In contrast, the CS3: 2013 imposes the requirement on the cleanliness of the fine aggregate as: if the fines content $> 10\%$, the methylene blue value shall be ≤ 1.4. The lower fines content limit of 14% and the new requirement on cleanliness in the CS3: 2013 are to improve the general quality of the fine aggregate.

The grading limits for the fine aggregate are given in Table 1 below. These grading limits are the same as those in BS 882: 1992.

Table 1 Grading limits for fine aggregate in CS3: 2013 and BS 882: 1992

Sieve size	Percentage passing by mass			
	Overall limits	Limits for declared grading		
		C	M	F
10.0 mm	100	–	–	–
5.0 mm	89 – 100	–	–	–
2.36 mm	60 – 100	60 – 100	65 – 100	80 – 100
1.18 mm	30 – 100	30 – 90	45 – 100	70 – 100
600 µm	15 – 100	15 – 54	25 – 80	55 – 100
300 µm	5 – 70	5 – 40	5 – 48	5 – 70
150 µm	0 – 20	–	–	–

To be compatible with CS3: 2013, the same standard sieve sizes and the same definition of fines should be followed in any specifications or new standards for aggregates for mortar. Moreover, the same test methods should be adopted.

3. European Standard BS EN 12620: 2013 – Aggregates for Concrete

This is the newest European Standard on aggregates for concrete. It is an update of BS EN 12620: 2002, which has replaced the British Standard BS 882: 1992 in the UK.

As in the 2002 version, the standard sieve sizes are 63 µm, 125 µm, 250 µm, 0.5 mm, 1 mm, 2 mm, 4 mm, 8 mm, 16 mm, 32 mm and 63 mm, which are totally different from those in the British Standards. The demarcation between coarse aggregate and fine aggregate is a particle size of 4 mm (in other words, coarse aggregate is defined as an aggregate comprising of particles larger than 4 mm whereas fine aggregate is defined as an aggregate comprising of particles smaller than 4 mm). Moreover, the definition of fines is the particle size fraction finer than 63 µm (passing the 63 µm sieve).

For fine aggregate with a declared maximum size of D not larger than 4 mm, the following general grading requirements apply: 100% passing the sieve of size $2D$, at least 95% passing the sieve of size $1.4D$, and 85 to 99 % passing the sieve of size D. So, up to 15% of the fine aggregate is allowed to be larger than the declared maximum size. Apart from these requirements, there are no additional requirements on the grading of fine aggregate.

As in the 2002 version, the aggregate producer is required to declare the typical grading of the fine aggregate produced but tolerance limits are applied to control the variability of the fine aggregate. The tolerance limits to be applied are as given in Table 2. It should, however, be noted that the tolerance limits stipulated in BS EN 12620: 2013 are quite different from the respective tolerance limits stipulated in BS EN 12620: 2002.

Table 2 Tolerances on declared typical grading for fine aggregate in BS EN 12620: 2013

Sieve size	Tolerance in percentage passing by mass		
	Category $G_{TC}10$	Category $G_{TC}20$	Category $G_{TC}25$
D[a]	± 5	± 5	± 7.5
D/2	± 10	± 20	± 25
250 µm	± 20	± 25	± 25
63 µm[b]	± 3	± 5	± 5

[a] Tolerance further limited by the requirements for percentage passing *D*.
[b] Tolerance further limited by the maximum allowed fines content.

Where specifiers wish to additionally describe the coarseness or fineness of the fine aggregate, so as to impose certain grading limits, the fine aggregate may be described as *C* (coarse graded), *M* (medium graded) or *F* (fine graded). For such descriptions of the fine aggregate, either Table 3 or Table 4, but not both, may be used.

Table 3 Coarseness/fineness based on percentage passing in BS EN 12620

Percentage passing 0.5 mm sieve by mass		
CP	*MP*	*FP*
5 to 45	30 to 70	55 to 100

Table 4 Coarseness/fineness based on fineness modulus in BS EN 12620

Fineness modulus		
CF	*MF*	*FF*
4.0 to 2.4	2.8 to 1.5	2.1 to 0.6

Comparing Tables 3 and 4 to Table 1, it can be seen that the coarse graded (*CP* or *CF*), medium graded (*MP* or *MF*) and fine graded (*FP* or *FF*) fine aggregates in the BS EN 12620: 2013 and BS EN 12620: 2002 are similar to the respective coarse graded (C), medium graded (M) and fine graded (F) fine aggregates in the CS3: 2013 and BS 882: 1992.

As in the 2002 version, there are no limits imposed on the fines contents in the aggregate. The aggregate producer is allowed to declare the maximum fines content in accordance with specified categories. However, in the 2013 version, one more specified category, the category f_6, has been added. In the 2002 version, the categories for maximum values of fines content are: f_3 – fines content ≤ 3%; f_{10} – fines content ≤ 10%; f_{16} – fines content ≤ 16%; and f_{22} – fines content ≤ 22%. In the 2013 version, the categories for maximum values of fines content are: f_3 – fines content ≤ 3%; f_6 – fines content ≤ 6%; f_{10} – fines content ≤ 10%; f_{16} – fines content ≤ 16%; and f_{22} – fines content ≤ 22%. Hence, the fines content categories in BS EN 12620: 2013 are more refined.

As in the 2002 version, unlike the British Standards, provided the aggregate producer declares the maximum fines content in the aggregate and exercise tight control of the fines content, fairly high fines contents are allowed.

Compared to the 2002 version, the requirements on fines quality in the 2013 version are more explicitly spelled out. According to Section 4.5 of BS EN 12620: 2013, the fines shall be considered non-harmful when any of the four following conditions apply:
(1) the fines content in the fine aggregate is not greater than 3%;
(2) the sand equivalent value is higher than a specified limit;
(3) the methylene blue value is lower than a specified limit; or
(4) there is documented evidence of satisfactory use.
No precise limits have been given for the fines content, sand equivalent value and methylene blue value. These limits shall be established from experience of existing requirements of materials in local satisfactory use according to the provisions valid in the place of use of the aggregate.

4. European Standard BS EN 13139: 2013 – Aggregates for Mortar

This is the newest European Standard on aggregates for mortar. It is an update of BS EN 13139: 2002, which has replaced the British Standards BS 1199 and 1200: 1976 in the UK.

The standard sieve sizes, the definition of fine aggregate as particles smaller than 4 mm, and the definition of fines as particles finer than 63 µm have not changed and remained the same as those in the 2002 version. They are also the same as those in BS EN 12620: 2013.

For fine aggregate with a declared maximum size of *D*, the following general grading requirements apply: 100% passing sieve of size 2*D*, at least 95% passing sieve of size 1.4*D*, and 85 to 99 % passing sieve of size *D*. So, up to 15% of the fine aggregate is allowed to be larger than the declared maximum size. Apart from these requirements, there are no additional requirements on the grading of fine aggregate. These requirements are the same as those in BS EN 12620: 2013.

As in the 2002 version, the aggregate producer is required to declare the typical grading for each fine aggregate size produced but tolerance limits are applied to control the variability of the fine aggregate. The tolerance limits to be applied are as given in Table 5. It should, however, be noted that the tolerance limits stipulated in BS EN 13139: 2013 are quite different from the respective tolerance limits stipulated in BS EN 13139: 2002.

Comparing Table 5 with Table 2, it can be seen that the tolerance limits in BS EN 13139: 2013 are not the same as those in BS EN 12620: 2013. Hence, a fine aggregate, which complies with BS EN 12620: 2013, does not necessarily comply with BS EN 13139: 2013. One major difference is that in BS EN

13139: 2013, the category $G_{TC}25$, which demands rather loose control on grading, is not allowed. Another major difference is that the $D/2$ tolerance requirement is applied only to 0/8 mm and 0/2 mm fine aggregates. For 0/4 mm fine aggregate, the $D/2$ (= 2.0 mm) tolerance limit is replaced by a 1.0 mm sieve tolerance limit with the same tolerance limit value applied.

Table 5 Tolerances on declared typical grading for fine aggregate in BS EN 13139: 2013

Sieve size	Tolerance in percentage passing by mass		
	Category $G_{TC}10$	Category $G_{TC}20$	Category $G_{TC}25$
D[a]	± 5	± 5	This category is not allowed
$D/2$[c]	± 10	± 20	
250 µm	± 20	± 25	
63 µm[b]	± 3	± 5	

[a] Tolerance further limited by the requirements for percentage passing *D*.
[b] Tolerance further limited by the maximum allowed fines content.
[c] For 0/4 mm aggregate, the *D*/2 sieve shall be replaced by 1.0 mm sieve.

Where specifiers wish to additionally describe the coarseness or fineness of the fine aggregate, so as to impose certain grading limits, the fine aggregate may be described as *C* (coarse graded), *M* (medium graded) or *F* (fine graded). For such descriptions of the fine aggregate, either Table 6 or Table 7, but not both, may be used. Note, however, that while Table 6 is identical to Table 3, Table 7 is slightly different from Table 4. Hence, the description of coarseness or fineness in BS EN 13139: 2013 is not exactly the same as that in BS EN 12620: 2013.

Table 6 Coarseness/fineness based on percentage passing in BS EN 13139

Percentage passing 0.5 mm sieve by mass		
CP	*MP*	*FP*
5 to 45	30 to 70	55 to 100

Table 7 Coarseness/fineness based on fineness modulus in BS EN 13139

Fineness modulus		
CF	*MF*	*FF*
≥ 2.4	2.8 to 1.5	2.1 to 0.6

As in the 2002 version, there are no limits imposed on the fines contents in the fine aggregate. The aggregate producer is allowed to declare the maximum fines content in accordance with specified categories. However, the specified categories in the 2013 version are not the same as the specified categories in the 2002 version, as summarized below.

In the 2002 version, the categories for maximum values of fines content are:
category 1 – fines content ≤ 3%;
category 2 – fines content ≤ 5%;
category 3 – fines content ≤ 8%; and

category 4 – fines content ≤ 30%.
Furthermore, examples of end uses for the different categories are given as:
category 1: floor screeds, sprayed, repair mortars, grouts (all aggregates)
category 2: rendering and plastering mortars (all aggregates)
category 3: masonry mortars (excluding crushed rock aggregate)
category 4: masonry mortars (crushed rock aggregate)

In the 2013 version, the categories for maximum values of fines content are:
category f_3 – fines content ≤ 3%;
category f_5 – fines content ≤ 5%;
category f_8 – fines content ≤ 8%; and
category f_{22} – fines content ≤ 22%.
No examples of end uses for the different categories are given anymore.

Compared to the 2002 version, the requirements on fines quality in the 2013 version are more explicitly spelled out. According to Section 4.5 of BS EN 13139: 2013, the fines shall be considered non-harmful when any of the four following conditions apply:

(1) the fines content in the fine aggregate is not greater than 3%;
(2) the sand equivalent value is higher than a specified limit;
(3) the methylene blue value is lower than a specified limit; or
(4) there is documented evidence of satisfactory use.

No precise limits have been given for the fines content, sand equivalent value and methylene blue value. These limits shall be established from experience of existing requirements of materials in local satisfactory use according to the provisions valid in the place of use of the aggregate. These requirements are exactly the same as those in BS EN 12620: 2013.

5. American Standard ASTM C33/C33M-13 – Standard Specification for Concrete Aggregates

This is the newest American Standard on aggregates for concrete published in 2013. In this standard, the standard sieve sizes are 75 µm, 150 µm, 300 µm, 0.6 mm, 1.18 mm, 2.36 mm, 4.75 mm and 9.5 mm, which are similar to those in the British Standard BS 882: 1992 and the Construction Standard CS3: 2013.

The demarcation between coarse aggregate and fine aggregate is a particle size of 4.75 mm (in other words, coarse aggregate is defined as an aggregate comprising of particles larger than 4.75 mm whereas fine aggregate is defined as an aggregate comprising of particles smaller than 4.75 mm). Moreover, the definition of fines is the particle size fraction finer than 75 µm (passing the 75 µm sieve). These are similar to those in the British Standard BS 882: 1992 and the Construction Standard CS3: 2013.

The grading limits for the fine aggregate are given in Table 8 below. Unlike BS 882: 1992 and the CS3: 2013, however, only one type of grading is specified. If not stated, the fines content limit shall be 3.0%. For concrete not subjected to abrasion, the fines content limit shall be 5.0%.

Table 8 Grading limits for fine aggregate in ASTM C33/C33M-13

Sieve size	Percentage passing by mass
9.5 mm	100
4.75 mm	95 – 100
2.36 mm	80 – 100
1.18 mm	50 – 85
600 µm	25 – 60
300 µm	5 – 30
150 µm	0 – 10
75 µm	0 – 3

For manufactured fine aggregate (i.e. crushed rock fine aggregate), if the fines content consists of dust of fracture, essentially free of clay or shale, the fines content limit shall be 5.0% for concrete subjected to abrasion and 7.0% for concrete not subjected to abrasion. These limits on the fines content are rather low and comparable to those in the Chinese Standards GB/T 14684: 2001 and JGJ 52: 2006.

For manufactured fine aggregate having elevated fines content, evaluation should be carried out to ensure that the fines content is essentially composed of dust of fracture derived from the parent rock in the crushing operation and does not contain an appreciable level of clay mineral or other deleterious constituents. Methylene blue adsorption and hydrometer analyses are accepted as reliable tests for characterizing the fines content and determining the suitability of the fine aggregate for use in concrete. Manufactured fine aggregate with less than 4% by mass finer than 2 µm and with methylene blue adsorption value less than 5 mg/g is considered suitable for use in concrete. However, fine aggregate that exceeds these values also may be considered suitable for use provided that fresh and hardened concrete properties are shown to be acceptable.

6. Overview of Newest Standards on Aggregates for Concrete and Mortar

The above standards are compared among themselves and with the British Standards and Chinese Standards with regard to the following aspects.

6.1 Standard sieve sizes

The standard sieve sizes in the British Standards (the standards used previously in Hong Kong), the local Construction Standards (the standards being used in Hong Kong), the Chinese Standards (the standards being used in Mainland China, where the majority of aggregate for use in Hong Kong is supplied from) and the American Standards are similar but the standard sieve sizes in the European Standards are totally different. Since many quarry operators are supplying aggregates to both Mainland China and Hong Kong, it is better to stay with the standard sieve sizes being used in Mainland China and Hong Kong, and not to change the standard sieve sizes to follow the European Standards.

6.2 Demarcation between coarse and fine aggregates

The demarcation between coarse and fine aggregates in the British Standards, local Construction Standards, Chinese Standards and American Standards are similar but the demarcation in the European Standard is totally different. Changing the demarcation from a sieve size of 5.0 mm as in the British Standards, local Construction Standards, Chinese Standards and American Standards to 4.0 mm as in the European Standards would lead to difficulties in changing equipment and bringing forward our previous experience for future use. It is better to stay with the demarcation being used in Mainland China and Hong Kong, and not to change the demarcation to follow the European Standards.

6.3 Grading limits for fine aggregate

In the British Standards, local Construction Standards and Chinese Standards, grading limits for fine aggregates of three different grading classes or zones are specified (the grading zones 1, 2 and 3 in the Chinese Standards are equivalent to the gradings C, M and F in the British Standards and local Construction Standards). In the American Standards, the grading limits for one type of fine aggregate are specified. However, in the European Standards, no grading limits are specified. Instead, the aggregate producer is allowed to declare the typical grading for each fine aggregate size produced but required to control the variability of the fine aggregate such that the grading is within certain tolerance limits. Nevertheless the coarseness/fineness of the fine aggregates may be specified as *C*, *M* and *F* (these grades are actually similar to the respective grades in the British Standards and local Construction Standards) according to the percentage passing the 0.5 mm sieve or the fineness modulus.

Relatively, from the specification and quality control points of view, it should be simpler to follow the practices in the British Standards, local Construction Standards, Chinese Standards and American Standards of directly specifying the grading limits rather than letting the aggregate producer declare the typical grading and then imposing tolerance limits on the grading.

6.4 Equivalent gradings

In BS 1199: 1976, two gradings, namely Type A or Type B, are recommended for external rendering and internal plastering. At the same time, in BS 1200: 1976, another two gradings, namely Type S and Type G, are recommended for masonry mortar. The gradings of Type A and Type B are compared to the declared gradings in CS3: 2013 and BS 882: 1992 in Table 9, whereas the gradings of Type S and Type G are compared to the declared gradings in CS3: 2013 and BS 882: 1992 in Table 10.

From Table 9, it can be seen that the declared gradings C and M in CS3: 2013 and BS 882: 1992 are very similar to the grading Type A in BS 1199: 1976. In fact, apart from the possible slightly higher percentage retained on the 5.0 mm sieve of 11% and the possible slightly higher percentage passing the 150 µm sieve of 20%, the gradings C and M would have totally complied with the grading requirements of Type A. In actual practice, such differences in percentage retained on the 5.0 mm sieve and percentage passing the 150 µm sieve are rather small and the gradings C and M may be regarded as equivalent to Type A. Furthermore, it can be seen that the declared grading F in CS3: 2013 and BS 882: 1992 is very similar to the grading Type B in BS 1199: 1976. In fact, apart from the possible slightly higher percentage retained on the 5.0 mm sieve of 11%, the grading F would have totally complied with the grading requirements of Type B. In actual practice, such difference in percentage retained on the 5.0 mm sieve is rather small and the grading F may be regarded as equivalent to Type B.

Table 9 Comparison of gradings in BS 1199: 1976 to those in CS3: 2013 and BS 882: 1992

Sieve size	Gradings in BS 1199: 1976		Declared gradings in CS3: 2013 and BS 882: 1992		
	Type A	Type B	C	M	F
10.0 mm	100	100	100	100	100
5.0 mm	95 – 100	95 – 100	89 – 100	89 – 100	89 – 100
2.36 mm	60 – 100	80 – 100	60 – 100	65 – 100	80 – 100
1.18 mm	30 – 100	70 – 100	30 – 90	45 – 100	70 – 100
600 µm	15 – 80	55 – 100	15 – 54	25 – 80	55 – 100
300 µm	5 – 50	5 – 75	5 – 40	5 – 48	5 – 70
150 µm	0 – 15	0 – 20	0 – 20	0 – 20	0 – 20

Table 10 Comparison of gradings in BS 1200: 1976 to those in CS3: 2013 and BS 882: 1992

Sieve size	Gradings in BS 1200: 1976		Declared gradings in CS3: 2013 and BS 882: 1992		
	Type S	Type G	C	M	F
10.0 mm	100	100	100	100	100
5.0 mm	98 – 100	98 – 100	89 – 100	89 – 100	89 – 100
2.36 mm	90 – 100	90 – 100	60 – 100	65 – 100	80 – 100
1.18 mm	70 – 100	70 – 100	30 – 90	45 – 100	70 – 100
600 µm	40 – 100	40 – 100	15 – 54	25 – 80	55 – 100
300 µm	5 – 70	20 – 90	5 – 40	5 – 48	5 – 70
150 µm	0 – 15	0 – 25	0 – 20	0 – 20	0 – 20

Table 10 shows that the gradings Type S and Type G in BS 1200: 1976 are required to have not more than 2% retained on the 5.0 mm sieve and not more than 10% retained on the 2.36 mm sieve. So, Type S and Type G are more like 2.36 mm maximum size aggregates (0/2.36 mm aggregates in European Standard terminology) rather than 5.0 mm maximum size aggregates (0/5.0

mm aggregates in European Standard terminology). On the other hand, the declared gradings C, M and F in CS3: 2013 and BS 882: 1992 are all 5.0 mm maximum size aggregates (0/5.0 mm aggregates). Hence, there is no equivalent grading in CS3: 2013 and BS 882: 1992 for Type S and Type G. In fact, the fine aggregates specified in CS3: 2013 and BS 882: 1992, which all have 5.0 mm maximum aggregate size, are for concrete, not for mortar. For applications in mortar layers having a small thickness, it should be better to use a 2.36 mm maximum size aggregate similar to Type S and Type G in BS 1200: 1976. In this regard, it is noteworthy that in the European Standards BS EN 13139: 2002 and BS EN 13139: 2013, the fine aggregate may be of size 0/2 mm or 0/4 mm. Although we are not strictly following the European Standards, it seems prudent to follow the practice of having a larger maximum size fine aggregate (say, 0/5.0 mm aggregate) and a smaller maximum size fine aggregate (say, 0/2.36 mm aggregate) for different applications.

6.5 Definition of fines

The British Standards, local Construction Standards, Chinese Standards and American Standards define the fines in aggregate as the materials finer than 75 µm or 80 µm, whereas the European Standards define the fines in aggregate as the materials finer than 63 µm. Such slight difference in the definition of fines is not really significant. It is better to stay with the definition of fines being used in Hong Kong, Mainland China and the US, and not to change the definition to follow the European Standards.

6.6 Limits on fines content

There are big differences in the maximum allowable limits on the fines content in the various standards. In BS 882: 1992, the fines content in crushed rock sand for concrete is limited to 16% for general use and to 9% for use in heavy duty floor finishes. In CS3: 2013, the fines content is limited to 14% for general use (with the additional requirement that if the fines content > 10%, the methylene blue value shall be ≤ 1.4) and to 10% for use in heavy duty floor finishes. In BS 1199: 1976 and BS 1200: 1976, the fines content in crushed rock sand for mortar is limited to 5% for rendering and plastering, to 10% for Type S sand for masonry mortar, and to 12% for Type G sand for masonry mortar. In ASTM C33/C33M-13, the fines content in manufactured fine aggregate (i.e. crushed rock fine aggregate) is limited to 5% for concrete subjected to abrasion and to 7% for concrete not subjected to abrasion.

In BS EN 12620: 2002 and BS EN 12620: 2013, no limits are imposed on the fines content in fine aggregates for concrete. In BS EN 13139: 2002, it is stipulated that fine aggregates for mortar are to be classified into four categories: category 1 (fines content ≤ 3%), category 2 (fines content ≤ 5%), category 3 (fines content ≤ 8%), and category 4 (fines content ≤ 30%), which are for the following recommended uses: category 1: floor screeds, sprayed, repair mortars, grout; category 2: rendering and plastering; category 3: masonry mortar not using crushed rock aggregate; and category 4: masonry mortar using crushed rock aggregate. In BS EN 13139: 2013, the categories for maximum fines content are: category f_3 (fines content ≤ 3%), category f_5 (fines content ≤ 5%), category f_8 (fines content ≤ 8%), and category f_{22} (fines content ≤ 22%), and no recommendations of their uses are given anymore. But this does not mean that no limit on the fines content should be specified.

In BSI PD 6682-3: 2003 (a British Standards Institution published document), the recommended maximum fines contents are: for levelling screeds, fines content ≤ 3%, for rendering and plastering, fines content ≤ 5%, for masonry mortar with Type S sand, fines content ≤ 5%, and for masonry mortar with Type G sand, fines content ≤ 8%.

In GB/T 14684: 2001 and JGJ 52: 2006, limits on fines content in fine aggregate are imposed according to source and usage of the fine aggregate. The limits for natural sand in GB/T 14684 (JGJ 52) are: for high strength concrete, fines content < 1.0% (≤ 2.0%); for medium strength concrete, fines content < 3.0% (≤ 3.0%); and for low strength concrete, fines content < 5.0% (≤ 5.0%). The limits for manufactured sand in GB/T 14684 (JGJ 52) are: (1) If the methylene blue test passes, then for high strength concrete, fines content < 3.0% (≤ 5.0%); for medium strength concrete, fines content < 5.0% (≤ 7.0%); and for low strength concrete, fines content < 7.0% (≤ 10.0%). (2) If the methylene blue test fails, then for high strength concrete, fines content < 1.0% (≤ 2.0%); for medium strength concrete, fines content < 3.0% (≤ 3.0%); and for low strength concrete, fines content < 5.0% (≤ 5.0%).

The maximum limits on fines content in fine aggregates for mortar given in the various standards are compared in Table 11.

Table 11 Limits on fines content in fine aggregates for mortar

Standard/ document	Limits on fines content
BS 1199: 1976/ BS 1200: 1976	Crushed rock sand for rendering and plastering: 5% Type S sand for masonry mortar: 10% Type G sand for masonry mortar: 12%
BS EN 13139: 2002	Category 1 (floor screeds, sprayed, repair mortars): ≤ 3% Category 2 (rendering and plastering): ≤ 5% Category 3 (masonry with non-crushed aggregate): ≤ 8% Category 4 (masonry with crushed aggregate): ≤ 30%
BS EN 13139: 2013	Category f_3 : ≤ 3% Category f_5 : ≤ 5% Category f_8 : ≤ 8% Category f_{22} : ≤ 22%
BSI PD 6682-3: 2003	Levelling screed: ≤ 3% Rendering and plastering: ≤ 5% Masonry with Type S sand: ≤ 5% Masonry with Type G sand: ≤ 8%
GB/T 14684: 2001	Natural sand: < 5.0%
	Manufactured sand: If the methylene blue test passes: < 7.0% If the methylene blue test fails: < 5.0%
JGJ 52: 2006	No recommendation

6.7 Assessment of harmfulness of fines

The British Standards do not require any assessment or tests on the harmfulness of the fines in aggregate. The European Standards require tests on the harmfulness of the fines in aggregate but do not give any acceptance criteria for the non-harmfulness of the fines. On the other hand, the Chinese Standards and American Standards require tests on the harmfulness of the fines in aggregate when the fines content exceeds certain limit and specify acceptance criteria for the non-harmfulness of the fines. This is a controversial issue. The BSI PD 6682-3 points out that the sand equivalent and methylene blue tests for assessing the harmfulness of the fines in aggregate are not sufficiently precise for the purpose of determining the harmful fines content in aggregate. It recommends that aggregates and filler aggregates should be assessed for harmful fines using either a fines content limit or evidence of satisfactory use. Nevertheless, the new Construction Standard CS3: 2013 requires the methylene blue test to be carried out and the methylene blue value to be not greater than 1.4 when the fines content is higher than 10%.

6.8 Distinction between aggregates for concrete and aggregates for mortar

In the British Standards and the European Standards, very clear distinction is made between aggregates for concrete and aggregates for mortar but in the Chinese Standards and American Standards, aggregates for concrete and aggregates for mortar are not clearly differentiated. Apparently, the Chinese Standards and American Standards are more for aggregates for concrete rather than for aggregates for mortar. It should be better to clearly differentiate aggregates for concrete and aggregates for mortar because their requirements are not the same. Nevertheless, the standard on aggregates for mortar should be compatible with the standard on aggregates for concrete so that the same terms would have the same meanings in the two standards, the same test methods may be used for both aggregates for concrete and aggregates for mortar, and some of the aggregate products may be used for both concrete and mortar.

7. Summary and Recommendations

From the above review, it is seen that the standard sieve sizes, demarcation between coarse and fine aggregates, and definition of fines vary from one standard to another standard. As the standard sieve sizes, demarcation between coarse and fine aggregates, and definition of fines in the British Standards that have been in use in Hong Kong for a long time are almost the same as those in the Chinese Standards and some of the quarries are supplying aggregate to both the Hong Kong market and the Mainland China market, it is better from the market operation point of view to stay with the standard sieve sizes, demarcation between coarse and fine aggregates, and definition of fines in the British Standards. This will also avoid the trouble of changing from an established practice to a totally new practice, save the cost of buying new equipment and help to preserve our previous experience for future use.

In general, different requirements are imposed on aggregates for concrete and aggregates for mortar. This is because concrete and mortar have different performance attributes and the quality of fine aggregate has different effects on concrete and mortar. Hence, aggregates for concrete and aggregates for mortar should be clearly differentiated.

For both aggregates for concrete and aggregates for mortar, the major issues seem to be the limits to be imposed on the fines content and the assessment of the harmfulness of the fines content. The fines content needs to be limited for the following reasons. In concrete, any harmful substances, such as clay, in the fines would adversely affect the abrasive resistance, maximum achievable strength, and durability of the concrete. Moreover, since the fines content has very large specific surface area, its quantity would affect the water and superplasticizer demands and thus also the workability of the concrete. The presence of high fines content in the concrete would render the concrete more cohesive, but this has little effect on the concreting operation. In mortar, the presence of clay or excessive fines would adversely affect the abrasive resistance, maximum achievable strength and workability of the mortar. Moreover, the increase in water demand due to higher fines content would force the worker to add more water to improve the workability of the mortar and thus cause the hardened mortar to have a relatively large drying shrinkage and a higher risk of shrinkage cracking. More importantly, the increase in cohesiveness and paste volume due to the presence of excessive fines would render the mortar too sticky and slippery to be properly trowelled because the mortar tends to stick to the trowel and slip downwards.

On the other hand, there are still no established methods for assessing the harmfulness of fines in aggregate and no established acceptance criteria for the non-harmfulness of fines. The BSI PD 6682-3 recommends that aggregates should better be assessed for harmful fines using either a fines content limit or evidence of satisfactory use. This seems to be a pragmatic way of avoiding the controversies regarding the methods of assessment and acceptance criteria. Hence, another reason for limiting the fines content is to reduce the risk of having harmful substance in the aggregate.

Lastly, whilst the fine aggregates stipulated in BS 1199: 1976, BS 1200: 1976, BS 882: 1992 and CS3: 2013 all have a maximum aggregate size of 5.0 mm, the fine aggregates in BS EN 13139: 2002 and BS EN 13139: 2013 may have a maximum aggregate size of 4.0 mm or 2.0 mm. Although we are not strictly following the European Standards, it seems prudent to follow the practice of having fine aggregates with different maximum aggregate sizes (of say, 5.0 mm and 2.36 mm) for different applications.

Based on the above, it is recommended that a separate local construction standard on aggregate for mortar should be produced. However, it should be compatible with CS3: 2013 so that the same terms would have the same meanings in the two standards, the same test methods may be used for both aggregates for concrete and aggregates for mortar, and some of the aggregate products may be used for both concrete and mortar. Moreover, unlike the previous standards on aggregates for concrete or mortar, which stipulate the maximum aggregate size of fine aggregate as 5.0 mm, the fine aggregate for mortar should be allowed to have a maximum aggregate size of 5.0 mm or 2.36 mm to suit different applications. Finally, although there are big differences in the maximum allowable limits on the fines content in the various standards, and the new European Standard BS EN 13139: 2013 does not impose any precise limits on the fines contents and no longer gives any examples of usage of the various categories of fine aggregates with different fines content limits, it is still considered prudent to impose fines content limits based on the fines content limits previously given in BS 1199: 1976, BS 1200: 1976, BS EN 13139: 2002, and BSI PD 6682-3: 2003 (a summary of these fines content limits has been given in Table 11).

- End of Appendix A -

Appendix B

Report on Laboratory Tests on Effects of Fines Content in Fine Aggregate and Possible Uses of Crushed Waste Glass and Recycled Fine Aggregate

1. Introduction

In the research project "Research on River Sand Substitutes for Concrete Production and Cement Sand Mortar Production (Phase Two)", laboratory tests are required to study:

(1) the effects of fines content in fine aggregate on the performance of concrete;

(2) the effects of fines content in fine aggregate on the performance of mortar;

(3) the feasibility of using crushed waste glass as aggregate for mortar; and

(4) the feasibility of using recycled old concrete as aggregate for concrete and mortar.

For the above required studies, the laboratory testing program was designed to comprise of four parts, each reported separately in the following sections.

2. Effects of Fines Content in Fine Aggregate on Performance of Concrete

This part of the testing program was to study the effects of fines content on performance of concrete so as to determine the optimum and allowable fines contents in aggregate for concrete.

From the literature review in "Research on River Sand Substitutes for Concrete Production and Cement Sand Mortar Production (Phase One)", it has been found that the maximum limits imposed on the fines content in aggregate for concrete vary from one standard to another. Whilst no limits are imposed in the European Standards, the limits imposed in the Chinese Standards and American Standards are rather stringent. Up to now, there is no general consensus regarding the effects of the fines content on the performance of the concrete produced and therefore the allowable fines content in fine aggregate for concrete has remained a controversial issue.

After completion of the Phase One study, there were some changes in the aggregate standards. In the year 2013, a new Hong Kong Standard CS3: 2013 – Aggregates for concrete, a new European Standard BS EN 12620: 2013 – Aggregates for concrete, and a new American Standard ASTM C33/C33M-13 – Standard specification for concrete aggregates were published. These three standards are highly relevant to the present study and thus have been reviewed and summarized in a Literature Review Report submitted separately.

The Hong Kong Standard CS3: 2013 is largely based on the British Standard BS 882: 1992. There are, however, two major differences between CS3: 2013 and BS 882: 1992. Firstly, the BS 882: 1992 imposes limits on the fines content in fine aggregate as: for use in heavy duty floor finishes, 9%; and for general use, 16%. In contrast, the CS3: 2013 imposes limits on the fines content in fine aggregate as: for Class I (use in heavy duty floor finishes), 10%; and for Class II (general use), 14%. Secondly, the BS 882: 1992 does not require checking of the cleanliness of the fine aggregate. In contrast, the CS3: 2013 imposes the requirement on the cleanliness of the fine aggregate as: if the fines content > 10%, the methylene blue value shall be ≤ 1.4. The lower fines content limit of 14% and the new requirement on cleanliness in the CS3: 2013 are to improve the general quality of the fine aggregate.

On the other hand, the European Standard BS EN 12620: 2013 is the newest European Standard on aggregates for concrete. In the European Standard, the standard sieve sizes are totally different from those in the British Standards, the demarcation between coarse aggregate and fine aggregate is a particle size of 4 mm, and the definition of fines is the size fraction finer than 63 µm. As in the 2002 version, there are no limits imposed on the fines contents in the aggregate. The aggregate producer is allowed to declare the maximum fines content in accordance with specified categories. Moreover, provided the aggregate producer declares the maximum fines content in the aggregate and exercise tight control of the fines content, fairly high fines contents are allowed. Compared to the 2002 version, the requirements on fines quality in the 2013 version are more explicitly spelled out. However, no precise limits have been given for the fines content, sand equivalent value and methylene blue value. These limits shall be established from experience of existing requirements of materials in local satisfactory use according to the provisions valid in the place of use of the aggregate.

The American Standard ASTM C33/C33M-13 is also the newest American Standard on aggregates for concrete. In the American Standard, the standard sieve sizes, the demarcation between coarse aggregate and fine aggregate and the definition of fines are similar to those in the Hong Kong Standard CS3: 2013 and the British Standard BS 882: 1992. For manufactured fine aggregate (i.e. crushed rock fine aggregate), if the fines content consists of dust of fracture, essentially free of clay or shale, the fines content limit is imposed as 5% for concrete subjected to abrasion and as 7% for concrete not subjected to abrasion. These limits on the fines content are rather low and comparable to those in the Chinese Standards GB/T 14684: 2001 and JGJ 52: 2006. Manufactured fine aggregate with less than 4% finer than 2 µm and with methylene blue adsorption value less than 5 mg/g is considered suitable for use in concrete. However, fine aggregate that exceeds these values also may be considered suitable provided that fresh and hardened concrete properties are shown to be acceptable.

The literature review revealed that there are big differences in the maximum allowable limits on the fines content in the various standards. In BS 882: 1992, the fines content in crushed rock sand for concrete is limited to 16% for general use and to 9% for use in heavy duty floor finishes. In CS3: 2013, the fines content is limited to 14% for general use (with the additional requirement that if the fines content > 10%, the methylene blue value shall be ≤ 1.4) and to 10% for use in heavy duty floor finishes. However, in BS EN 12620: 2002 and BS EN 12620: 2013, no limits are imposed on the fines content in fine aggregates for concrete. In ASTM C33/C33M-13, the fines content in manufactured fine aggregate (i.e. crushed rock fine aggregate) is limited to 5%

for concrete subjected to abrasion and to 7% for concrete not subjected to abrasion. Hence, even after publication of the three new standards, there is still no general consensus regarding the effects of the fines content on the performance of the concrete produced and the allowable fines content in fine aggregate for concrete has remained a controversial issue. We are left to ourselves to determine by experiments the optimum and allowable fines contents in aggregate for concrete.

To study the effects of the fines content in fine aggregate on the overall performance of the concrete produced, a testing program has been worked out, as depicted in Table 1 below. In the testing program, there are four combinations of water/cement (W/C) ratio ranging from 0.30 to 0.60, three combinations of paste volume (PV) ranging from 25% to 35%, four combinations of fines content ranging from 6% to 15%, and two combinations of superplasticizer (SP) dosage ranging from no SP added to SP added (however, the SP dosage when added varied from 1.0 litre/m^3 of concrete at a W/C ratio of 0.60 to 4.0 litre/m^3 of concrete at a W/C ratio of 0.30). During the course of testing, some of the concrete mixes were found to be too dry to be mixed and therefore not tested. For this reason, the actual number of concrete mixes produced for testing was 80.

Table 1. Testing program on effects of fines content on concrete

Water/ cement ratio	Paste volume (%)	Fines content (%)	SP dosage (litre/m^3)
0.30	25	6, 9, 12, 15	0, 4
	30	6, 9, 12, 15	0, 4
	35	6, 9, 12, 15	0, 4
0.40	25	6, 9, 12, 15	0, 3
	30	6, 9, 12, 15	0, 3
	35	6, 9, 12, 15	0, 3
0.50	25	6, 9, 12, 15	0, 2
	30	6, 9, 12, 15	0, 2
	35	6, 9, 12, 15	0, 2
0.60	25	6, 9, 12, 15	0, 1
	30	6, 9, 12, 15	0, 1
	35	6, 9, 12, 15	0, 1

The fine aggregate (FA) and coarse aggregate (CA) used in the tests were crushed granite rock aggregates obtained from the local market. These aggregates are the same as those being used by some concrete producers in Hong Kong. The particle size distributions of the FA (with the fines content removed) and the CA, as determined by mechanical sieving, are presented in Figure 1. The relative densities of the FA and CA were measured as 2.54 and 2.61, respectively. The water absorptions of the FA, 10 mm CA and 20 mm CA were measured as 1.81%, 1.04% and 0.61%, respectively. From time to time, the moisture contents of the fine and coarse aggregates were measured and the water absorptions of the aggregates were allowed for in determining the amount of water to be added to the trial concrete mixes.

Samples of the fine aggregate have been sent to Anderson Concrete Ltd and Gammon Construction Ltd for methylene blue tests. The MB value obtained by Anderson Concrete Ltd was 0.8 while the MB value obtained by Gammon Construction Ltd was 1.0. Hence, the fines content in the fine aggregate may be regarded as of good quality containing little deleterious materials.

To produce fine aggregates with the prescribed fines contents of 6%, 9%, 12% or 15%, the fines content in the fine aggregate was first removed by mechanical sieving so that the fine aggregate contained a fines content of exactly 0%. Then, the right amount of fines was put back into the fine aggregate so that the fine aggregate contained the prescribed fines content.

Regarding the cement used, it was an ordinary Portland cement (OPC) of strength class 52.5 N complying with BS EN 197-1: 2000. The relative density of the cement has been measured in accordance with BS EN 196-6: 2010 as 3.11. Regarding the superplasticizer (SP) used, it was a polycarboxylate-based SP commonly used in Hong Kong. It has a solid content of 20% and a relative density of 1.03.

For the OPC and the fines content (the portion of fine aggregate finer than 75 μm), the particle size distributions were measured using a laser diffraction particle size analyzer, as presented in Figure 1.

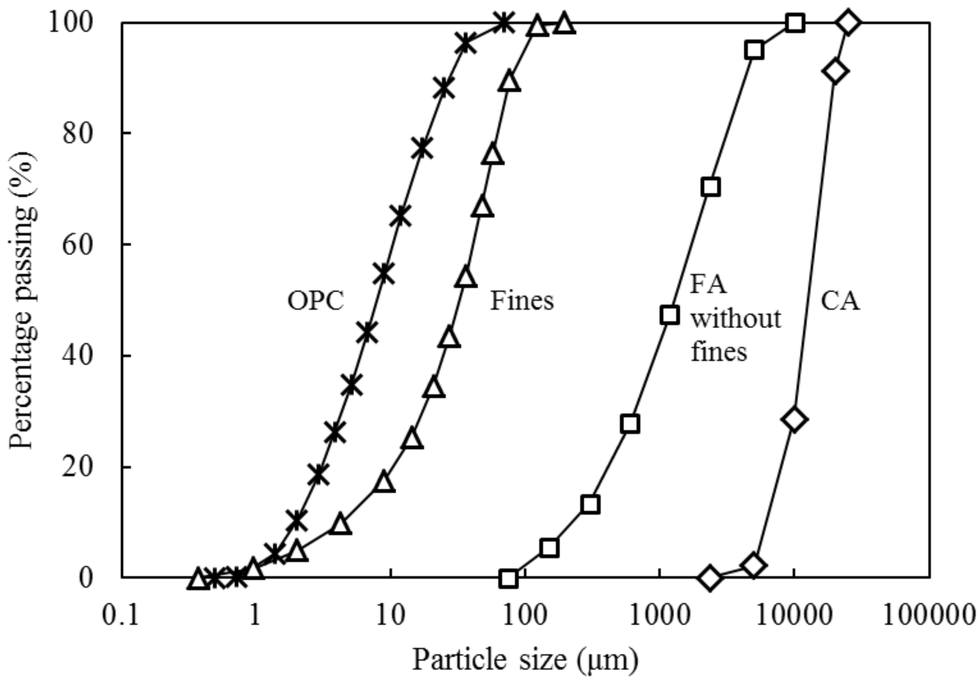

Figure 1. Particle size distributions of OPC, fines, FA without fines and CA

A pan mixer was used to mix the ingredients in the trial concrete mix. Electronic balances were used to weigh the correct quantities of ingredients to be added to the mixer. During mixing, all the solid ingredients were added at the same time to the mixer. After about one minute of dry mixing, water was added to the mixer and the concrete mix was further mixed for two minutes. If SP was to be added, it was added last and after adding, the concrete mix was further mixed for another two minutes.

Upon completion of mixing, a fresh sample was taken from the mixer for the slump-flow test. The slump-flow test was carried out using the standard slump cone in accordance with BS EN 12350-8: 2010 (in this European Standard, the slump measurement is the same as that in CS1: 2010, but the flow spread measurement is very different from that in CS1: 2010). After placing the fresh concrete into the slump cone and lifting the slump cone vertically upwards, the drop in height of the concrete was taken as the slump (a measure of deformability) and the average value of two perpendicular diameters of the concrete patty formed was taken as the flow spread (a measure of flowability). It should be noted that since the base diameter of the slump cone is 200 mm, a flow spread of 200 mm actually means no flowability.

After the slump-flow test, the edge of the concrete patty was observed for any sign of segregation. If there was a strip of cement paste/mortar with no coarse aggregate at the edge, the average width of the strip of cement paste/mortar was measured and recorded as the segregation width. A segregation width of not more than 10 mm should be considered acceptable but a segregation width of larger than 10 mm indicates unacceptable segregation.

Meanwhile, another fresh sample was taken from the mixer for sieve segregation test. The sieve segregation test was carried out using a 5 mm test sieve in accordance with BS EN 12350-11: 2010 (this test has become a standard test for self-consolidating concrete). The weight of concrete mix dripped through the sieve and collected by a base receiver was measured and expressed as a percentage of the weight of concrete mix poured onto the sieve. The result so obtained is recorded as the sieve segregation index of the concrete mix. A sieve segregation index of not higher than 10% should be considered acceptable but a sieve segregation index of higher than 10% indicates unacceptable segregation.

Finally, after completion of the slump-flow and sieve segregation tests, all the concrete samples were put back into the mixer and remixed. Then, six 100 mm concrete cubes were cast from the remixed fresh concrete. After casting, the concrete cubes, together with their moulds, were covered and stored in the laboratory. At 24 hours after casting, the cubes were demoulded and put into a lime-saturated water curing tank controlled at a temperature of 27 ± 2 °C. Three of the cubes were tested at the age of 7 days and the remaining three of the cubes were tested at the age of 28 days. The average value of the measured strengths of the three cubes tested at the age of 7 days was taken as the 7-day cube strength while the average value of the measured strengths of the three cubes tested at the age of 28 days was taken as the 28-day cube strength.

The detailed test results are presented in the following tables.

Table 2. Test results of concrete mixes with W/C = 0.6 and SP = 0 litre/m^3

Mix no. (W/C-PV-Fines%-SP)	Slump (mm)	Flow spread (mm)	Segregation width (mm)	Sieve segregation index (%)	7-day cube strength (MPa)	28-day cube strength (MPa)
0.60-25-6-0	0	200	0	0.0	40.4	51.1
0.60-25-9-0	3	200	0	0.0	44.7	55.4
0.60-25-12-0	3	200	0	0.0	43.8	56.0
0.60-25-15-0	0	200	0	0.0	44.5	56.2
0.60-30-6-0	15	200	0	0.1	37.3	51.6
0.60-30-9-0	30	200	0	0.0	39.3	52.5
0.60-30-12-0	25	203	0	0.0	41.3	53.8
0.60-30-15-0	35	200	0	0.0	41.1	53.3
0.60-35-6-0	160	250	0	0.2	35.4	49.7
0.60-35-9-0	125	220	0	0.0	33.6	49.8
0.60-35-12-0	125	273	0	0.1	31.5	43.5
0.60-35-15-0	105	213	0	0.0	33.9	46.4

These results show that:
(1) at PV > 30%, the fines content has significant adverse effect on the workability and at PV ≤ 30%, the workability is too low to reveal any effect of the fines content on the workability; and
(2) the fines content has little effect on the strength.

Table 3. Test results of concrete mixes with W/C = 0.5 and SP = 0 litre/m^3

Mix no. (W/C-PV-Fines%-SP)	Slump (mm)	Flow spread (mm)	Segregation width (mm)	Sieve segregation index (%)	7-day cube strength (MPa)	28-day cube strength (MPa)
0.50-25-6-0	0	200	0	0.2	61.6	71.8
0.50-25-9-0	0	200	0	0.1	61.2	69.4
0.50-25-12-0	0	200	0	0.0	61.6	68.3
0.50-25-15-0	0	200	0	0.1	61.0	65.1
0.50-30-6-0	19	200	0	0.1	59.9	71.1
0.50-30-9-0	10	200	0	0.1	55.5	67.0
0.50-30-12-0	15	200	0	0.1	54.9	67.3
0.50-30-15-0	10	200	0	0.1	57.1	68.8
0.50-35-6-0	95	200	0	0.1	48.8	65.2
0.50-35-9-0	55	200	0	0.1	54.9	66.6
0.50-35-12-0	40	200	0	0.0	51.1	68.1
0.50-35-15-0	30	200	0	0.1	51.5	68.7

These results show that:
(1) at PV > 30%, the fines content has significant adverse effect on the workability and at PV ≤ 30%, the workability is too low to reveal any effect of the fines content on the workability; and
(2) the fines content has little effect on the strength.

Table 4. Test results of concrete mixes with W/C = 0.4 and SP = 0 litre/m^3

Mix no. (W/C-PV-Fines%-SP)	Slump (mm)	Flow spread (mm)	Segregation width (mm)	Sieve segregation index (%)	7-day cube strength (MPa)	28-day cube strength (MPa)
0.40-25-6-0	Much too dry to be mixed					
0.40-25-9-0						
0.40-25-12-0						
0.40-25-15-0						
0.40-30-6-0	0	200	0	0.0	68.3	78.9
0.40-30-9-0	0	200	0	0.0	64.9	69.6
0.40-30-12-0	0	200	0	0.0	64.3	74.9
0.40-30-15-0	0	200	0	0.0	64.5	70.6
0.40-35-6-0	17	200	0	0.0	63.0	72.7
0.40-35-9-0	15	200	0	0.0	61.1	72.7
0.40-35-12-0	10	200	0	0.0	60.3	71.8
0.40-35-15-0	5	200	0	0.0	62.5	74.4

These results show that:
(1) at PV > 30%, the fines content has significant adverse effect on the workability and at PV ≤ 30%, the workability is too low to reveal any effect of the fines content on the workability; and
(2) the fines content has little effect on the strength.

Table 5. Test results of concrete mixes with W/C = 0.3 and SP = 0 litre/m^3

Mix no. (W/C-PV-Fines%-SP)	Slump (mm)	Flow spread (mm)	Segregation width (mm)	Sieve segregation index (%)	7-day cube strength (MPa)	28-day cube strength (MPa)
0.30-25-6-0	Much too dry to be mixed					
0.30-25-9-0						
0.30-25-12-0						
0.30-25-15-0						
0.30-30-6-0	Much too dry to be mixed					
0.30-30-9-0						
0.30-30-12-0						
0.30-30-15-0						
0.30-35-6-0	0	200	0	0.1	71.5	88.1
0.30-35-9-0	0	200	0	0.1	70.1	82.8
0.30-35-12-0	0	200	0	0.1	72.8	79.8
0.30-35-15-0	0	200	0	0.3	64.9	72.2

These results show that:
(1) the workability is too low to reveal any effect of the fines content on the workability; and
(2) a fines content of up to 9% has little effect on the strength, but a fines content of 12% or more has significant adverse effect on the strength due to difficulties in compaction.

Table 6. Test results of concrete mixes with W/C = 0.6 and SP = 1 litre/m^3

Mix no. (W/C-PV-Fines%-SP)	Slump (mm)	Flow spread (mm)	Segregation width (mm)	Sieve segregation index (%)	7-day cube strength (MPa)	28-day cube strength (MPa)
0.60-25-6-1	10	200	0	0.2	45.0	53.6
0.60-25-9-1	5	200	0	0.0	47.0	55.9
0.60-25-12-1	5	200	0	0.0	44.8	53.9
0.60-25-15-1	0	200	0	0.1	46.8	53.6
0.60-30-6-1	140	435	0	0.9	38.3	47.8
0.60-30-9-1	35	200	0	0.3	41.0	50.6
0.60-30-12-1	20	200	0	0.0	44.5	53.3
0.60-30-15-1	35	200	0	0.0	43.0	51.9
0.60-35-6-1	205	408	0	0.5	37.3	49.9
0.60-35-9-1	170	363	0	0.9	38.1	49.0
0.60-35-12-1	155	340	0	1.5	39.5	51.0
0.60-35-15-1	84	305	0	1.1	41.5	50.6

These results show that:
(1) the fines content has significant adverse effect on the workability; and
(2) the fines content has little effect on the strength.

Table 7. Test results of concrete mixes with W/C = 0.5 and SP = 2 litre/m^3

Mix no. (W/C-PV-Fines%-SP)	Slump (mm)	Flow spread (mm)	Segregation width (mm)	Sieve segregation index (%)	7-day cube strength (MPa)	28-day cube strength (MPa)
0.50-25-6-2	0	200	0	0.0	60.5	71.1
0.50-25-9-2	2	200	0	0.0	59.9	70.4
0.50-25-12-2	2	200	0	0.0	59.5	67.9
0.50-25-15-2	0	200	0	0.0	58.9	67.0
0.50-30-6-2	187	443	0	0.4	54.2	64.4
0.50-30-9-2	65	200	0	0.0	57.2	66.8
0.50-30-12-2	56	200	0	0.0	60.3	68.0
0.50-30-15-2	27	200	0	0.0	56.9	65.3
0.50-35-6-2	200	500	19	2.3	54.9	65.7
0.50-35-9-2	218	543	0	3.2	54.2	64.0
0.50-35-12-2	177	419	0	0.1	55.1	63.2
0.50-35-15-2	146	297	0	0.1	56.2	64.0

These results show that:
(1) the fines content has significant adverse effect on the workability; and
(2) the fines content has little effect on the strength.

Table 8. Test results of concrete mixes with W/C = 0.4 and SP = 3 litre/m^3

Mix no. (W/C-PV-Fines%-SP)	Slump (mm)	Flow spread (mm)	Segregation width (mm)	Sieve segregation index (%)	7-day cube strength (MPa)	28-day cube strength (MPa)
0.40-25-6-3	5	200	0	0.4	78.6	90.5
0.40-25-9-3	1	200	0	0.8	76.4	86.5
0.40-25-12-3	6	200	0	0.3	74.3	87.4
0.40-25-15-3	0	200	0	0.5	68.9	82.7
0.40-30-6-3	18	200	0	0.0	75.2	87.9
0.40-30-9-3	34	200	0	0.0	75.3	84.9
0.40-30-12-3	16	200	0	0.0	73.1	84.3
0.40-30-15-3	11	200	0	0.1	70.6	83.4
0.40-35-6-3	231	559	0	1.6	72.3	87.0
0.40-35-9-3	184	398	0	0.0	72.1	84.1
0.40-35-12-3	110	200	0	0.0	69.0	80.3
0.40-35-15-3	34	200	0	0.0	70.2	81.8

These results show that:
(1) the fines content has significant adverse effect on the workability; and
(2) the fines content has little effect on the strength.

Table 9. Test results of concrete mixes with W/C = 0.3 and SP = 4 litre/m^3

Mix no. (W/C-PV-Fines%-SP)	Slump (mm)	Flow spread (mm)	Segregation width (mm)	Sieve segregation index (%)	7-day cube strength (MPa)	28-day cube strength (MPa)
0.30-25-6-4	Much too dry to be mixed					
0.30-25-9-4						
0.30-25-12-4						
0.30-25-15-4						
0.30-30-6-4	0	200	0	0.2	88.4	100.3
0.30-30-9-4	0	200	0	0.3	85.8	96.0
0.30-30-12-4	0	200	0	0.6	81.2	90.0
0.30-30-15-4	0	200	0	0.5	83.4	96.3
0.30-35-6-4	5	200	0	0.0	87.8	100.6
0.30-35-9-4	0	200	0	0.0	84.8	97.0
0.30-35-12-4	1	200	0	0.2	83.9	94.8
0.30-35-15-4	0	200	0	0.2	83.6	93.9

These results show that:
(1) the fines content has significant adverse effect on the workability; and
(2) a fines content of up to 9% has little effect on the strength, but a fines content of 12% or more has significant adverse effect on the strength due to difficulties in compaction.

For detailed analysis, the slump and flow spread results are plotted against the fines content in Figures 2 and 3.

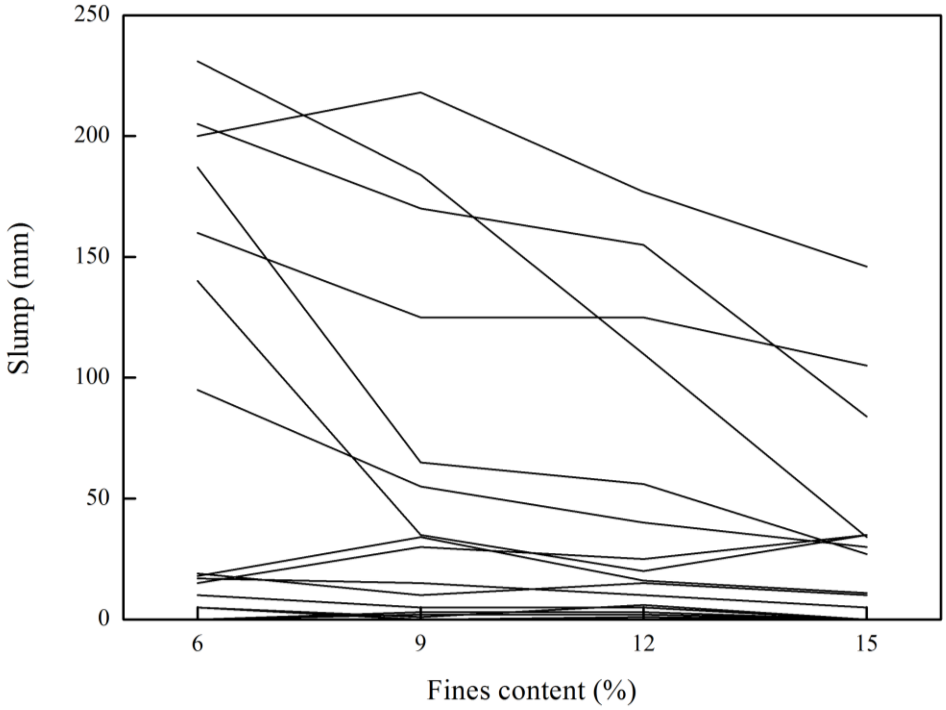

Figure 2. Slump plotted against fines content in fine aggregate

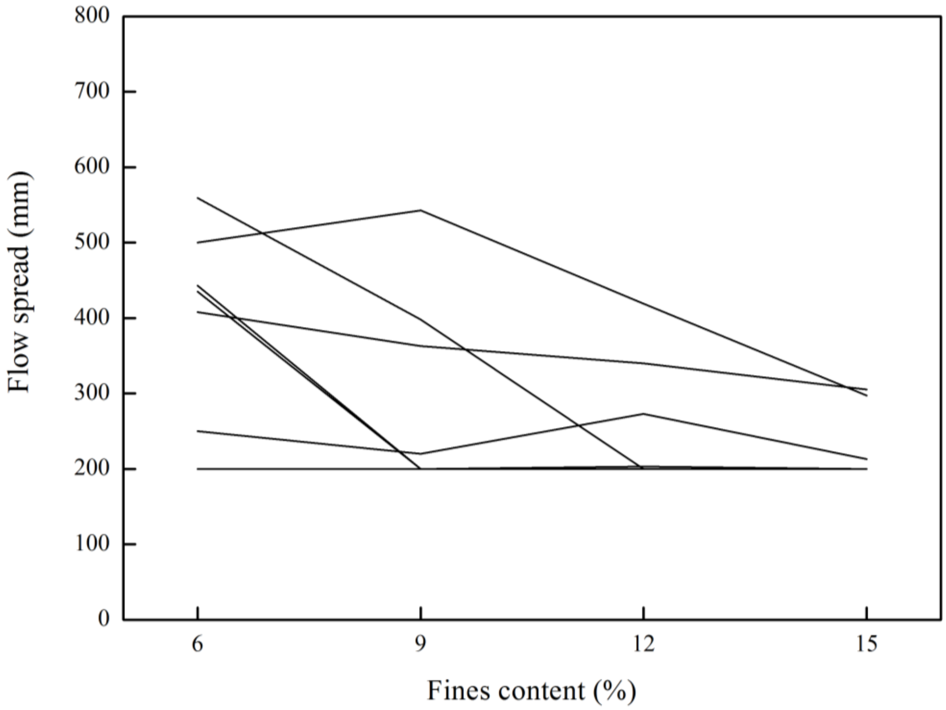

Figure 3. Flow spread plotted against fines content in fine aggregate

For detailed analysis, the 7-day strength and 28-day strength results are plotted against the fines content in Figures 4 and 5.

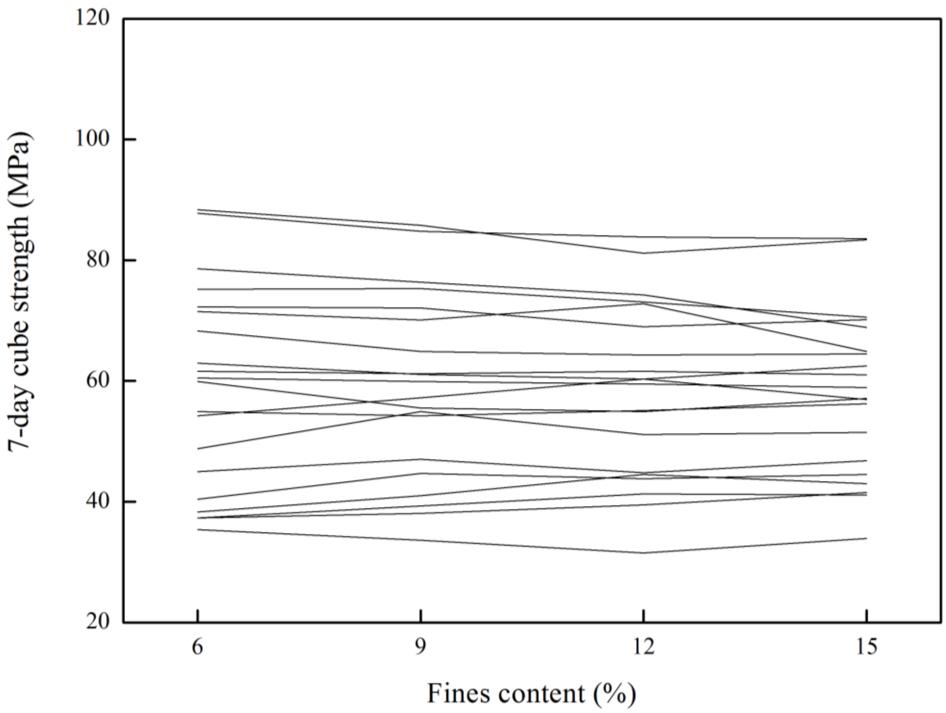

Figure 4. 7-day cube strength plotted against fines content in fine aggregate

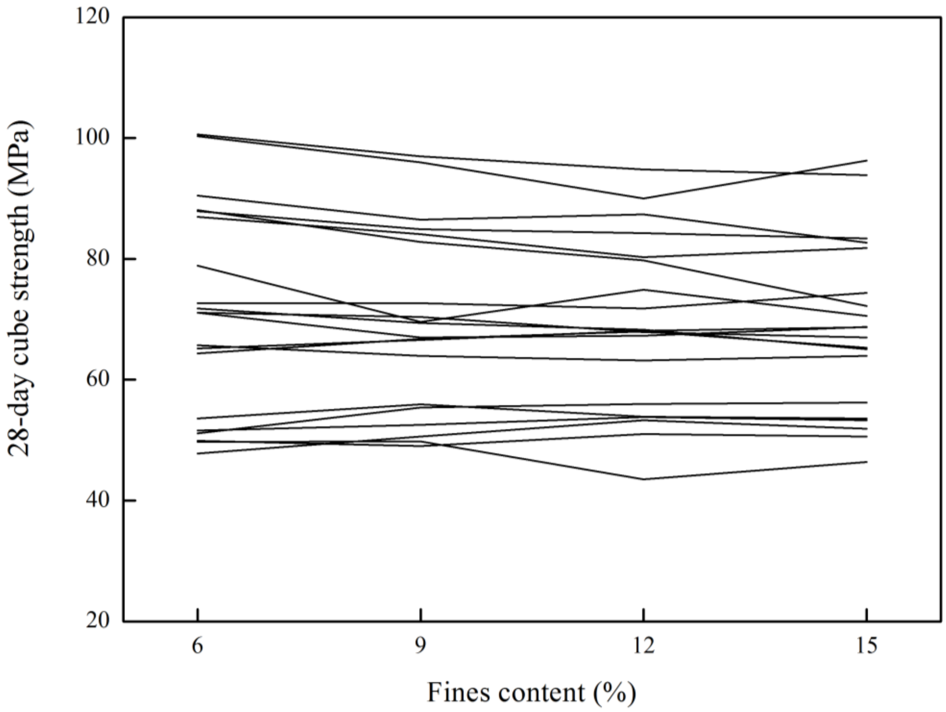

Figure 5. 28-day cube strength plotted against fines content in fine aggregate

The test results of the concrete mixes, without or with superplasticizer added, reveal the following effects of the fines content on the performance of concrete:

(1) The fines content has significant adverse effect on the workability of concrete, except at very low slump or flow spread, in which case, the effect of fines content on workability is not revealed.

(2) The fines content has little effect on the strength, except at W/C = 0.3, in which case, a fines content of 12% or higher has significant adverse effect on the strength due to difficulties in compaction caused by the high fines content.

(3) Although the segregation width and sieve segregation index results indicate no segregation and high cohesiveness for all the concrete mixes tested, hands on experience with the concrete mixes reveals that generally, a concrete mix with a higher fines content is more sticky, or in other words has a higher cohesiveness or a higher segregation resistance. Hence, the fines content has certain beneficial effect on the cohesiveness and segregation resistance of concrete.

Overall, a higher fines content in the fine aggregate would lead to a lower workability of the concrete produced but if the fines content does not exceed 10%, the decrease in workability can be more than compensated by adding more superplasticizer. Hence, it may be said that provided the fines content in the fine aggregate is of good quality and contains little deleterious materials, a fines content of up to 10% may be considered acceptable.

A fines content of higher than 10% may still be considered acceptable if trial concrete mixing has demonstrated that the required workability can still be achieved without using an excessively high dosage of superplasticizer. Even then, it is still considered advisable to set a certain maximum limit to the fines content. In CS3: 2013, the fine content is limit to 14% for general use (with the additional requirement that if the fines content > 10%, the methylene blue value shall be ≤ 1.4) and to 10% for use in heavy duty floor finishes. These are very reasonable maximum limits to be imposed. Another reason of setting a maximum limit to the fines content is that in practice, the fines content could fluctuate quite substantially within the specified limit and if the fluctuation in fines content is too large, the workability of the concrete produced would vary from time to time and the concrete producer might find it difficult to adjust the superplasticizer dosage to compensate for the variation in workability. In this regard, the concrete producer is advised to check regularly the actual fines content in the fine aggregate (perhaps for each consignment).

Moreover, it has been found from this study that at a low W/C ratio of 0.3, a fines content of 12% or higher has significant adverse effect on the strength due to difficulties in compaction caused by the high fines content. Since the W/C ratio of high-strength concrete tends to be low, it is recommended that for the production of high-strength concrete, the fines content should be limited to not higher than 10%. In other words, the fines content should be limited to 10% not only for use in heavy duty floor finishes, but also for use in high-strength concrete.

3. Effects of Fines Content in Fine Aggregate on Performance of Mortar

This part of the testing program was to study the effects of fines content on performance of mortar so as to determine the optimum and allowable fines contents in aggregate for mortar.

Unprocessed crushed rock fine is not really suitable as aggregate for mortar works. There are two major issues in the use of crushed rock fine as aggregate for mortar works. Firstly, the fines content would greatly affect the water demand of the mortar. Secondly, the use of a smaller size aggregate would improve the trowelabilty of the mortar. However, there has been little research on the effects of the fines content and maximum size of the fine aggregate on the performance of mortar.

From the literature review in "Research on River Sand Substitutes for Concrete Production and Cement Sand Mortar Production (Phase One)", it has been found that the maximum limits imposed on the fines content in aggregate for mortar vary from one standard to another. In the British Standards BS 1199: 1976 and BS 1200: 1976, the fines content in crushed rock sand for mortar is limited to 5% for rendering and plastering and to 10% for type S sand for masonry mortar and 12% for type G sand for masonry mortar. In the European Standard BS EN 13139: 2002, it is stipulated that fine aggregates for mortar are to be classified into four categories: category 1 (fines content ≤ 3%), category 2 (fines content ≤ 5%), category 3 (fines content ≤ 8%), and category 4 (fines content ≤ 30%), which are for the following recommended uses: category 1: floor screeds, sprayed, repair mortars, grout; category 2: rendering and plastering; category 3: masonry mortar not using crushed rock aggregate; and category 4; masonry mortar using crushed rock aggregate. In the Chinese Standards GB/T 14684 and JGJ 52, there is no distinction between aggregate for concrete and aggregate for mortar and very stringent limits are imposed on the fines content in fine aggregate, depending on the source of aggregate. Up to now, there is no general consensus regarding the effects of the fines content on the performance of the mortar produced and therefore the allowable fines content in fine aggregate for mortar has remained a controversial issue.

After completion of the Phase One study, there were some changes in the aggregate standards. In the year 2013, a new Hong Kong Standard CS3: 2013 – Aggregates for concrete, a new European Standard BS EN 12620: 2013 – Aggregates for concrete, and a new American Standard ASTM C33/C33M-13 – Standard specification for concrete aggregates were published. However, these standards are on aggregates for concrete, not aggregates for mortar. Nevertheless, a new European Standard BS EN 13139: 2013 – Aggregates for mortar was also published. This standard is highly relevant to the present study and thus has been reviewed and summarized in a Literature Review Report submitted separately.

The European Standard BS EN 13139: 2013 is the newest European Standard on aggregates for mortar. It is an update of BS EN 13139: 2002. The standard sieve sizes, the definition of fine aggregate as particles smaller than 4 mm, and the definition of fines as particles finer than 63 μm have not changed and remained the same as those in the 2002 version. As before, there are no limits imposed on the fines contents in the fine aggregate. The aggregate producer is allowed to just declare the maximum fines content in accordance with certain specified categories. However, the specified categories of fines content in the 2013 version are not the same as the specified categories of fines content in the 2002 version, as summarized below.

In the 2002 version, the categories for maximum values of fines content are:
category 1 – fines content ≤ 3%;
category 2 – fines content ≤ 5%;
category 3 – fines content ≤ 8%; and
category 4 – fines content ≤ 30%.
Furthermore, examples of end uses for the different categories are given as:
category 1: floor screeds, sprayed, repair mortars, grouts (all aggregates)
category 2: rendering and plastering mortars (all aggregates)
category 3: masonry mortars (excluding crushed rock aggregate)
category 4: masonry mortars (crushed rock aggregate)

In the 2013 version, the categories for maximum values of fines content are:
category f_3 – fines content ≤ 3%;
category f_5 – fines content ≤ 5%;
category f_8 – fines content ≤ 8%; and
category f_{22} – fines content ≤ 22%.
No examples of end uses for the different categories are given any more (i.e., no restrictions on the possible uses of the different categories are imposed).

Hence, even after the publication of the new European Standard, there is still no general consensus regarding the effects of the fines content on the performance of the mortar produced and the allowable fines content in fine aggregate for mortar has remained a controversial issue. We are left to ourselves to determine by experiments the optimum and allowable fines contents in aggregate for mortar.

To study the effects of fines content and maximum size of aggregate on the overall performance of mortar, a testing program has been worked out, as depicted in Table 10 below. In the testing program, there are four combinations of water/cement (W/C) ratio ranging from 0.30 to 0.60, two combinations of paste volume (PV) ranging from 42% to 48%, two combinations of maximum size of aggregate (MSA) ranging from 2.36 mm to 5.0 mm, and four combinations of fines content ranging from 2% to 10%. No superplasticizer was added to any of the mortar mixes. During the course of testing, some of the mortar mixes were found to be too dry to be mixed and therefore not produced for testing. Moreover, it was found that a PV of 42% was a bit too small for trowelling and a MSA of 5.0 mm tended to produce fairly rough trowelled surfaces. Hence, the mortar mixes originally designed to have a PV of 42% and a MSA of 5.0 mm were not tested. For these reasons, the actual number of mortar mixes produced for testing was 36.

Table 10. Testing program on effects of fines content on mortar

Water/ cement ratio	Paste volume (%)	Maximum size of aggregate (mm)	Fines content (%)
0.30	42	2.36, 5.0	2, 5, 8, 10
	48	2.36, 5.0	2, 5, 8, 10
0.40	42	2.36, 5.0	2, 5, 8, 10
	48	2.36, 5.0	2, 5, 8, 10
0.50	42	2.36, 5.0	2, 5, 8, 10
	48	2.36, 5.0	2, 5, 8, 10
0.60	42	2.36, 5.0	2, 5, 8, 10
	48	2.36, 5.0	2, 5, 8, 10

The fine aggregate (FA) used in the tests was crushed granite rock fine aggregate obtained from the local market. This fine aggregate is the same as those being used by some concrete producers in Hong Kong. The particle size distributions of the 2.36 mm maximum size fine aggregate with the fines content removed and the 5.0 mm maximum size fine aggregate with the fines content removed, as determined by mechanical sieving, are presented in Figure 6. The relative density of the fine aggregate was measured as 2.54. The water absorption of the fine aggregate was measured as 1.81%. From time to time, the moisture content of the fine aggregate was measured and the water absorption of the fine aggregate was allowed for in determining the amount of water to be added to the trial mortar mixes.

Samples of the fine aggregate have been sent to Anderson Concrete Ltd and Gammon Construction Ltd for methylene blue tests. The MB value obtained by Anderson Concrete Ltd was 0.8 while the MB value obtained by Gammon Construction Ltd was 1.0. Hence, the fines content in the fine aggregate may be regarded as of good quality containing little deleterious materials.

To produce fine aggregates with the prescribed fines contents of 2%, 5%, 8% or 10%, the fines content in the fine aggregate was first removed by mechanical sieving so that the fine aggregate contained a fines content of exactly 0%. Then, the right amount of fines was put back into the fine aggregate so that the fine aggregate contained the prescribed fines content. Such fine aggregates with the fines content controlled at certain maximum levels may be regarded as manufactured sand (processed crushed rock fine).

Regarding the cement used, it was an ordinary Portland cement (OPC) of strength class 52.5 N complying with BS EN 197-1: 2000. The relative density of the cement has been measured in accordance with BS EN 196-6: 2010 as 3.11.

For the OPC and the fines content (the portion of fine aggregate finer than 75 μm), the particle size distributions were measured using a laser diffraction particle size analyzer, as presented in Figure 6.

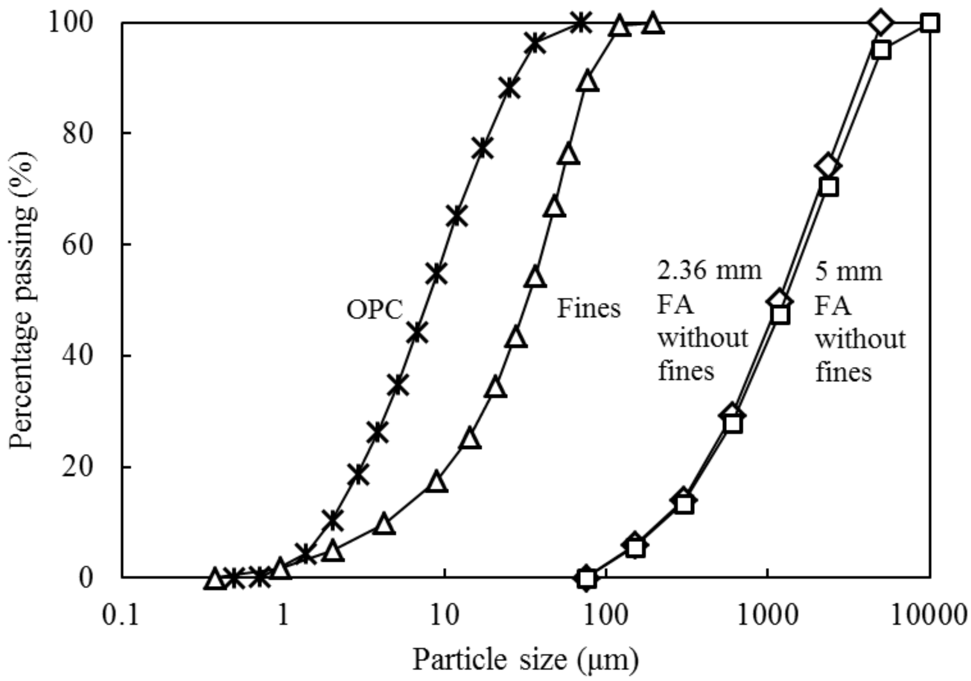

Figure 6. Particle size distributions of OPC, fines, 2.36 mm FA without fines and 5.0 mm FA without fines

A Hobart mixer was used to mix the ingredients in the trial mortar mix. Electronic balances were used to weigh the correct quantities of ingredients to be added to the mixer. During mixing, all the solid ingredients were added at the same time to the mixer. After about one minute of dry mixing, water was added to the mixer and the mortar mix was further mixed for two minutes.

Upon completion of mixing, a fresh sample was taken from the mixer for the mini slump-flow test. The mini slump-flow test for mortar was similar to the slump-flow test for concrete, except that a mini slump cone was used instead. The mini slump cone used was the same as the one developed by Okamura and Ouchi (H. Okamura and M. Ouchi, Self-compacting concrete, Journal of Advanced Concrete Technology, Vol.1, No.1, 2003, 5-15). It has a base diameter of 100 mm, a top diameter of 70 mm and a height of 60 mm. The test procedures were similar to those of the slump-flow test. The drop in height of mortar was taken as the slump (a measure of deformability) whereas the average value of two perpendicular diameters of the mortar patty formed minus the base diameter of the mini slump cone was taken as the flow spread (a measure of flowability). It should be noted that a flow spread of zero means no flowability and a flow spread of 100 mm is a very good flowability.

Meanwhile, another fresh sample was taken from the mixer for the stone rod adhesion test, which was developed by Li and Kwan (L.G. Li and A.K.H. Kwan, Mortar design based on water film thickness, Construction and Building Materials, Vol.25, No.5, 2011, 2381-2390). The test setup consisted of a handle with six granite stone rods vertically fixed underneath and a container. Each stone rod has a diameter of 10 mm and an exposed length of 110 mm. To perform the test, the six stone rods were immersed into the mortar until the immersion depth was 100 mm and then slowly extracted. The weight of mortar adhering to the stone rods was taken as a measure of the adhesion of the mortar.

After completion of the mini slump-flow and stone rod adhesion tests, all the mortar samples were put back into the mixer and remixed. Then, three 70.7 mm mortar cubes were cast from the remixed fresh mortar. After casting, the mortar cubes, together with their moulds, were covered and stored in the laboratory. At 24 hours after casting, the cubes were demoulded and put into a lime-saturated water curing tank controlled at a temperature of 27 ± 2 ℃. The cubes were tested at the age of 7 days and the average value of the measured strengths of the three cubes was taken as the 7-day cube strength.

For testing of the trowelability and pull-out strength of the mortar plastered onto a vertical concrete surface, another sample of the fresh mortar was taken from the mixer and plastered onto the moulded surface of a 300 mm width × 300 mm width × 70 mm thick precast concrete panel in vertical position. The plaster was applied in two layers, each 10 mm thick, with the first layer applied in the first day and the second layer applied in the second day. Each time a layer of plaster was applied, the surface to be plastered was pre-wetted by spraying water onto the surface at about 15 minutes before plastering. No primer was used in the plastering. After plastering, the plastered specimen was kept in the laboratory with no specific curing applied, as in real practice. At the age of 7 days after application of the second layer of plaster, the pull-out strength of the mortar layer was measured in accordance with BS EN 1015-12: 2000 as the 7-day pull-out strength. In general, a pull-out strength of at least 0.5 MPa is regarded as acceptable whereas a pull-out strength of lower than 0.5 MPa is regarded as unacceptable.

During plastering onto the vertical concrete surface, the trowelability of the mortar was judged visually and manually into one of the following ratings:

Too dry – the mortar appears to be very dry and un-cohesive; it does not adhere to the concrete surface at all

Dry – the mortar appears to be dry and un-cohesive; it adheres to the concrete surface if pressed very hard against the concrete surface

Slight dry – the mortar appears to be slightly dry; it adheres well to the concrete surface if pressed hard against the concrete surface

Optimum – the mortar appears to have good consistence and cohesiveness; it adheres well to the concrete surface without the need of pressing hard against the concrete surface and would not drip downwards after plastering

Slight wet – the mortar appears to be slightly wet; it adheres well to the concrete surface but tends to drip downwards after plastering

Wet – the mortar appears to be wet and un-cohesive; it adheres to the concrete surface but drips downwards with time after plastering

Too wet – the mortar appears to be very wet and un-cohesive; it does not adhere to the concrete surface at all due to continuous dripping

The detailed test results are presented in the following tables (note that PV means paste volume and MSA means maximum size of aggregate).

Table 11. Test results of mortar mixes with PV = 42% and MSA = 2.36 mm

Mix no. (W/C-PV-MSA-Fines%)	Slump (mm)	Flow spread (mm)	Adhesion (g)	7-day cube strength (MPa)	Trowel-ability	7-day pull-out strength (MPa)
0.30-42-2.36-2	Much too dry to be mixed					
0.30-42-2.36-5						
0.30-42-2.36-8						
0.30-42-2.36-10						
0.40-42-2.36-2	0	0	0.4	56.6	Too dry	Not done
0.40-42-2.36-5	0	0	0.4	53.5	Too dry	Not done
0.40-42-2.36-8	0	0	0.2	47.5	Too dry	Not done
0.40-42-2.36-10	0	0	0.2	53.9	Too dry	Not done
0.50-42-2.36-2	0	0	0.6	39.7	Dry	0.12
0.50-42-2.36-5	3	1	0.7	47.3	Dry	0.79
0.50-42-2.36-8	3	0	0.6	47.6	Dry	0.58
0.50-42-2.36-10	0	0	0.6	39.2	Dry	0.43
0.60-42-2.36-2	3	0	0.8	33.3	Slight dry	0.99
0.60-42-2.36-5	1	0	0.8	37.0	Slight dry	1.15
0.60-42-2.36-8	3	1	0.6	35.1	Slight dry	1.21
0.60-42-2.36-10	3	1	1.1	38.8	Slight dry	1.03

These results show that:

(1) at PV=42% and MSA=2.36 mm, the mortar is too dry for trowelling when W/C ≤ 0.50,

(2) at PV=42% and MSA=2.36 mm, the suitable W/C ratio for trowelling is about 0.60,

(3) at PV=42% and MSA=2.36 mm, a fines content of up to 8% has no adverse effects on trowelability and strength, and

(4) overall, a PV of 42% appears to be a bit too small for trowelling.

Table 12. Test results of mortar mixes with PV = 48% and MSA = 2.36 mm

Mix no. (W/C-PV-MSA-Fines%)	Slump (mm)	Flow spread (mm)	Adhesion (g)	7-day cube strength (MPa)	Trowel-ability	7-day pull-out strength (MPa)
0.30-48-2.36-2 0.30-48-2.36-5 0.30-48-2.36-8 0.30-48-2.36-10	Much too dry to be mixed					
0.40-48-2.36-2	2	5	0.7	57.8	Dry	0.46
0.40-48-2.36-5	3	2	1.1	60.7	Dry	0.50
0.40-48-2.36-8	3	3	1.1	63.8	Dry	0.55
0.40-48-2.36-10	2	4	0.6	63.7	Dry	0.25
0.50-48-2.36-2	13	7	2.1	43.0	Optimum	1.53
0.50-48-2.36-5	13	6	2.2	45.8	Optimum	0.96
0.50-48-2.36-8	10	5	0.9	46.5	Optimum	0.71
0.50-48-2.36-10	8	5	0.9	45.6	Optimum	1.05
0.60-48-2.36-2	19	9	3.1	34.7	Wet	Not done
0.60-48-2.36-5	16	10	2.4	38.5	Wet	Not done
0.60-48-2.36-8	10	9	2.2	36.9	Wet	Not done
0.60-48-2.36-10	12	5	2.3	35.8	Wet	Not done

These results show that:

(1) at PV=48% and MSA=2.36 mm, the mortar is too dry for trowelling when W/C ≤ 0.40,

(2) at PV=48% and MSA=2.36 mm, the suitable W/C ratio for trowelling is about 0.50,

(3) at PV=48% and MSA=2.36 mm, a fines content of up to 8% has no adverse effects on trowelability and strength, and

(4) overall, a PV of 48% is better than 42% for trowelling.

Table 13. Test results of mortar mixes with PV = 48% and MSA = 5.0 mm

Mix no. (W/C-PV-MSA-Fines%)	Slump (mm)	Flow spread (mm)	Adhesion (g)	7-day cube strength (MPa)	Trowel-ability	7-day pull-out strength (MPa)
0.30-48-5.0-2	Much too dry to be mixed					
0.30-48-5.0-5						
0.30-48-5.0-8						
0.30-48-5.0-10						
0.40-48-5.0-2	12	1	2.2	45.2	Optimum	1.82
0.40-48-5.0-5	10	1	2.5	48.2	Optimum	1.03
0.40-48-5.0-8	8	2	2.2	48.6	Optimum	1.24
0.40-48-5.0-10	9	2	5.2	50.9	Optimum	0.91
0.50-48-5.0-2	50	85	16.2	33.3	Wet	Not done
0.50-48-5.0-5	20	18	11.9	41.9	Wet	Not done
0.50-48-5.0-8	15	12	6.9	42.0	Wet	Not done
0.50-48-5.0-10	12	7	6.2	42.3	Wet	Not done
0.60-48-5.0-2	45	83	14.2	30.8	Too wet	Not done
0.60-48-5.0-5	32	28	15.8	29.1	Too wet	Not done
0.60-48-5.0-8	25	24	13.8	30.3	Too wet	Not done
0.60-48-5.0-10	22	17	15.5	30.6	Too wet	Not done

These results show that:

(1) at PV=48% and MSA=5.0 mm, the mortar is too dry for trowelling when W/C ≤ 0.30 and too wet for trowelling when W/C ≥ 0.50,
(2) at PV=48% and MSA=5.0 mm, the suitable W/C ratio for trowelling is about 0.40,
(3) at PV=48% and MSA=5.0 mm, a fines content of up to 8% has no adverse effects on trowelability and strength,
(4) overall, at MSA=5.0 mm, a PV of 48% is suitable for trowelling, and
(5) at MSA=5.0 mm, the trowelled surfaces tend to be quite rough.

For detailed analysis, the trowelability results are plotted against the slump and stone-rod adhesion in Figures 7 and 8, respectively.

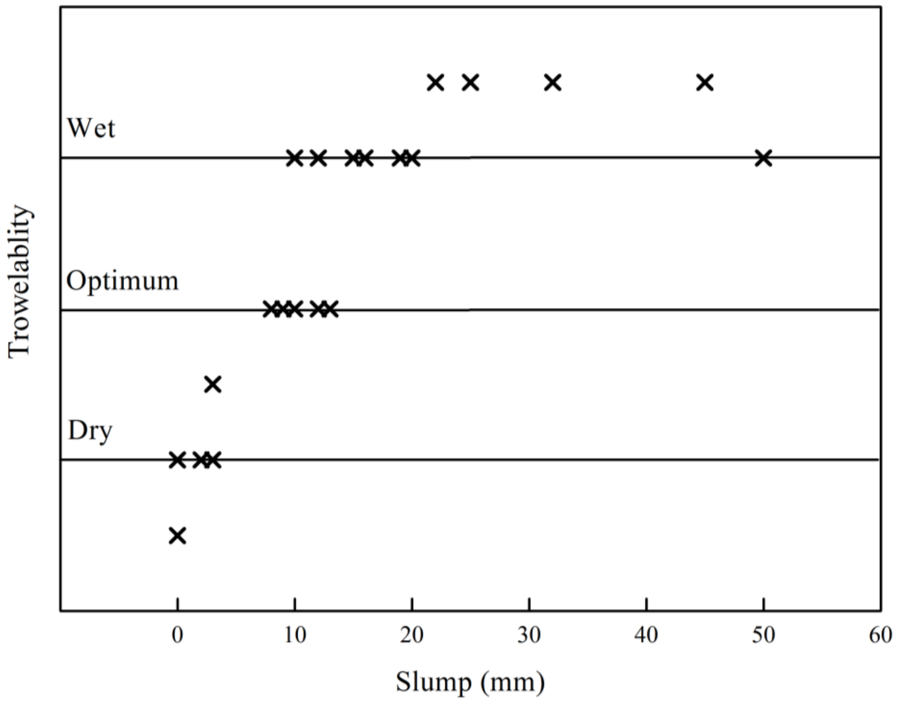

Figure 7. Trowelability plotted against slump

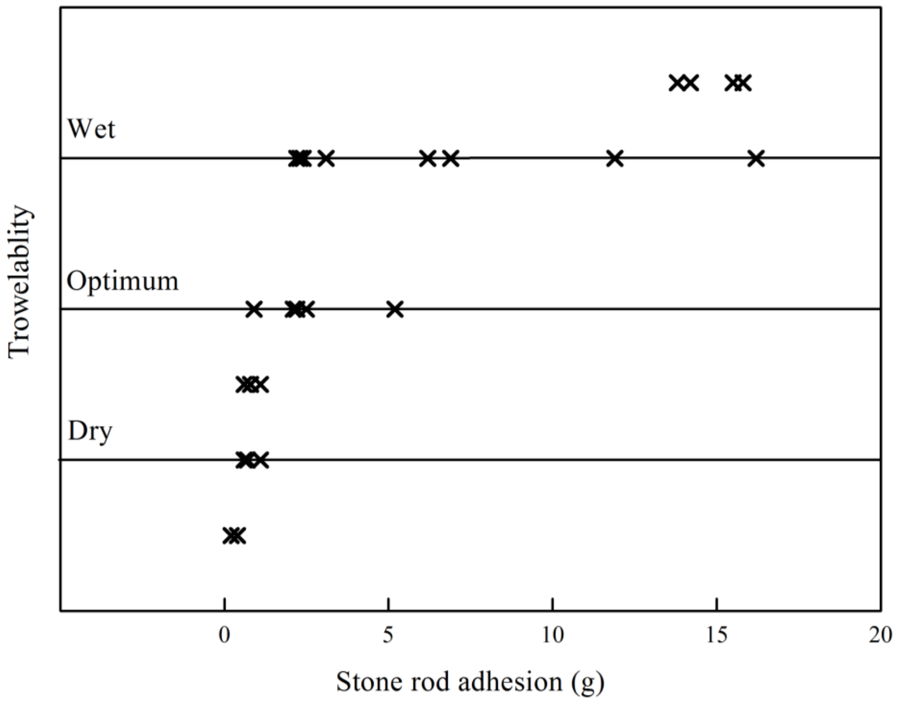

Figure 8. Trowelability plotted against stone rod adhesion

For detailed analysis, the 7-day cube strength and 7-day pull-out strength are plotted against the fines content in Figures 9 and 10, respectively.

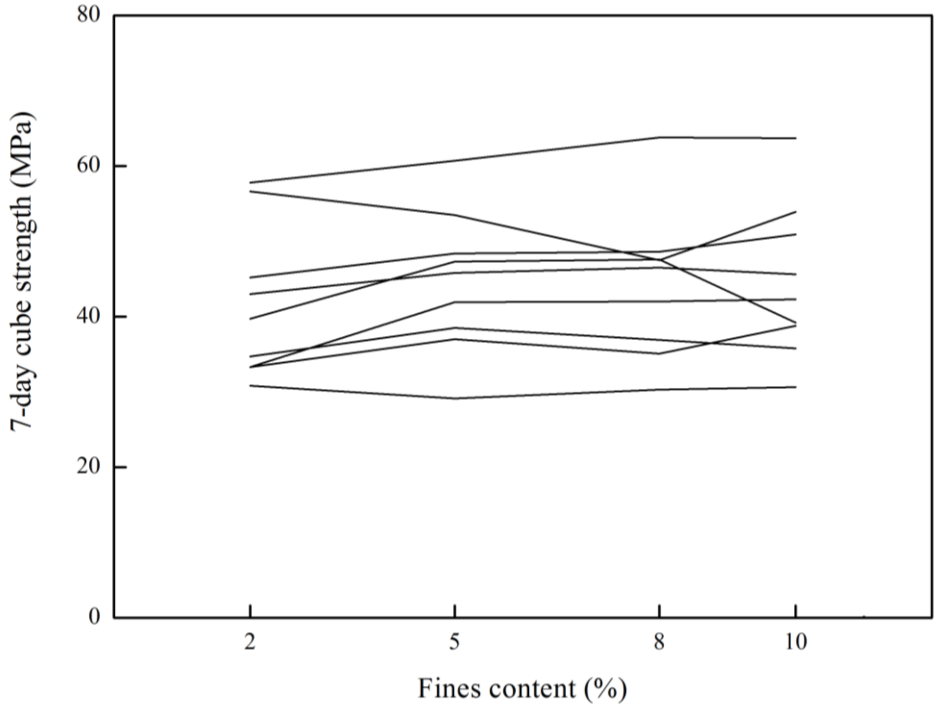

Figure 9. 7-day cube strength plotted against fines content in fine aggregate

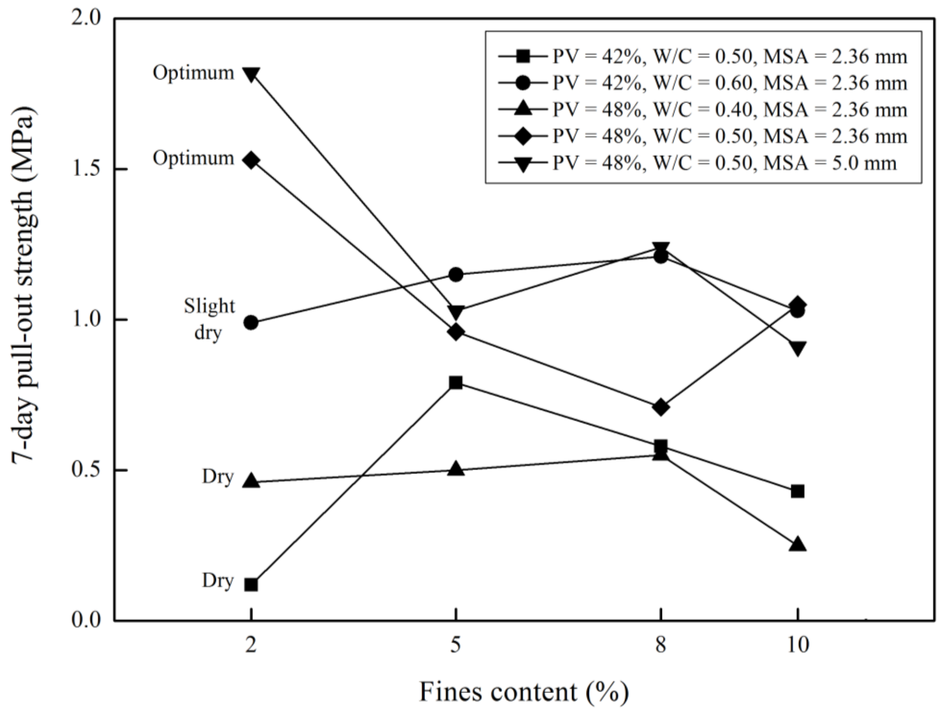

Figure 10. 7-day pull-out strength plotted against fines content in fine aggregate

From Figure 7, it can be seen that the trowelability is closely related to the slump of the mortar mix. Basically, the range of slump for optimum trowelability is from about 8 to 13 mm (or simply 10 ± 3 mm). A lower slump indicates that the mortar mix is on the dry side whereas a higher slump indicates that the mortar mix is on the wet side.

From Figure 8, it can be seen that the trowelability is not directly related to the adhesion measured by the stone rod adhesion test. It was originally thought that the stone rod adhesion test might give an objective measure of trowelability and that a higher adhesion as measured by the stone rod adhesion test should indicate a better trowelability. Somehow, the test results reveal that a higher adhesion as measured by the stone rod adhesion test does not always indicate a better trowelability. Hence, the stone rod adhesion test is not a suitable test for measuring the trowelability of mortar. Apart from the slump test, which does indicate whether the wetness is within the appropriate range for optimum trowelability, we still have to rely on the current subjective judgement of trowelability.

From Figure 9, it is evident that a fines content of up to 8 % has no adverse effect on the 7-day cube strength. In fact, on the whole, the fines content has little effect on the 7-day cube strength.

From Figure 10, it is apparent that the 7-day pull-out strength fluctuated quite significantly, indicating that there were some random variations due probably to differences in surface condition and workmanship. Moreover, there appears to be no obvious correlation between the 7-day pull-out strength and the fines content. In other words, the fines content has little effect on the 7-day pull-out strength. More importantly, a fines content of up to 8% has no adverse effect on the 7-day pull-out strength.

However, it does appear from Figure 10 that the trowelability has certain effect on the 7-day pull-out strength. In the figure, five curves are plotted. The mortar mixes in these five curves have different trowelability ratings as summarized in the followings:
Curve for PV=42%, W/C=0.50, MSA=2.36 mm: trowelability = “Dry”
Curve for PV=42%, W/C=0.60, MSA=2.36 mm: trowelability = “Slight dry”
Curve for PV=48%, W/C=0.40, MSA=2.36 mm: trowelability = “Dry”
Curve for PV=48%, W/C=0.50, MSA=2.36 mm: trowelability = “Optimum”
Curve for PV=48%, W/C=0.60, MSA=5.0 mm: trowelability = “Optimum”
It can be seen from the figure that the mortar mixes with a trowelability rating of “Dry” all have relatively low 7-day pull-out strengths. Nevertheless, the mortar mixes with a trowelability rating of either “Slight dry” or “Optimum” have relatively high 7-day pull-out strengths of at least 0.7 MPa. Hence, the trowelability rating is not just a measure of the ease of trowelling; it also gives an indication of whether a relatively high pull-out strength could be achieved. From the results obtained so far, it seems that the trowelability has to be either “Slight dry” or “Optimum”. But the trowelability rating is dependent more on the W/C ratio or the water content, rather than on the fines content. So the key issue of trowelability is the control of water content, not the fines content.

Summarizing, the test results of the mortar mixes with a maximum aggregate size of 2.36 mm reveal the following effects of the fines content on the performance of mortar:

(1) At PV = 42%, the mortar is too dry for trowelling when W/C ≤ 0.50 and the suitable W/C ratio for trowelling is about 0.60. Generally, a PV of 42% appears to be a bit too small for trowelling.

(2) At PV = 42%, a fines content of up to 8% has no adverse effects on trowelability and strength.

(3) At PV = 48%, the mortar is too dry for trowelling when W/C ≤ 0.40 and the suitable W/C ratio for trowelling is about 0.50. Generally, a PV of 48% is better than 42% for trowelling.

(4) At PV = 48%, a fines content of up to 8% has no adverse effects on trowelability and strength.

Summarizing, the test results of the mortar mixes with a maximum aggregate size of 5.0 mm reveal the following effects of the fines content on the performance of mortar:

(1) At PV = 48%, the mortar is too dry for trowelling when W/C ≤ 0.30 and too wet for trowelling when W/C ≥ 0.50, and the suitable W/C ratio for trowelling is about 0.40. Generally, at MSA = 5.0 mm, a PV of 48% is suitable for trowelling. However, even at such PV, the trowelled surfaces tend to be quite rough.

(2) At PV=48%, a fines content of up to 8% has no adverse effects on trowelability and strength.

Overall, it may be concluded that the trowelability of a mortar is best when the mortar is neither too dry nor too wet. However, this seems to be dependent more on the W/C ratio or the water content of the mortar mix, rather than the fines content in the fine aggregate. The suitable W/C ratios for trowelling are as follows:

(1) At MSA = 2.36 mm and PV = 42%, suitable W/C = 0.60;

(2) At MSA = 2.36 mm and PV = 48%, suitable W/C = 0.50; and

(3) At MSA = 5.0 mm and PV = 48%, suitable W/C = 0.40.

The suitable W/C for trowelling varies with the MSA and PV, and for each given mortar mix, the acceptable range of W/C or water content for trowelling is very narrow and thus the W/C ratio or the water content has to be controlled carefully. Nevertheless, within the ranges of MSA and PV covered in this study, a fines content of up to 8% has no adverse effects on trowelability and strength. Lastly, at a suitable W/C for trowelling and with the fines content limited to not more than 8%, a pull-out strength of at least 0.7 MPa can be achieved, which should be sufficiently high because the required pull-out strength is only 0.5 MPa.

From the above test results, it appears that there is no real necessity to impose a fines content limit of 3% in any fine aggregate for mortar. In other words, the class F3 fine aggregate (fines content ≤ 3%) is not really necessary, and it may be simpler to remove the class F3 fine aggregate and just allow the use of class F5 fine aggregate (fines content ≤ 5%) in all kinds of plastering and screeding works.

Moreover, from the above test results, it appears that a paste volume of 48% is better for plastering. A slightly smaller paste volume of 45% may also be acceptable. Converting to cement to sand ratio, which is more commonly used for batching on site, a paste volume of PV = 48% is equivalent to a cement to sand ratio of 1:2.36, and a paste volume of PV = 45% is equivalent to a cement to sand ratio of 1:2.66. Hence, the cement to sand ratio of mortar for plastering should be set at around 1:2.5.

In conventional practice, the W/C ratio or water content of the mortar mix is not explicitly specified and the workers are left to themselves to judge the appropriate amount of water to be added to give the optimum trowelability. This requires the workers to have proper training and good experience. From the present study, a general guideline has been produced as a slump of 10 ± 3 mm, as measured by the mini slump-flow test. So, to overcome the common workmanship problem of often putting in too little or too much water into the mortar mix, the workers should be encouraged and trained to perform the mini slump-flow test of the mortar to determine the appropriate amount of water to be added to the mortar mix.

Alternatively, pre-packed dry plastering mortar can be used. The use of pre-packed materials can ensure that the fine aggregate is of the right quality and the cement to sand ratio has been accurately controlled. Moreover, the mortar supplier should know by tests and experience the appropriate amount of water to be added and thus should be able to explicitly specify the amount of water to be added to the dry mortar. With the amount of water to be added explicitly specified, the workers need only add the specified amount of water without having to determine the appropriate amount of water to be added by trial and error on site. This could at least partly resolve the common workmanship problems with plastering.

4. Feasibility of Using Crushed Waste Glass as Aggregate for Mortar

This part of the testing program was to study the feasibility of crushing and processing waste glass for recycling as aggregate for mortar.

Currently, only about 4% to 5% of waste glass is being recycled as aggregate in precast concrete paving blocks. The Hong Kong SAR Government is very keen in increasing the recycling rate so as to avoid dumping waste glass to landfills. Crushing the waste glass to sand size for use as river sand substitute could be one good way of using up the waste glass.

There are two possible ways of increasing the consumption of crushed waste glass. First, the proportion of crushed waste glass aggregate in precast concrete paving blocks may be increased. At present, the crushed waste glass aggregate in eco-glass paving blocks constitutes only 20 to 25% by weight of the total aggregate. It is felt that the crushed waste glass aggregate content in eco-glass blocks may be increased to 70% or even 100% of the total aggregate. Second, crushed waste glass may also be used as aggregate in mortar for plastering, rendering, screeding and masonry. Since the consumption of river sand as aggregate for mortar is more than 1,000,000 tons per year and there is a shortage of river sand in Hong Kong, the use of crushed waste glass as aggregate in mortar would resolve not only the waste glass recycling problem but also the river sand shortage problem.

Two materials suppliers have helped to produce some crushed waste glass for testing. From the samples obtained, it does appear that the fines content in the crushed waste glass is quite low and the glass particles are fairly un-cohesive (probably because glass is hydrophobic). Moreover, the glass particles are angular in shape, having many sharp edges and corners. This is probably due to the high brittleness of glass which causes the formation of cleavage planes during crushing. In theory, a rounded particle shape should be better than an angular particle shape. However, according to the suppliers, although it is possible to grind the waste glass to make the glass particles rounded in shape, the production cost is very high and thus such grinding is not really practical. Nevertheless, it appears at first sight that it may be necessary to crush the waste glass to a higher fineness than the usual fine aggregate (so that the grading is F instead of C) so as to improve the cohesiveness and adhesiveness of the mortar made from the crushed waste glass.

It was originally proposed to study the above possible uses of crushed waste glass as river sand substitute by producing mortar mixes with 70% crushed waste glass + 30% crushed rock fine or 100% crushed waste glass used as fine aggregate for the making of precast paving blocks and mortars for plastering, rendering, screeding and masonry. For this purpose, the testing program was originally set as depicted in Table 14. In the testing program, there are four combinations of W/C ratio ranging from 0.30 to 0.60, three combinations of paste volume (PV) ranging from 45% to 55%, two combinations of crushed waste glass aggregate grading and two combinations of crushed waste glass aggregate content.

Table 14. Original testing program on use of crushed waste glass in mortar

Water/ cement ratio	Paste volume (%)	Grading of crushed waste glass aggregate	Crushed waste glass aggregate content (%)
0.30	45	C, F	70, 100
	50	C, F	70, 100
	55	C, F	70, 100
0.40	45	C, F	70, 100
	50	C, F	70, 100
	55	C, F	70, 100
0.50	45	C, F	70, 100
	50	C, F	70, 100
	55	C, F	70, 100
0.60	45	C, F	70, 100
	50	C, F	70, 100
	55	C, F	70, 100

From these tests, we should be able to determine whether it is really necessary to crush waste glass to a higher fineness than usual (so that the grading is F instead of C) and whether crushed waste glass aggregate may be used up to 70% or even 100% in mortar for use in precast paving blocks, plastering, rendering, screeding and masonry. If crushed waste glass aggregate can be used up to at least 70%, then the recycling rate of waste glass in Hong Kong can be substantially increased.

Later, when the testing program was half completed, it was found that the use of a high percentage of crushed waste glass as aggregate in plastering and rendering works would lead to lack of adhesion and difficulties in trowelling. It was therefore suggested and agreed at a meeting between Prof. Albert K.H. Kwan and Construction Industry Council held on April 15, 2014 that instead of continuing to study the possible use of 70% crushed waste glass as aggregate in plastering and rendering works, it should be more worthwhile to study the possible use of 50% crushed waste glass as aggregate in plastering and rendering works. Hence, in the further tests, the 70% crushed waste glass was changed to 50% crushed waste glass. Details of the revised testing program are depicted in Table 15 below.

Table 15. Revised testing program on use of crushed waste glass in mortar

Water/ cement ratio	Paste volume (%)	Grading of crushed waste glass aggregate	Crushed waste glass aggregate content (%)
0.30	45	C, F	50, 100
	50	C, F	50, 100
	55	C, F	50, 100
0.40	45	C, F	50, 100
	50	C, F	50, 100
	55	C, F	50, 100
0.50	45	C, F	50, 100
	50	C, F	50, 100
	55	C, F	50, 100
0.60	45	C, F	50, 100
	50	C, F	50, 100
	55	C, F	50, 100

The fine aggregate (FA) used in the tests was crushed granite rock fine aggregate obtained from the local market. This FA is actually the same as that used in the previous tests on concrete and mortar. Its maximum size of aggregate (MSA) was 5.0 mm. Its fines content was measured by mechanical sieving as 5.0%. The fines content was not removed from the FA but rather was retained in the FA to mimic manufactured sand with similar fines content. The particle size distribution of the FA, as determined by mechanical sieving, is presented in Figure 11. As before, the relative density of the FA was measured as 2.54 and the water absorption of the FA was measured as 1.81%. From time to time, the moisture content of the FA was measured and the water absorption of the FA was allowed for in determining the amount of water to be added to the trial mortar mixes.

Samples of the fine aggregate have been sent to Anderson Concrete Ltd and Gammon Construction Ltd for methylene blue tests. The MB value obtained by Anderson Concrete Ltd was 0.8 while the MB value obtained by Gammon Construction Ltd was 1.0. Hence, the fines content in the fine aggregate may be regarded as of good quality containing little deleterious materials.

The crushed waste glass (CWG) was obtained from a material supplier in Mainland China. It was crushed from white colour glass bottles bought from the market. The glass bottles were first cleaned and then crushed to become a sand sized material. To control its particle size distribution, the CWG was first sieved into different size fractions and then the different size fractions were blended together according to certain mix proportions to produce CWG with a grading of C and CWG with a grading of F. Their particle size distributions, as determined by mechanical sieving, are presented in Figure 11. Furthermore, the relative density of the CWG was measured as 2.33 and the water absorption of the CWG was measured as 0%.

Regarding the cement used, it was an ordinary Portland cement (OPC) of strength class 52.5 N complying with BS EN 197-1: 2000. The relative density of the cement has been measured in accordance with BS EN 196-6: 2010 as 3.11. Its particle size distribution, as measured using a laser diffraction particle size analyzer, is presented in Figure 11.

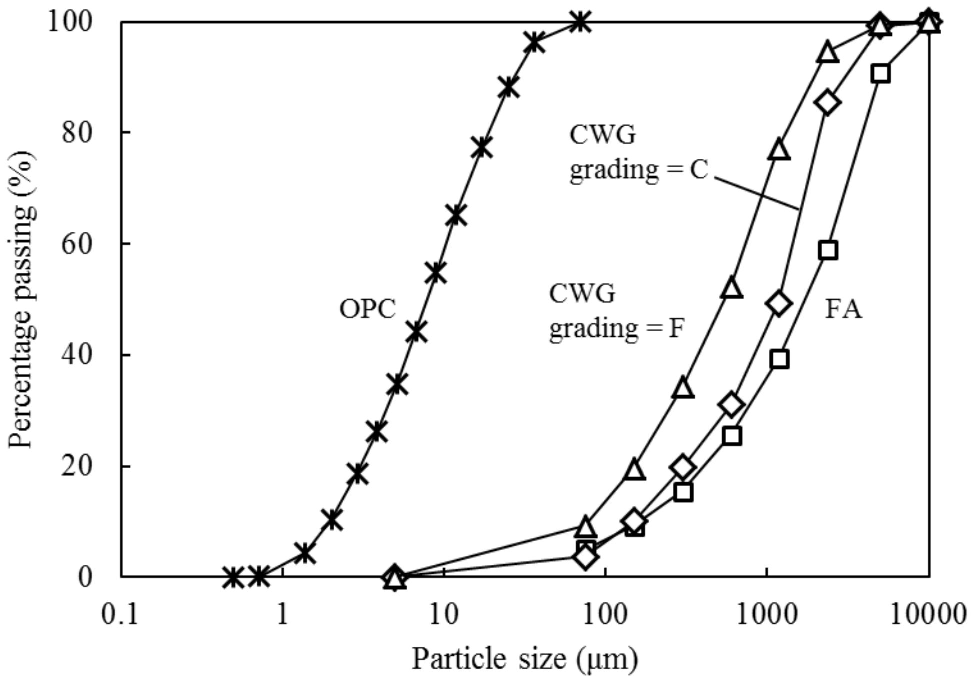

Figure 11. Particle size distributions of OPC, fine aggregate (FA) and crushed waste glass (CWG) with gradings of C and F

The detailed test results are presented in the following tables.

Table 16. Test results of mortar mixes with crushed waste glass grading = C and crushed waste glass content = 100%

Mix no. (W/C-PV-Grading-Waste glass content%)	Slump (mm)	Flow spread (mm)	Adhesion (g)	7-day cube strength (MPa)	Trowel-ability	7-day pull-out strength (MPa)
0.30-45-C-100	Much too dry to be mixed					
0.40-45-C-100	3	0	1.8	53.4	Slight dry	1.13
0.50-45-C-100	17	2	3.8	37.6	Slight wet	1.72
0.60-45-C-100	20	20	4.2	31.5	Too wet	Not done
0.30-50-C-100	1	1	0.8	55.0	Too dry	Not done
0.40-50-C-100	3	2	2.0	52.6	Optimum	2.69
0.50-50-C-100	13	7	3.3	37.4	Too wet	Not done
0.60-50-C-100	31	53	5.0	25.7	Too wet	Not done
0.30-55-C-100	2	1	1.2	53.1	Slight dry	1.11
0.40-55-C-100	11	4	3.3	54.2	Slight wet	1.57
0.50-55-C-100	29	48	8.7	37.0	Too wet	Not done
0.60-55-C-100	50	99	13.9	25.9	Too wet	Not done

These results show that:
(1) at PV=45%, 50% and 55%, the suitable W/C ratios for trowelling are 0.45, 0.40 and 0.35,
(2) regardless of the PV, the mortar is often either too dry or too wet for trowelling,
(3) at all PV, the suitable range of W/C ratio for trowelling is rather narrow, and
(4) a maximum 7-day strength of 55.0 MPa has been obtained.

Table 17. Test results of mortar mixes with crushed waste glass grading = F and crushed waste glass content = 100%

Mix no. (W/C-PV-Grading-Waste glass content%)	Slump (mm)	Flow spread (mm)	Adhesion (g)	7-day cube strength (MPa)	Trowel-ability	7-day pull-out strength (MPa)
0.30-45-F-100	Much too dry to be mixed					
0.40-45-F-100	0	0	0.7	43.1	Dry	Not done
0.50-45-F-100	2	0	2.0	34.9	Slight dry	1.08
0.60-45-F-100	14	4	2.7	28.8	Slight wet	1.44
0.30-50-F-100	0	0	0.4	58.1	Too dry	Not done
0.40-50-F-100	2	0	0.8	50.4	Slight dry	0.67
0.50-50-F-100	13	4	3.7	38.7	Slight wet	1.29
0.60-50-F-100	31	8	4.4	25.6	Too wet	Not done
0.30-55-F-100	2	1	0.7	54.9	Dry	Not done
0.40-55-F-100	11	3	1.7	55.8	Optimum	1.34
0.50-55-F-100	26	5	2.3	37.5	Wet	0.17
0.60-55-F-100	40	43	2.8	26.1	Too wet	Not done

These results show that:
(1) at PV=45%, 50% and 55%, the suitable W/C ratios for trowelling are 0.55, 0.45 and 0.40,
(2) regardless of the PV, the mortar is often either too dry or too wet for trowelling,
(3) at all PV, the suitable range of W/C ratio for trowelling is rather narrow, and
(4) a maximum 7-day strength of 58.1 MPa has been obtained.

Table 18. Test results of mortar mixes with crushed waste glass grading = C and crushed waste glass content = 50%

Mix no. (W/C-PV-Grading-Waste glass content%)	Slump (mm)	Flow spread (mm)	Adhesion (g)	7-day cube strength (MPa)	Trowel-ability	7-day pull-out strength (MPa)
0.30-45-C-50	Much too dry to be mixed					
0.40-45-C-50	2	0	1.2	56.8	Dry	0.24
0.50-45-C-50	5	3	1.6	46.8	Slight dry	1.62
0.60-45-C-50	8	4	2.6	34.1	Slight wet	0.61
0.30-50-C-50	0	0	0.5	57.2	Too dry	Not done
0.40-50-C-50	4	1	2.4	55.1	Slight dry	1.43
0.50-50-C-50	8	2	3.7	40.4	Slight wet	0.78
0.60-50-C-50	16	12	8.8	28.1	Wet	0.48
0.30-55-C-50	0	0	1.2	67.1	Too dry	Not done
0.40-55-C-50	15	5	3.6	57.2	Optimum	1.78
0.50-55-C-50	23	23	6.6	50.4	Wet	1.23
0.60-55-C-50	34	88	12.0	41.0	Too wet	Not done

These results show that:
(1) at PV=45%, 50% and 55%, the suitable W/C ratios for trowelling are 0.50, 0.45 and 0.40,
(2) regardless of the PV, the mortar is often either too dry or too wet for trowelling,
(3) at all PV, the suitable range of W/C ratio for trowelling is rather narrow, and
(4) a maximum 7-day strength of 67.1 MPa has been obtained.

Table 19. Test results of mortar mixes with crushed waste glass grading = F and crushed waste glass content = 50%

Mix no. (W/C-PV-Grading-Waste glass content%)	Slump (mm)	Flow spread (mm)	Adhesion (g)	7-day cube strength (MPa)	Trowel-ability	7-day pull-out strength (MPa)
0.30-45-F-50	Much too dry to be mixed					
0.40-45-F-50	0	0	0.2	54.0	Too dry	Not done
0.50-45-F-50	2	0	1.1	46.7	Dry	0.33
0.60-45-F-50	7	3	2.0	36.8	Slight dry	0.87
0.30-50-F-50	0	0	0.1	58.6	Too dry	Not done
0.40-50-F-50	3	0	1.3	55.0	Dry	0.10
0.50-50-F-50	7	4	1.5	45.3	Slight dry	0.56
0.60-50-F-50	11	8	3.0	33.1	Slight wet	1.58
0.30-55-F-50	0	0	0.6	69.7	Too dry	Not done
0.40-55-F-50	5	1	1.1	56.1	Slight dry	1.27
0.50-55-F-50	10	3	2.9	48.6	Slight wet	1.35
0.60-55-F-50	38	67	7.8	39.1	Too wet	Not done

These results show that:
(1) at PV=45%, 50% and 55%, the suitable W/C ratios for trowelling are 0.60, 0.55 and 0.50,
(2) regardless of the PV, the mortar is often either too dry or too wet for trowelling,
(3) at all PV, the suitable range of W/C ratio for trowelling is rather narrow, and
(4) a maximum 7-day strength of 69.7 MPa has been obtained.

For detailed analysis, the trowelability results are plotted against the slump and W/C ratio in Figures 12 and 13, respectively.

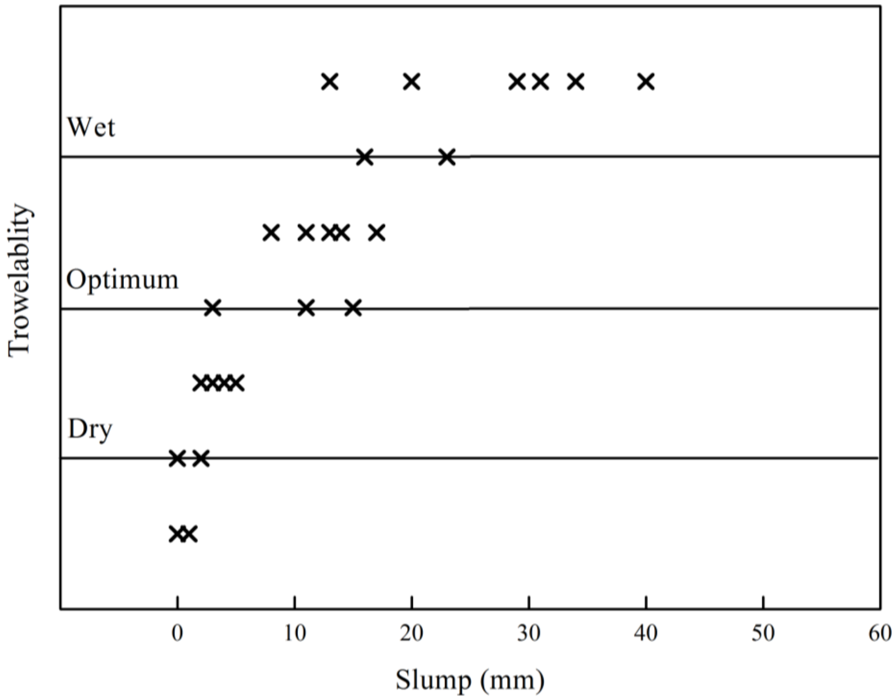

Figure 12. Trowelability plotted against slump

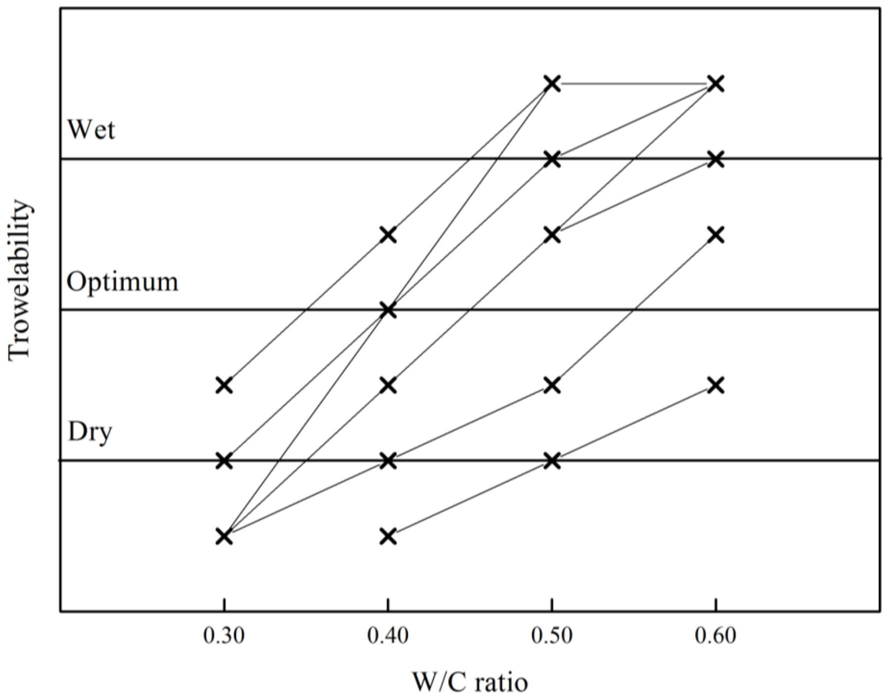

Figure 13. Trowelability plotted against W/C ratio

For detailed analysis, the 7-day cube strength and 7-day pull-out strength are plotted against the W/C ratio in Figures 14 and 15, respectively.

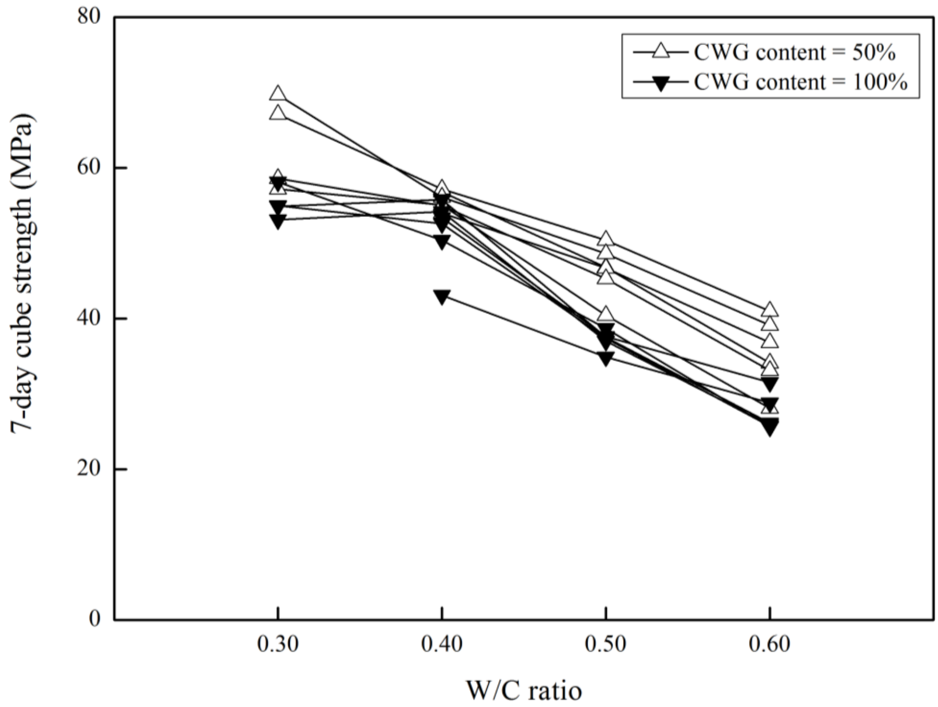

Figure 14. 7-day cube strength plotted against W/C ratio

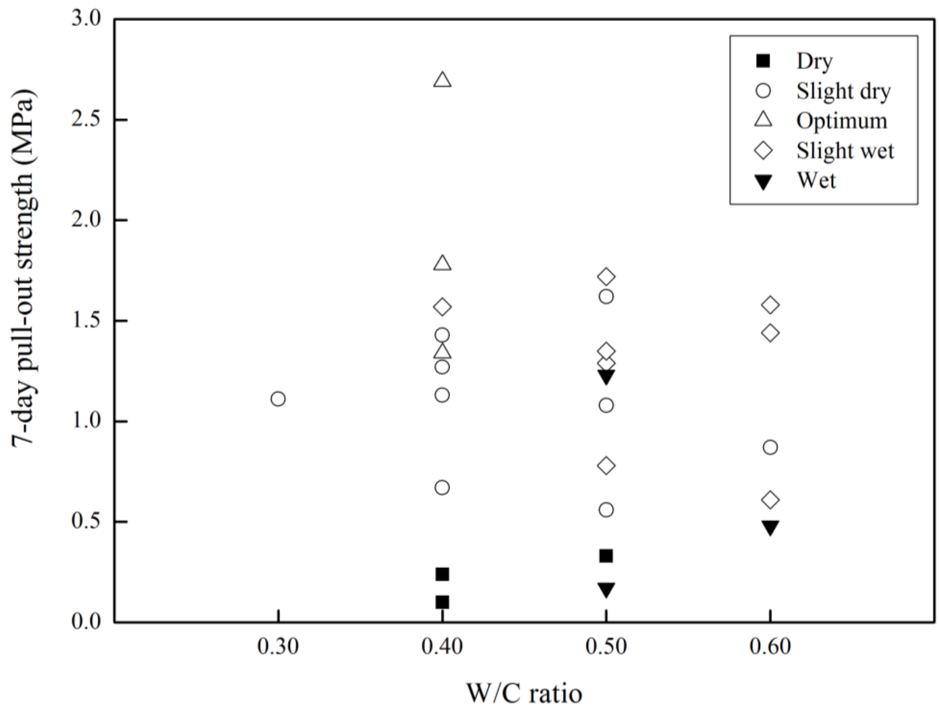

Figure 15. 7-day pull-out strength plotted against W/C ratio

From Figure 12, it can be seen that as for other plastering mortar, the trowelability of mortar containing CWG is closely related to the slump of the mortar mix. Basically, the range of slump for optimum trowelability is from about 3 to 15 mm (or simply 9 ± 6 mm). A lower slump indicates that the mortar mix is on the dry side whereas a higher slump indicates that the mortar mix is on the wet side.

From Figure 13, it can be seen that the relationship between the trowelability and the W/C ratio is dependent on the PV and the CWG grading and content. More specifically, the W/C ratio for optimum trowelabilty varies with the PV and the CWG grading and content, being generally lower at higher PV, higher at higher CWG fineness and lower at higher CWG content.

From Figure 14, it is found, as expected, that the 7-day cube strength increased as the W/C ratio decreased from 0.60 to 0.30. In other words, the 7-day cube strength is higher at lower W/C ratio and lower at higher W/C ratio. For mortar containing a CWG content of 100%, a maximum 7-day cube strength of 58.1 MPa has been achieved whereas for mortar containing a CWG content of 50%, a maximum 7-day cube strength of 69.1 MPa has been achieved. Hence, the use of 100% CWG as fine aggregate in mortar has certain adverse effect on the strength of the mortar produced. For the production of Grade 45 precast paving blocks (Grade 45 is needed for paving blocks in vehicle access and EVA), it is better to use only up to 50% CWG as the fine aggregate.

From Figure 15, it is apparent that the 7-day pull-out strength fluctuated quite significantly, indicating that there were some random variations due probably to differences in surface condition and workmanship. Moreover, there appears to be no obvious correlation between the 7-day pull-out strength and the W/C ratio. Hence, the 7-day pull-out strength is not directly related to the W/C ratio (the W/C ratio affects the trowelability and it is the trowelability that actually determines the pull-out strength, as explained below).

However, it does appear from Figure 15 that the trowelability has certain effect on the 7-day pull-out strength. In the figure, the trowelability ratings of the mortar mixes are indicated by a set of five different symbols for the five different trowelability ratings, “Dry”, “Slight dry”, “Optimum”, “Slight wet” and “Wet”. For the ratings “Slight dry”, “Optimum” and “Slight wet”, hollow symbols are used whereas for the ratings “Dry” and “Wet”, solid symbols are used. It can be seen from the figure that the mortar mixes with a trowelability rating of “Dry” or “Wet” (marked by solid symbols) all have relatively low 7-day pull-out strengths. Nevertheless, the mortar mixes with a trowelability rating of either “Slight dry”, “Optimum” or “Slight wet” (marked by hollow symbols) have relatively high 7-day pull-out strengths of at least 0.6 MPa. Hence, the trowelability is a governing factor of the pull-out strength. From the results obtained so far, it seems that the trowelability has to be “Slight dry”, “Optimum” or “Slight wet”. It is only that the trowelability rating is dependent not just on the W/C ratio, but also on the PV, CWG grading and CWG content. There is still a necessity for the worker to judge by himself the amount of water to be added so as to achieve optimum trowelability.

Summarizing, the test results of the mortar mixes containing 100% crushed waste glass as aggregate reveal that:

(1) Regardless of the CWG grading and the PV, the mortar is often either too dry or too wet for trowelling and the suitable range of W/C ratio for trowelling is rather narrow.

(2) For CWG grading = C, the suitable W/C ratios for trowelling are 0.45 at PV = 45%, 0.40 at PV = 50% and 0.35 at PV = 55%.

(3) For CWG grading = F, the suitable W/C ratios for trowelling are 0.55 at PV = 45%, 0.45 at PV = 50% and 0.40 at PV = 55%.

(4) For trowelling, the CWG grading of F and the CWG grading of C perform similarly. Hence, there is no need to crush the waste glass to a higher fineness than usual.

(5) At W/C = 0.30, a 7-day cube strength of at least 55.0 MPa can be achieved. Hence, crushed waste glass aggregate may be used up to 100% for precast blocks up to a mean cube strength of 55 MPa (good enough for production of grade 35 precast paving blocks).

Summarizing, the test results of the mortar mixes containing 50% crushed waste glass as aggregate reveal that:

(1) Regardless of the CWG grading and the PV, the mortar is often either too dry or too wet for trowelling and the suitable range of W/C ratio for trowelling is rather narrow.

(2) For CWG grading = C, the suitable W/C ratios for trowelling are 0.50 at PV = 45%, 0.45 at PV = 50% and 0.40 at PV = 55%.

(3) For CWG grading = F, the suitable W/C ratios for trowelling are 0.60 at PV = 45%, 0.55 at PV = 50% and 0.50 at PV = 55%.

(4) For trowelling, the CWG grading of F and the CWG grading of C perform similarly. Hence, there is no need to crush the waste glass to a higher fineness than usual.

(5) At W/C = 0.30, a 7-day cube strength of at least 65.0 MPa can be achieved. Hence, crushed waste glass aggregate may be used up to 50% for precast blocks up to a mean cube strength of 65 MPa (good enough for production of grade 45 precast paving blocks).

Overall, the test results obtained so far are generally positive. Firstly, it should be possible to use up to 50% crushed waste glass aggregate to make grade 45 precast paving blocks and up to 100% crushed waste glass aggregate to make grade 35 precast paving blocks. Secondly, it should be possible to use up to 50% crushed waste glass aggregate in mortar for plastering. The use of 100% crushed waste glass aggregate in mortar for plastering is not recommended because the mortar produced tends to be less cohesive than usual and thus more difficult to apply. Thirdly, since CWG grading of F and CWG grading of C perform similarly, there is no particular advantage and no real necessity of crushing the waste glass to higher fineness than usual.

Regarding the PV of mortar for plastering, a PV of 45% to 50% should be appropriate. The suitable W/C ratio is dependent on the PV and the CWG grading and content. With suitable W/C ratio adopted to ensure optimum trowelability, a pull-out strength of at least 0.6 MPa can be achieved.

However, there remains the problem of how the workers can determine the right amount of water to be added to the mortar mix to give the optimum trowelability. This requires the workers to have proper training and good experience. From the results obtained herein, a general guideline may be worked out as a slump of 10 ± 5 mm, as measured by the mini slump-flow test. Apart from judging by experience, the workers should be encouraged and trained to perform the mini slump-flow test of the mortar to determine the appropriate amount of water to be added to the mortar mix. Alternatively, the CWG aggregate may be pre-blended with manufactured sand and cement, and then supplied in the form of pre-packed dry plastering mortar. In general, the quality control of using pre-packed dry mortar materials is better than batching the various ingredients on site. Moreover, the mortar supplier should know by tests and experience the appropriate amount of water to be added and thus should be able to explicitly specify the amount of water to be added. With the amount of water to be added explicitly specified, the workers need only add the specified amount of water without having to determine the appropriate amount of water to be added by trial and error on site.

5. Feasibility of Using Recycled Old Concrete as Aggregate for Concrete and Mortar

This part of the testing program was to study the feasibility of crushing and processing old concrete for recycling as aggregate for concrete and mortar.

Millions of tonnes of old concrete are generated as inert solid waste every year in Hong Kong. The Hong Kong SAR Government has been promoting the crushing of old concrete to produce recycled aggregate for reuse in new construction. However, the recycled aggregate, especially the fine portion, tends to have old cement paste adhered onto the particle surfaces that may adversely affect the quality of the concrete or mortar produced. Hence, most engineers hesitate to use recycled aggregate. Currently, the usage of recycled aggregate (mainly in the production of precast paving blocks) is very low and most of the old concrete is just dumped as waste in landfills or shipped to outside Hong Kong.

To increase the recycling rate of old concrete, we need to make better use of crushed old concrete, which is available as grade 200 recycled rockfill from government fill banks. The cheapest way is to use the crushed old concrete as a filling material in reclamation works, earth works, road works and pipe laying works.

To allow greater use of recycled coarse aggregate in concrete works other than precast concrete paving blocks, there is a need to increase the allowable percentage replacement of fresh natural coarse aggregate by recycled coarse aggregate in concrete up to 35 MPa. But first of all, we need to improve the quality of the recycled coarse aggregate by removing the old cement paste on the surfaces of the aggregate particles. It is envisaged that the old cement paste can be removed by grinding the coarse aggregate particles using the grinding technology being adopted in the production of manufactured sand to improve particle roundness. However, since recycled coarse aggregate is not really a river sand substitute, research on improving the quality of recycled coarse aggregate for greater use of recycled coarse aggregate is outside the scope of the present study on river sand substitutes.

The present research should focus more on the possible use of recycled fine aggregate as river sand substitute in mortar. In the original research proposal, it was suggested to seek help from the quarry operators and manufactured sand suppliers to produce the following two types of recycled fine aggregate for testing:

CRFA – crushed recycled fine aggregate with only crushing for size reduction applied and no grinding applied.

GRFA – ground recycled fine aggregate with grinding applied after crushing to remove old cement paste adhered onto particle surfaces.

However, none of the quarry operators and manufactured sand suppliers contacted is interested in producing recycled concrete aggregate for testing. In fact, they are rather pessimistic about the future of the old concrete recycling industry in Hong Kong. Nevertheless, Prof. Albert K.H. Kwan has recently contacted LVFAR Green Technology Corp (LVFAR), who have a factory in Shenzhen crushing and recycling about one million tons of construction and demolition waste per year. They have sent some samples of their recycled fine aggregate, which belongs to the CRFA type, to The University of Hong Kong for testing. They are not producing any recycled fine aggregate of the GRFA type, which to them is much too expensive to produce. Nevertheless, they are using 100% recycled fine aggregate in some of their building products, such as precast paving blocks and pre-packed dry mortar.

In theory, the recycled fine aggregate should be air classified to control its fines content. However, the recycled fine aggregate samples sent to The University of Hong Kong have not been processed by any means to control their fines contents. On receipt, the recycled fine aggregate samples have been tested to have fines contents of about 12%. To control the fines contents of these recycled fine aggregate samples, the recycled fine aggregate samples were first mechanically sieved to remove all the fines contained therein and then the right amounts of fines were put back to produce recycled fine aggregate samples with different prescribed fines contents for testing. It is envisaged that with the fines content controlled, even recycled fine aggregate of the CRFA type may be good enough to be used up to 100% in low grade concrete and mortar for plastering, rendering, screeding and masonry.

To study the possible use of recycled fine aggregate up to 100% in concrete and mortar, a testing program has been worked out, as depicted in Table 20 below. In the testing program, there are four combinations of W/C ratio ranging from 0.30 to 0.60, two combinations of PV ranging from 42% to 48%, two combinations of fines content ranging from 5% to 10%, but only one type of recycled fine aggregate, namely the CRFA type (no recycled fine aggregate of the GRFA was available for testing). The tests carried out were the same as in the previous testing programs.

Table 20. Testing program on possible use of recycled fine aggregate

Water/ cement ratio	Paste volume (%)	Fines content (%)	Type of recycled fine aggregate
0.30	42	5, 10	CRFA
	48	5, 10	CRFA
0.40	42	5, 10	CRFA
	48	5, 10	CRFA
0.50	42	5, 10	CRFA
	48	5, 10	CRFA
0.60	42	5, 10	CRFA
	48	5, 10	CRFA

The recycled fine aggregate has a maximum size of 5.0 mm. It has been processed by mechanical sieving to have a fines content of either 5.0% or 10%. The particle size distributions of the CRFA with 5% fines and the CRFA with 10% fines, as determined by mechanical sieving, are presented in Figure 16. The CRFA with 5% fines and the CRFA with 10% fines were measured to have the same relative density of 2.29 but different water absorptions of 9.0% and 12.0%, respectively. In determining the amount of water to be added to the trial mortar mixes, the water absorption of the CRFA was allowed for.

The cement used was an ordinary Portland cement (OPC) of strength class 52.5 N complying with BS EN 197-1: 2000. The relative density of the cement has been measured as 3.11. Its particle size distribution, as measured using a laser diffraction particle size analyzer, is presented in Figure 16.

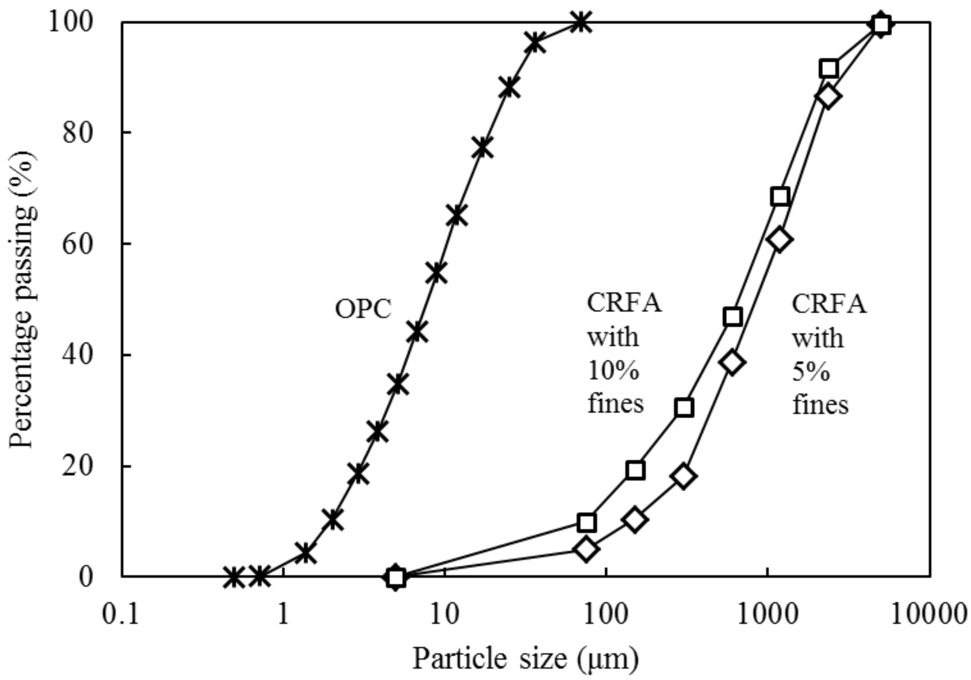

Figure 16. Particle size distributions of OPC and CRFA

The detailed test results are presented in the following tables.

Table 21. Test results of mortar mixes with PV = 42% and CRFA used

Mix no. (W/C-PV-Fines%)	Slump (mm)	Flow spread (mm)	Adhesion (g)	7-day cube strength (MPa)	Trowel-ability	7-day pull-out strength (MPa)
0.30-42-5	Much too dry to be mixed					
0.30-42-10						
0.40-42-5	5	1	2.0	45.8	Slight wet	0.44
0.40-42-10	5	1	1.9	34.5	Optimum	1.86
0.50-42-5	21	25	4.4	29.7	Wet	Not done
0.50-42-10	15	11	2.9	24.8	Slight wet	0.71
0.60-42-5	27	40	6.0	19.0	Too wet	Not done
0.60-42-10	32	64	6.2	17.2	Too wet	Not done

These results show that:
(1) the fines content in the recycled fine aggregate has significant adverse effect on the strength,
(2) at a fines content of 5%, a maximum 7-day strength of 45.8 MPa can be achieved,
(3) at a fines content of 10%, a maximum 7-day strength of 34.5 MPa can be achieved,
(4) the suitable range of W/C ratio for trowelling is around 0.45, and
(5) at a fines content of not more than 10%, a pull-out strength of at least 0.5 MPa can be achieved.

Table 22. Test results of mortar mixes with PV = 48% and CRFA used

Mix no. (W/C-PV-Fines%)	Slump (mm)	Flow spread (mm)	Adhesion (g)	7-day cube strength (MPa)	Trowel-ability	7-day pull-out strength (MPa)
0.30-48-5	Much too dry to be mixed					
0.30-48-10						
0.40-48-5	12	6	3.1	45.6	Slight wet	0.55
0.40-48-10	18	4	4.2	38.0	Slight wet	0.70
0.50-48-5	29	60	7.5	30.5	Too wet	Not done
0.50-48-10	31	58	11.4	26.4	Too wet	Not done
0.60-48-5	39	70	12.3	21.1	Too wet	Not done
0.60-48-10	45	109	13.9	18.2	Too wet	Not done

These results show that:
(1) the fines content in the recycled fine aggregate has significant adverse effect on the strength,
(2) at a fines content of 5%, a maximum 7-day strength of 45.6 MPa can be achieved,
(3) at a fines content of 10%, a maximum 7-day strength of 38.0 MPa can be achieved,
(4) the suitable range of W/C ratio for trowelling is around 0.40, and
(5) at a fines content of not more than 10%, a pull-out strength of at least 0.5 MPa can be achieved.

For detailed analysis, the trowelability is plotted against the slump in Figure 17 and the 7-day cube strength is plotted against the fines content in Figure 18.

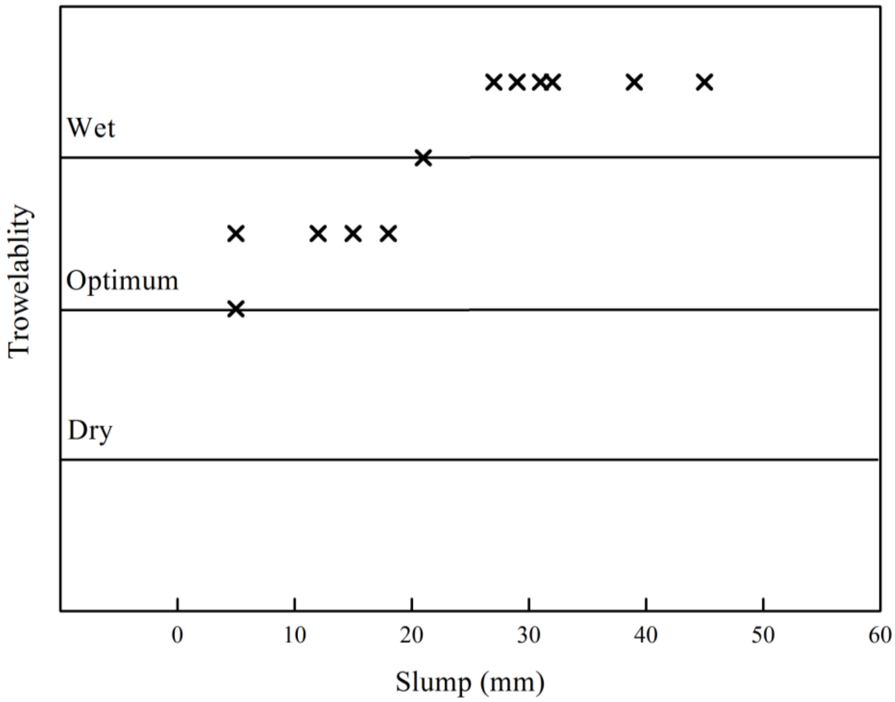

Figure 17. Trowelability plotted against slump

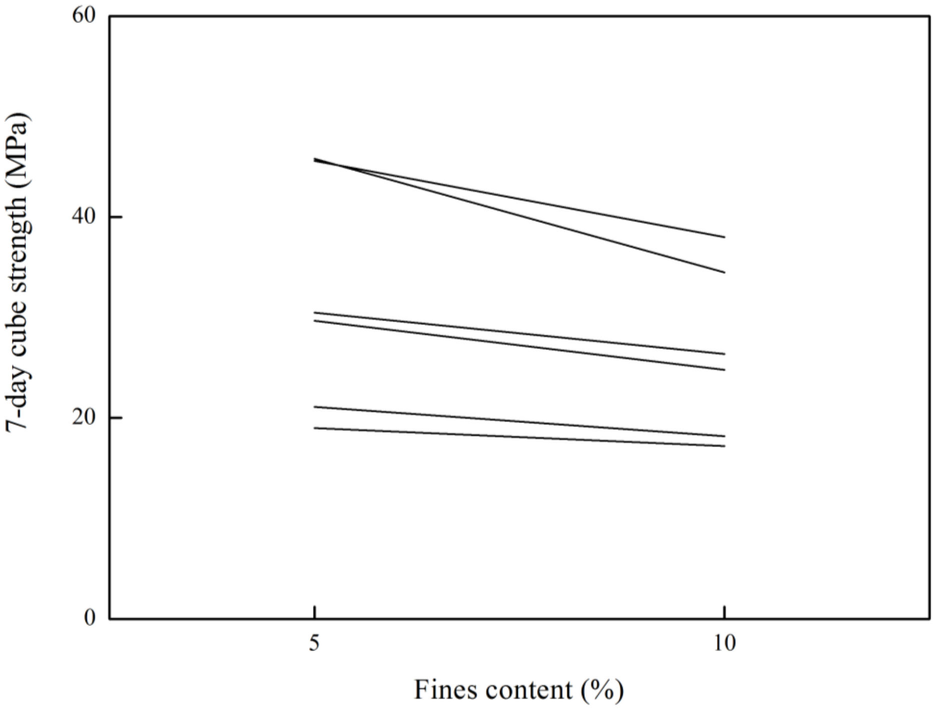

Figure 18. 7-day cube strength against fines content in CRFA

From Figure 17, it is seen that a slump of 10 ± 5 mm often yielded a trowelability rating of “Slight wet” instead of “Optimum”. In this particular case, the difficulty encountered was that although the measured slump was within the optimum range of 10 ± 5 mm, the mortar still appeared to drip slightly downwards after plastering (that was why the trowelability rating was recorded as “Slight wet”). One possible reason is that the water absorption of the CRFA was much too high (the CRFA with 5% fines and the CRFA with 10% fines have water absorptions of 9.0% and 12.0%, respectively) and the additional water added to allow for the water absorption had rendered the mortar mix relatively wet. Perhaps, for mortar made with CRFA, care should be taken in allowing for the water absorption of the aggregate to avoid the mortar mix from becoming wetter than expected.

From Figure 18, it is noted that the fines content has significant adverse effect on the 7-day cube strength. This is because the fines content in the recycled fine aggregate is mainly the cement paste in the old concrete, which generally have a relatively low strength.

Summarizing, the test results of the mortar mixes made with CRFA reveal that:

(1) The fines content has significant adverse effect on the strength. Hence, there is a necessity to control the fines content in the recycled fine aggregate at not higher than 10% and preferably at not higher than 5%.

(2) At a fines content of 5%, a maximum 7-day cube strength of at least 45 MPa can be achieved, whereas at a fines content of 10%, a maximum 7-day cube strength of 38 MPa can be achieved. Such 7-day strengths should be high enough for the production of grade 30 concrete (good for precast paving blocks in footpaths) and grade 20 concrete (good for blinding layers and non-structural concrete), respectively.

(3) Regardless of the PV, the suitable range of W/C ratio for trowelling is rather narrow. At a PV of 42%, the suitable W/C ratio for trowelling is around 0.45, whereas at a PV of 48%, the suitable W/C ratio for trowelling is around 0.40.

(4) A higher fines content of up to 10% does not necessary cause problem in trowelling. At a fines content of not more than 10%, a pull-out strength of 0.5 MPa can be achieved.

Overall, the test results obtained so far are generally positive. Firstly, it should be possible to use 100% recycled fine aggregate in concrete. However, there is a necessity to control the fines content in the recycled fine aggregate at not higher than 5% when used to produce grade 30 concrete, and at not higher 10% when used to produce grade 20 concrete. Secondly, it should be possible to use 100% recycled fine aggregate in mortar for plastering. The suitable range of W/C ratio for trowelling is in general rather narrow but at the right W/C ratio, a pull-out strength of at least 0.5 MPa can be achieved. Although a fines content of up to 10% is still acceptable, it is considered advisable to limit the fines content at not higher than 5% because a larger variation in fines content would lead to a larger variation in water absorption and eventually difficulty on site in determining the right amount of water to be added to the mortar mix.

Only a small quantity of recycled fine aggregate has been tested in this study. Hence, the possible variation in quality of the recycled fine aggregate has not been reflected in the test results. It is expected that the quality of recycled fine aggregate can be quite variable. To render the quality of fine aggregate more consistent, one possible way is to blend 50% recycled fine aggregate with 50% manufactured sand (processed crushed rock fine) so that the quality variation would become smaller. However, such usage of recycled fine aggregate only up to 50% would reduce the recycling rate of old concrete. Nevertheless, even with only 50% recycled fine aggregate used in various kinds of mortar works, the recycling rate of construction and demolition waste in Hong Kong can be substantially increased and the demand of river sand as fine aggregate for mortar works can be greatly decreased.

- End of Appendix B -

Appendix C

Report on Field Trials on Use of Manufactured Sand in Plastering

1. Introduction

As a part of the research project “Research on River Sand Substitutes for Concrete Production and Cement Sand Mortar Production (Phase Two)”, field trials on the use of manufactured sand in plastering have been carried out. The field trials were to invite experienced workers to evaluate the trowelability of cement sand mortar made with manufactured sand.

Two manufactured sand samples were obtained for testing. The first sample was provided by Man Fai Tai Holdings Ltd, who is currently the only supplier of manufactured sand for cement sand mortar in Hong Kong. The second sample was provided by Alliance Concrete Ltd, who currently has no interest in supplying manufactured sand for cement sand mortar in Hong Kong and is producing manufactured sand solely for use in concrete production. According to Man Fai Tai and Alliance, both the two manufactured sand samples were obtained from crushed rock fine processed by air classification to have the fines content controlled at relatively low levels.

The first sample provided by Man Fai Tai is herein named as MS1 whereas the second sample provided by Alliance is herein named as MS2. For comparison, a river sand sample obtained from the market was also used in the trial; it is herein named as RS.

2. Properties of Manufactured Sand Samples

The particle size distributions of the two manufactured sand samples, MS1 and MS2, and the river sand sample, RS, are presented in the following table.

Table 1. Particle size distributions of MS1, MS2 and RS

Sieve size	Cumulative percentage passing (%)		
	MS1	MS2	RS
5.0 mm	100.0	100.0	99.5
2.36 mm	97.2	84.0	94.2
1.18 mm	74.9	58.9	79.5
600 µm	46.2	37.5	52.4
300 µm	18.9	20.0	19.1
150 µm	5.2	8.2	2.8
75 µm	0.6	2.5	0.5
0	0.0	0.0	0.0

From the above table, it can be seen that MS1 has 2.8% coarser than 2.36 mm and 0.6% finer than 75 µm, and that MS2 has 16.0% coarser than 2.36 mm and 2.5% finer than 75 µm. Comparatively, MS1 is on average finer and has a lower fines content of 0.6% whereas MS2 is on average coarser and has a higher fines content of 2.5%. MS1 may be regarded as a fine aggregate with a maximum particle size of 2.36 mm whereas MS2 may be regarded as a fine aggregate with a maximum particle size of 5.0 mm.

3. Field Trials on the Uses of Manufactured Sand in Plastering

Thanks to the arrangements made by Mr. Ho Wai Wah, Construction Industry Council and Hop Yuen Building Materials Ltd, two field trials on the use of manufactured sand in plastering have been carried out.

First plastering trial:

The first plastering trial was carried out at the Kowloon Bay Training Centre of Construction Industry Centre on March 24, 2015. During the trial, a total of 5 mortar mixes were produced for testing. The mix details of the 5 mortar mixes, named as MM1, MM2, MM3, MM4 and MM5, are given in the following table.

Table 2. Mix details of mortar mixes produced in first plastering trial

Mortar mix no.	Fine aggregate	Water: cement: sand ratio (by weight)
MM1	MS1	0.40: 1.0: 2.5
MM2	MS1	0.45: 1.0: 2.5
MM3	MS1	0.50: 1.0: 2.5
MM4	MS2	0.50: 1.0: 2.5
MM5	MS2	0.55: 1.0: 2.5

All plastering trials were conducted on vertical concrete surfaces, which were pre-wetted with water for about 10 minutes and then wiped dry before the plastering.

MM1 was found to be a bit too dry, rather un-cohesive, and quite difficult to apply. It could be applied up to a thickness of about 10 mm by hard pressing but the mortar layer formed appeared to be rather unstable because it tended to slip downwards after application. Nevertheless, the mortar surface could be troweled smooth. The workers who did the trial commented that the water content of this mortar mix was significantly lower than what they would normally add. Overall, the results were not satisfactory.

MM2 was found to have the right consistence for plastering (i.e. neither too dry nor too wet) and good cohesiveness. It could be applied up to a thickness of about 10 mm by hard pressing. Nevertheless, the mortar surface could be troweled smooth. The workers who did the trial commented that the force required to press the mortar mix against the concrete surface was a bit high and that this was because the water content of this mortar mix was still lower than what they would normally add. Overall, the results were satisfactory.

MM3 was found to have the right consistence for plastering (i.e. neither too dry nor too wet) and good cohesiveness. It could be applied up to a thickness of about 15 mm without hard pressing and the mortar surface could be troweled smooth quite easily. The workers who did the trial commented that this mortar mix was easier to apply than MM2 and that this was because the water content of this mortar mix was just right and about the same as what they would normally add. Overall, the results were satisfactory.

MM4 was found to be a bit dry but sufficiently cohesive. It could be applied up to a thickness of about 10 mm by hard pressing. Despite the presence of 16% by weight of particles larger than 2.36 mm, the mortar surface could be troweled smooth, though slightly more difficult. The workers who did the trial commented that the water content of this mortar mix was slightly lower than what they would normally add. Overall, the results were satisfactory.

MM5 was found to have the right consistence for plastering (i.e. neither too dry nor too wet) and good cohesiveness. It could be applied up to a thickness of about 15 mm without hard pressing and the mortar surface could be troweled smooth quite easily. However, it was noted that after plastering, the mortar layer formed had a slight tendency to drip downwards. The workers who did the trial commented that this mortar mix was easier to apply than MM4 and that this was because the water content of this mortar mix was just right and about the same as what they would normally add. Overall, the results were satisfactory.

After hardening, the plastered concrete panels were sent back to the laboratory of The University of Hong Kong for pull-out tests at the age of 7 days. For each plastered concrete panel, three pull-out tests were carried out. The pull-out test results are tabulated in the following table.

Table 3. Pull-out test results of first plastering trial

Mortar mix no.	Thickness of plaster (mm)	7-day pull-out strength (MPa)			
		Test 1	Test 2	Test 3	Average
MM3	7	2.04	1.78	0.13	1.32
MM3	15	0.59	0.83	0.17	0.53
MM4	7	0.16	0.13	0.10	0.13
MM5	15	0.39	0.39	1.53	0.77

From the above table, it can be seen that in general, the pull-out strength fluctuated quite substantially, probably because the pull-out strength was highly sensitive to the workmanship (for instance, whether appropriate pressure had been applied during plastering). Nevertheless, for the mortar mix MM3, fairly good average pull-out strengths of higher than 0.5 MPa were achieved. For the mortar mix MM4, a rather low average pull-out strength of lower than 0.5 MPa was achieved. Nevertheless, this should not be taken to imply that MS2 was not good; it was quite possible that the workmanship during plastering of MM4 was not good enough. For the mortar mix MM5, a fairly good average pull-out strength of significantly higher than 0.5 MPa was achieved. However, it was also noted that one shrinkage crack was formed on the plaster layer made of this mortar mix. Overall, judging from the above pull-out test results, it appears that for both MS1 and MS2, the most suitable water/cement ratio is around 0.50.

Second plastering trial:

The second plastering trial was carried out at the Training Centre of Hop Yuen Building Materials Ltd in Kowloon Bay on April 2, 2015. During the trial, a total of 5 mortar mixes were produced for testing. The mix details of the 5 mortar mixes, named as MM6, MM7, MM8, MM9 and MM10, are given in the following table.

Table 4. Mix details of mortar mixes produced in second plastering trial

Mortar mix no.	Fine aggregate	Water: cement: sand ratio (by weight)
MM6	MS1	0.40: 1.0: 2.5
MM7	MS1	0.45: 1.0: 2.5
MM8	MS1	0.50: 1.0: 2.5
MM9	MS1	0.55: 1.0: 2.5
MM10	RS	0.50: 1.0: 2.5

The plastering trials were conducted on vertical concrete surfaces and where possible also on the ceiling of a concrete slab, which were pre-wetted with water for about 10 minutes and then wiped dry before the plastering.

MM6 was found to be a bit too dry, rather un-cohesive, and quite difficult to apply. It could be applied onto a vertical concrete surface up to a thickness of 10 mm by hard pressing but the mortar layer formed appeared to be rather unstable because it tended to slip downwards after application. It could not be applied onto the ceiling of a concrete slab. Nevertheless, the mortar surface could be troweled smooth. The worker who did the trial commented that the water content of this mortar mix was significantly lower than what he would normally add. Overall, the results were not satisfactory.

MM7 was found to have the right consistence for plastering (i.e. neither too dry nor too wet) and good cohesiveness. It could be applied onto a vertical concrete surface up to a thickness of 10 mm by hard pressing but could not be applied onto the ceiling of a concrete slab. Nevertheless, the mortar surface could be troweled smooth. The worker who did the trial commented that although the force needed to press the mortar mix against the concrete surface was a bit high, the water content of this mortar mix was only slightly lower than what he would normally add. Overall, the results were satisfactory.

MM8 was found to have the right consistence for plastering (i.e. neither too dry nor too wet) and good cohesiveness. It could be applied onto a vertical concrete surface up to a thickness of 15 mm without hard pressing and onto the ceiling of a concrete slab up to a thickness of 7 mm by hard pressing. Moreover, the mortar surface could be troweled smooth quite easily. The worker who did the trial commented that this mortar mix was easier to apply than MM7 and that this was because the water content of this mortar mix was just right and about the same as what he would normally add. Overall, the results were satisfactory.

MM9 was found to be slightly too wet but still quite cohesive. It was relatively easy to work with and trowel smooth. It could be applied onto a vertical concrete surface up to a thickness of 15 mm without hard pressing but the mortar layer formed had a tendency to drip downwards. It could be applied onto the ceiling of a concrete slab up to a thickness of 5 mm by only light pressing but the mortar layer formed had a tendency to drip downwards. The worker who did the trial commented that the water content of this mortar mix was slightly higher than what he would normally add. Overall, the results were marginally satisfactory.

MM10 was found to have the right consistence for plastering (i.e. neither too dry nor too wet) and good cohesiveness. It could be applied onto a vertical concrete surface up to a thickness of 15 mm without hard pressing and onto the ceiling of a concrete slab up to a thickness of 10 mm by hard pressing. Moreover, the mortar surface could be troweled smooth quite easily. The worker who did the trial commented that the trowelability of this mortar mix was similar to that of MM8. Overall, the results were satisfactory.

After hardening, the plastered concrete panels were sent back to the laboratory of The University of Hong Kong for pull-out tests at the age of 7 days. For each plastered concrete panel, three pull-out tests were carried out. The pull-out test results are tabulated in the following table.

Table 5. Pull-out test results of second plastering trial

Mortar mix no.	Thickness of plaster (mm)	7-day pull-out strength (MPa)			
		Test 1	Test 2	Test 3	Average
MM7	13	0.61	0.32	0.31	0.41
MM8	13	0.14	1.88	1.00	1.01
MM9	15	0.62	0.70	0.83	0.71
MM10	15	0.77	0.13	0.03	0.31

From the above table, it can be seen that in general, the pull-out strength fluctuated quite substantially, probably because the pull-out strength was highly sensitive to the workmanship (for instance, whether appropriate pressure had been applied during plastering). For the mortar mix MM7, a fairly low average pull-out strength of lower than 0.5 MPa was achieved, probably because of inadequate workmanship and intrinsic variation in pull-out strength. For the mortar mixes MM8 and MM9, fairly high average pull-out strengths of higher than 0.5 MPa were achieved. Lastly, for the mortar mix MM10, a lower than expected average pull-out strength of lower than 0.5 MPa was achieved; again this may be attributed to inadequate workmanship and intrinsic variation in pull-out strength. No shrinkage crack was found in all the plaster layers formed of these mortar mixes. Overall, judging from the above pull-out test results, it may be concluded that for MS1, the most appropriate water/cement ratio is around 0.50 and that at this water/cement ratio, the trowelability and pull-out strength of mortar made with MS1 are at least as good as those of mortar made with RS.

4. Conclusions

Summing up, the following conclusions may be drawn:

(1) The manufactured sand MS1, which has a fines content of 0.6% and a maximum particle size of 2.36 mm, is suitable for use as fine aggregate in mortar for plastering works. With MS1 used as fine aggregate, the mortar mix should be designed to have a cement:sand ratio of 1:2.5 and a water/cement ratio of around 0.50. At a water/cement ratio of 0.50 (or any water/cement ratio giving the right consistence), the mortar could be applied to both vertical concrete walls and concrete slab ceilings, and an average pull-out strength of higher than 0.5 MPa could be achieved. At a water/cement ratio of lower than or higher than 0.50, the mortar might become too dry or too wet and could be applied only to vertical concrete walls but not concrete slab ceilings. Hence, the suitable range of water/cement ratio is rather narrow and, therefore, careful control of the water content and good judgement of consistence are needed.

(2) The manufactured sand MS2, which has a fines content of 2.5% and a maximum particle size of 5.0 mm, is also suitable for use as fine aggregate in mortar for plastering works, although it was originally intended for use as fine aggregate in concrete production. With MS2 used as fine aggregate, the mortar mix should be designed to have a cement: sand ratio of 1:2.5 and a water/cement ratio of around 0.50. At a water/cement ratio of 0.50 (or any water/cement ratio giving the right consistence), the mortar could be applied to vertical concrete walls and concrete slab ceilings (the plastering trial in phase one of this research had demonstrated that this same manufactured sand could be applied to concrete slab ceilings). Due to the presence of some relatively coarse particles (particles larger than 2.36 mm), the troweling tended to be slightly more difficult, although the mortar surfaces could still be troweled smooth. Hence, it might be better to limit the maximum particle size of manufactured sand to 2.36 mm.

(3) The river sand RS, which is quite commonly used in the construction industry, is also suitable for use as fine aggregate in mortar for plastering works. With RS used, the mortar mix should be designed to have a cement:sand ratio of 1:2.5 and a water/cement ratio of around 0.50. With a suitable water/cement ratio adopted, the mortar could be applied to both vertical concrete walls and concrete slab ceilings. However, it should be borne in mind that the characteristics (mainly the fineness and moisture content) of river sand could fluctuate a lot (depending on where it was dredged) and thus the exact amount of water to be added has to be judged during mixing and good experience and skill are needed to produce a mortar mix with right consistence for application onto vertical concrete walls and concrete slab ceilings.

- End of Appendix C -

Appendix D

Recommended Specifications for Aggregates for Mortar

1. BACKGROUND

This Recommended Specifications has been prepared as part of the deliverable of a Construction Industry Council research project entitled "Research on River Sand Substitutes for Concrete Production and Cement Sand Mortar Production (Phase Two)". It provides the general requirements for aggregates for mortar in Hong Kong.

The preparation of this Recommended Specifications is to help resolve the problem that the European Standard BS EN 13139: Aggregates for Mortar is inapplicable in Hong Kong and in fact incompatible with the local Construction Standard CS3: 2013 Aggregates for Concrete, but there is up to now no local standard for aggregates for mortar. At the same time, there has been acute shortage of river sand, which has been commonly used as aggregates for mortar, but the unprocessed crushed rock fine available in the market is not a suitable aggregate for mortar. During the research project, it has been found that the unprocessed crushed rock fine, which is intended for use as aggregates for concrete, is unsuitable as aggregates for mortar mainly because of its relatively high fines content and large aggregate size.

To be used as aggregates for mortar, the crushed rock fine needs to be processed to control its fines content, maximum aggregate size, grading and other characteristics. However, without a standard stipulating the requirements, the aggregate producers and suppliers have no guidelines to follow. In fact, there has been little research on how the aggregate, whether natural from river sand or crushed rock fine, or recycled from inert solid waste materials, should be processed to optimize their various characteristics for best performance of the mortar produced. Based on the test results from this research project and consultation with stakeholders in the construction industry, the general requirements for aggregates for mortar have been worked out and incorporated into this Recommended Specification as an interim measure until a formal local construction standard for aggregates for mortar is issued by the Hong Kong SAR Government. It is hoped that after some years, this Recommended Specifications could become a good basis for a formal local standard.

Before closing, the contributions from the following organizations to the drafting of this Recommended Specifications are gratefully acknowledged:

- Standing Committee on Concrete Technology of HKSAR Government
- Public Works Central Laboratory of HKSAR Government
- Buildings Department, HKSAR Government
- Hong Kong Construction Association
- General Building Contractors Association
- Hong Kong Concrete Producers Association
- Institute of Quarrying, Hong Kong Branch
- Import Aggregates Suppliers Association Ltd.
- Hong Kong Construction Sub-contractors Association
- Hong Kong Plastering Sub-contractors Association
- H.K. Brick-laying & Construction Trade Workers' Union

- Hong Kong Institute of Engineers, Materials Division
- Hong Kong Concrete Institute
- Contractor's Authorized Signatory Association

2. SCOPE, STANDARDS AND TERMS

2.1 SCOPE

This Recommended Specifications specifies the requirements of the properties of natural aggregates and recycled aggregates, obtained by processing natural and recycled materials respectively, and mixtures of these aggregates for use in production of mortar. It also specifies the requirements of quality control and the methods for testing of aggregates. These requirements shall apply to both natural and recycled aggregates unless specified otherwise.

This Recommended Specifications is limited to natural aggregates and recycled aggregates. It covers aggregates having an oven-dried particle density not less than 2,000 kg/m^3, and does not cover lightweight aggregates and heavyweight aggregates.

The mortars to be produced are limited to floor screeds, sprayed mortars, repair mortars, grouts, rendering and plastering mortars, and masonry mortars.

2.2 ASSOCIATED STANDARDS

The Hong Kong SAR Government has, in May 2013, published a local Construction Standard CS3: 2013 Aggregates for Concrete. This standard is substantially different from the corresponding European Standard BS EN 12620: Aggregates for Concrete, which does not suit the local conditions and is therefore not applicable in Hong Kong. To avoid referring to other standards that may be outdated or may not be applicable in Hong Kong, the Construction Standard CS3: 2013 is produced as a self-contained standard with all the requirements explicitly stated and all the test methods given.

On the other hand, there is no local construction standard for aggregates for mortar, although the European Standard BS EN 13139: Aggregates for Mortar has also been found to be inapplicable in Hong Kong. This Recommended Specifications is to help resolve this problem. To be compatible with the Construction Standard CS3: 2013 and to make good use of the stipulations given therein, this Recommended Specifications follows the general requirements and employs the same test methods given in CS3: 2013. For this reason, this Recommended Specifications refers extensively to CS3: 2013.

To draw on the credential of the European Standard BS EN 13139: Aggregates for Mortar, this Recommended Specifications is written in such a way that wherever applicable, the requirements stipulated in BS EN 13139 are followed. Where the requirements stipulated in BS EN 13139 cannot be followed, the requirements in this Recommended Specifications are stipulated based on considerations of the local conditions.

2.3 TERMS AND DEFINITIONS

For the purpose of this Recommended Specifications, the following terms and definitions shall apply.

2.3.1 Aggregate

Granular material used in construction; it may be natural or recycled.

2.3.2 Natural aggregate

Aggregate from mineral sources subjected to nothing more than mechanical processing.

2.3.3 Recycled aggregate

Aggregate resulting from the processing of old concrete or other inert solid waste materials.

2.3.4 Coarse aggregate

Aggregate mainly retained on a 5 mm test sieve and containing no more finer material than is permitted.

2.3.5 Fine aggregate

Aggregate mainly passing a 5 mm test sieve and containing no more coarser material than is permitted.

2.3.6 Fines

Particle size fraction of an aggregate passing the 75 µm test sieve.

2.3.7 Grading

Particle size distribution expressed as the percentages by mass passing a specified set of test sieves.

2.3.8 Test sieve

Test sieve of metal wire cloth complying with ISO 3310-1:2000 or of square-hole perforated metal plate complying with ISO 3310-2:1999.

2.3.9 Constant dry mass

A test portion or test specimen is regarded to have achieved constant dry mass after it has been heated in an oven at a temperature of 105 ± 5℃ for at least 24 h or its change in mass is within 0.1% when weighed at an interval of 1 h after heating at 105 ± 5℃ for a minimum of 16 h.

3. GEOMETRICAL REQUIREMENTS

3.1 GENERAL

The geometrical properties of aggregates shall be determined with consideration of the application conditions and origin of the aggregates, and in accordance with the test methods specified in CS3: 2013.

3.2 AGGREGATE SIZES

All aggregates shall be described in terms of aggregate sizes using the designations *d*/*D*, in which *d* is the lower sieve size and *D* is the upper sieve size. The presence of a small amount of oversized particles retained on the upper sieve and a small amount of undersized particles passing the lower sieve is accepted. In other words, an aggregate of size *d*/*D* is an aggregate mainly retained on the *d* size test sieve and mainly passing the *D* size test sieve.

In this Recommended Specifications, aggregates for mortar are limited in their grading to $D \leq 5.0$ mm. In other words, aggregates for mortar are limited to fine aggregates with an upper sieve size of not larger than 5.0 mm. Depending on the thickness of mortar application and the surface finish wanted, the upper sieve size of the aggregate may be selected between 5.0 mm and 2.36 mm.

3.3 GRADING

The grading (i.e. C, M or F) of fine aggregates, determined in accordance with Section 10 of CS3: 2013, shall be declared and documented by the aggregate producer or supplier. This grading shall comply with both the overall limits and the limits for the declared grading given in Tables 2.1 and 2.2 for fine aggregates of size 0/5.0 mm and 0/2.36 mm, respectively. In addition, not more than one in ten consecutive samples shall have a grading outside the limits for the declared grading.

Table 2.1 - Grading of fine aggregates of size 0/5.0 mm

Sieve size	Percentage by mass passing test sieves (%)			
	Overall limits	Limits for declared grading		
		C	M	F
10 mm	100	-	-	-
5 mm	89-100	-	-	-
2.36 mm	60-100	60-100	65-100	80-100
1.18 mm	30-100	30-90	45-100	70-100
600 µm	15-100	15-54	25-80	55-100
300 µm	5-70	5-40	5-48	5-70
150 µm	0-20	-	-	-

Table 2.2 - Grading of fine aggregates of size 0/2.36 mm

Sieve size	Percentage by mass passing test sieves (%)			
	Overall limits	Limits for declared grading		
		C	M	F
5 mm	100	-	-	-
2.36 mm	89-100	-	-	-
1.18 mm	60-100	60-100	65-100	80-100
600 µm	30-100	30-90	45-100	70-100
300 µm	15-100	15-54	25-80	55-100
150 µm	5-70	5-40	5-48	5-70
75 µm	0-14	-	-	-

3.4 FINES CONTENT

The amount of material passing the 75 µm test sieve, determined in accordance with Section 10 of CS3: 2013, shall not exceed the quantities given in Table 2.3. The aggregate producer or supplier shall declare the class (i.e. Class F5, F10 or F14) of the aggregate for mortar.

Table 2.3 - Limits for fines content

Fines content class	Maximum percentage by mass passing 75 µm test sieve (%)
F5	5
F10	10
F14	> 10 and ≤ 14

Notes:
1. For floor screeds, sprayed mortars, repair mortars, grouts, and rendering and plastering mortars, F5 fine aggregates shall be used.
2. For masonry mortars, F10 or F14 fine aggregates shall be used.
3. For F14 fine aggregates, the methylene blue value, determined in accordance with Section 13 of CS3: 2013, shall be ≤ 1.4.

3.5 FOREIGN MATERIALS CONTENT

The maximum content of foreign materials in the aggregate, determined by manual sorting, shall not exceed the quantities given in Table 2.4.

Table 2.4 - Limits for foreign materials in the fine aggregate

Type of foreign materials	Maximum percentage by mass (%)
Wood and other material less dense than water	0.5
Other foreign materials (e.g. shell, metals, plastics, clay lumps, asphalt and tar etc.)	1.0

4. PHYSICAL REQUIREMENTS

4.1 GENERAL

The physical properties of aggregates shall be determined with consideration of the application conditions and origin of the aggregates, and in accordance with the test methods specified in this Standard.

4.2 PARTICLE DENSITY

The oven dried particle density of aggregates, determined in accordance with Section 17 of CS3: 2013, shall not be less than 2,000 kg/m^3.

4.3 DURABILITY

4.3.1 Drying shrinkage

The drying shrinkage of the aggregate, when determined in accordance with Section 20 of CS3: 2013, shall not exceed 0.075%.

4.3.2 Alkali-silica reactivity

The linear expansion of mortar-bars immersed in NaOH solution at elevated temperature, determined in accordance with Section 22 of Construction Standard CS1:2010 (CS1), shall be evaluated using Equation 22-1 of CS1. The potential alkali-reactivity of aggregates can then be obtained from Table 10 of CS1.

Alternatively, the concrete prism test in accordance with Section 23 of CS1 may also be used and the potential alkali-reactivity of aggregates can then be obtained from Table 13 of CS1.

5. CHEMICAL REQUIREMENTS

5.1 GENERAL

The chemical properties of aggregates shall be determined with consideration of the application conditions and origin of the aggregates, and in accordance with the test methods specified in CS3: 2013.

5.2 CHLORIDES

5.2.1 Water-soluble chloride ion content

The water-soluble chloride ion content of natural aggregates shall be determined in accordance with Cl. 21.3 of Section 21 of CS3: 2013.

5.2.2 Acid-soluble chloride ion content

The acid-soluble chloride ion content of recycled aggregates shall be determined in accordance with Cl. 21.4 of Section 21 of CS3: 2013.

5.2.3 Chloride ion content

The chloride ion contents of the natural aggregate, recycled aggregate and combined aggregate (natural and recycled aggregates combined) shall not exceed the limits given in Table 4.1.

Table 4.1 - Limits for chloride ion content

Type and use of mortar	Chloride ion content expressed as percentage by mass of combined aggregate (%)
Mortar containing embedded metal	0.05
Plain mortar (mortar not containing embedded metal)	0.15

The imposed chloride content limits are to minimize the risk of corrosion of metals embedded in mortar and avoid the formation of efflorescence on exposed surfaces of mortar.

If the mortar is structural (i.e. the mortar would become part of the concrete structure), the total chloride content derived from all constituents in the mortar shall be checked against the limits stipulated in the relevant concrete codes (the European Standard EN 206-1 or the local Code of Practice for Structural Use of Concrete, whichever is applicable).

5.3 SULPHUR CONTAINING COMPOUNDS

5.3.1 Acid-soluble sulphate content

The acid-soluble sulphate content of natural aggregates, when determined in accordance with Cl. 21.5 of Section 21 of CS3: 2013, shall not exceed 0.8% by mass.

The acid-soluble sulphate content of recycled aggregates, when determined in accordance with Cl. 21.5 of Section 21 of CS3: 2013, shall not exceed 1.0% by mass.

5.3.2 Total sulphur content

The total sulphur content of the natural aggregate, recycled aggregate and combined aggregate (natural and recycled aggregates combined), when determined in accordance with Cl. 21.6 of Section 21 of CS3: 2013, shall not exceed 1.0% by mass.

5.4 OTHER CONSTITUENTS

Aggregates shall be free of organic substances. The aggregate producer or supplier shall demonstrate that the supplied aggregate is free of organic substances or alternatively the presence of organic substances does not affect the stiffening or hardening of mortar.

The presence of organic substances in the form of humus shall be determined in accordance with Cl. 21.7 of Section 21 of CS3: 2013. Where the test result under Cl. 21.7 is negative, the aggregate shall be considered to be free of organic substances. Otherwise the aggregate shall be further tested in accordance with Section 22 of CS3: 2013 to assess the effect of organic substances on the stiffening time and compressive strength of mortar. The organic substances shall be of such proportion that:

(a) the stiffening time of mortar test specimens does not increase by more than 120 minutes; and
(b) the 28-day compressive strength of mortar test specimens does not decrease by more than 20%.

- END of Appendix D -

Appendix E

Comments by Stakeholders on the Recommended Specifications for Aggregates for Mortar

1. Background

As a part (Objective 1) of the research project, a preliminary draft of a local construction standard entitled “Recommended Specifications for Aggregates for Mortar (Version 1.0)” has been produced and submitted together with Progress Report No.1 in September 2013.

This preliminary draft local standard is largely based on the existing standards in Europe, UK and China. To be compatible with the Hong Kong Construction Standard CS3: 2013 Aggregates for Concrete, the same standard sieve sizes in CS3: 2013 are followed in the draft local standard on aggregates for mortar. Moreover, the same style, same terminology, and same tests, if applicable, are also followed so that the same terms in the CS3: 2013 and the local standard on aggregates for mortar would have the same meaning and the same tests could be used for both aggregates for concrete and aggregates for mortar.

It is envisaged that the most important issue is the allowable fines content in the aggregate. Since the maximum allowable fines contents are quite different in the various existing standards in different countries, this issue could be quite controversial. On the other hand, there is the general concern on the presence of harmful substances (such as clay and dirt) in the fines and the high water demand of the mortar produced due to the large surface area of the fines (finer materials have larger specific surface area). Hence, certain limits on the fines content in the aggregate have to be imposed. It is just a matter of what limits should be imposed and whether the stakeholders could come to any agreement on any proposed limits.

After the Progress Meeting No. 1 held in September 2013, the preliminary draft Recommended Specifications was sent to the stakeholders (1) to (12) for consultation. Later on, as requested by Construction Industry Council, the preliminary draft Recommended Specifications was also sent to Buildings Department of HKSAR Government, i.e. stakeholder (13), and Contractor’s Authorized Signatory Association, i.e. stakeholder (14), for consultation. The full list of stakeholders consulted is as follows:

(1) Standing Committee on Concrete Technology of HKSAR Government;
(2) Public Works Central Laboratory of HKSAR Government;
(3) Hong Kong Construction Association;
(4) General Building Contractors Association;
(5) Hong Kong Concrete Producers Association;
(6) Institute of Quarrying Hong Kong Branch;
(7) Import Aggregates Suppliers Association Ltd.;
(8) Hong Kong Construction Sub-contractors Association;
(9) Plastering Sub-contractors Association;
(10) Brick-laying & Construction Trade Workers Union;
(11) Hong Kong Institution of Engineers Materials Division;
(12) Hong Kong Concrete Institute;
(13) Buildings Department of HKSAR Government; and
(14) Contractor’s Authorized Signatory Association.

Ir. Prof. Albert K.H. Kwan (AKHK) had also arranged meetings with the stakeholders to explain to them the rationale behind the draft Recommended Specifications and listen to their comments. The comments received are presented in the next section.

Based on the comments received, the preliminary draft Recommended Specifications was revised to become the revised draft Recommended Specifications entitled "Recommended Specifications for Aggregates for Mortar: 2015" and the revised draft was sent out for another round of consultation. The comments received are also presented in the next section.

2. Comments Received

2.1 Standing Committee on Concrete Technology of HKSAR Government

The preliminary draft Recommended Specifications was sent to the Standing Committee on Concrete Technology on November 26, 2013 to seek their comments. On January 2, 2014, Mr. K.C. Lam, the Chairman of Standing Committee on Concrete Technology, replied to AKHK as follows:
Thank you for your email dated 26.11.2013 seeking our comment on the draft "Recommended Specification for Aggregates for Mortar". The draft recommended specification was discussed at the meeting of the Standing Committee on Concrete Technology (SCCT) on 19 December 2013. Members of the SCCT note that the mortars are mainly for rendering and plastering in building works rather than in civil engineering works, and is therefore outside the ambit of SCCT's terms of reference. Therefore, the SCCT have no particular comment on the draft specification from the point of view of concrete technology. Should you have any queries, please do not hesitate to contact the Secretary of SCCT, Mr. H.D. Wong at telephone no. 2305 1289.

The revised draft Recommended Specifications was sent to the Standing Committee on Concrete Technology on March 22, 2015 for their advice and comments. So far, there was no reply from them. Presumably, they have no specific comments and no request for making any changes to the revised draft Recommended Specifications.

2.2 Public Works Central Laboratory of HKSAR Government

Both Mr. Peter Leung (Senior Engineer) and Mr. H.D. Wong (Engineer) of the Public Works Central Laboratory were members of the Standing Committee on Concrete Technology (SCCT). They replied verbally that they would discuss within the SCCT and their views or comments would be conveyed back to AKHK through the SCCT. In other words, they would not give any comments in addition to those of the SCCT.

The revised draft Recommended Specifications was sent to Mr. Greg Leung (Senior Engineer) and Mr. H.D. Wong on March 22, 2015 to seek their advice and comments. Mr. H.D. Wong replied on April 21, 2015 saying that they have no further comments on the revised draft Recommended Specifications from the laboratory testing point of view.

2.3 Hong Kong Construction Association

An email enclosing the draft Recommended Specifications was sent to the secretary general of HK Construction Association (HKCA) on November 27, 2013 to request the arrangement of a meeting. Eventually, a meeting between AKHK and HKCA (attended by Mr. David Leong and Mr. Derek Zen) was arranged and held on April 17, 2014. At the meeting, AKHK explained to HKCA the background of the river sand shortage problem and the Construction Industry Council (CIC) research project on river sand substitutes..

HKCA started by saying that they were aware of the river sand shortage problem. However, they emphasized that the Recommended Specifications should be practicable and not too complicated. Moreover, the river sand substitute should not alter the physical and chemical characters of the final products, e.g. mortar and cementitious adhesives. HKCA further suggested AKHK to contact other trade associations including subcontractor association to seek their views. AKHK responded by saying that mortar trials would be carried out before proposing any specification requirements to be imposed and that any specification requirements to be imposed would be to ensure fit for purpose of the fine aggregate to be used as river sand substitute. HKCA suggested that for non-structural applications, the durability requirements in Section 3.3 of the Recommended Specifications may not be suitable. They also raised two issues to be considered by AKHK: first, the cost implication of using manufactured sand instead of river sand, and second, the adaptability of workers to the use of manufactured sand. AKHK replied that the price of river sand fluctuates but seems to be rising with time. He added that eventually, we shall have no other option but to use manufactured sand instead of river sand. Regarding the adaptability of workers, some form of training will need to be provided to the workers. HKCA also suggested that the trowelability could vary with the quality or characteristics of the concrete surface; for instance, the trowlability of mortar onto steel formed concrete surface and the trowelability of mortar onto timber formed concrete surface could be different. AKHK replied that the effect of the formwork system used is another issue needing further research but in the meantime, the river sand substitute problem has to be resolved first. HKCA also requested AKHK to provide a briefing to their members after the completion of trials.

The revised draft Recommended Specifications was sent to Mr. Thomas Tse, General Secretary of HKCA, on March 22, 2015 to seek HKCA's advice and comments on the revised draft Recommended Specifications. So far, there was no reply from them. Presumably, they have no specific comments on the revised draft Recommended Specifications and no request for making any changes.

2.4 General Building Contractors Association

An email enclosing the preliminary draft Recommended Specifications was sent to Mr. David Tse and Mr. K.K. Pun of General Building Constructors Association on November 27, 2013 to request the arrangement of a meeting. So far, there was no response. Another email enclosing the preliminary draft Recommended Specifications again and asking for their advice and comments was sent to them on May 11, 2014 but there was no reply. Presumably, they have no specific comments on the preliminary draft.

The revised draft Recommended Specifications was sent to them on March 22, 2015 to seek their advice and comments. So far, there was no reply from them. Presumably, they have no specific comments and no request for making any changes to the revised draft Recommended Specifications.

2.5 Hong Kong Concrete Producers Association

An email enclosing the preliminary draft Recommended Specifications was sent to Mr. Frank Lo, Chairman of Hong Kong Concrete Producers Association (HKCPA), on November 27, 2013 to request the arrangement of a formal meeting. Since then, AKHK had met with some members of HKCPA on several occasions but so far, no formal meeting had been arranged and no specific comments on the preliminary draft Recommended Specifications were received. Nevertheless, according to unofficial comments from certain members of HKCPA, all concrete suppliers in Hong Kong have already adapted to the use of crushed rock fine as river sand substitute for the production of concrete and do not have any specific problems with finding suitable river sand substitutes.

The revised draft Recommended Specifications was sent to HKCPA on March 22, 2015 to seek their advice and comments. So far, there was no reply from them. Presumably, they have no specific comments and no request for making any changes to the revised draft Recommended Specifications.

2.6 Institute of Quarrying Hong Kong Branch

An email enclosing the preliminary draft Recommended Specifications was sent to Institute of Quarrying Hong Kong Branch (IOQ-HK) on November 27, 2013. Subsequently, a meeting between AKHK and IOQ-HK was held on March 11, 2014. At the meeting, IOQ-HK expressed the concern that the fines content in 0/2.36 mm fine aggregate tends to be higher than the fines content in 0/5.0 mm fine aggregate because when calculating the fines content as a percentage, the denominator in the 0/2.36 mm fine aggregate is smaller than the denominator in the 0/5.0 mm fine aggregate. As a result, it is generally more difficult to control the fines content in 0/2.36 fine aggregate than in 0/5.0 mm fine aggregate. AKHK explained that for the specification, it is difficult to impose different fines content limits to the 0/2.36 mm and 0/5.0 mm fine aggregates. IOQ-HK also suggested that the difference between class F3 fine aggregate (fines content ≤ 3%) and class F5 fine aggregate (fines content ≤ 3%)

is not really significant and the workers may not feel the difference at all, and for this reason, it may be simpler to remove the class F3 fine aggregate and just allow the use of class F5 fine aggregate in plastering and screeding works. AKHK said that he will consider this suggestion after the mortar troweling trials are completed. If the workers really feel no significant difference between the F3 and F5 fine aggregates, then perhaps the F3 class can be removed.

AKHK also explained that since 0/2.36 mm fine aggregate is generally preferred for use in mortar works, especially plastering and screeding, the aggregate manufacturers should consider producing two types of fine aggregate: 0/2.36 mm fine aggregate for use in mortar works and 0/5.0 mm fine aggregate for use in concrete production. IOQ-HK said it all depends on the market demand, but some manufacturers may just produce one type of fine aggregate so as to avoid the extra storage and handling needed for the other type of fine aggregate.

The revised draft Recommended Specifications was sent to IOQ-HK on March 22, 2015 to seek their advice and comments. So far, there was no reply from them. Presumably, they have no specific comments and no request for making any changes to the revised draft Recommended Specifications.

2.7 Import Aggregates Suppliers Association Ltd.

An email enclosing the preliminary draft Recommended Specifications was sent to Import Aggregates Suppliers Association Ltd. (IASA) on November 27, 2013. Subsequently, a meeting between AKHK and IASA was held on December 5, 2013. At the meeting, AKHK explained to IASA the background of the river sand shortage problem and the Construction Industry Council research project on river sand substitutes. IASA said they were well aware of the problem and were happy to see that the Construction Industry Council had taken the initiative to conduct this research, which will benefit the construction industry a lot. AKHK also briefed IASA the contents of the preliminary draft Recommended Specifications.

IASA advised that most of the river sand being used for mortar falls within the grading of F in Table 2.1 of the Recommended Specifications, which has a maximum aggregate size of 5.0 mm but at least 80% passing the 2.36 mm sieve. Hence, there may not be a necessity to specify a fine aggregate with a maximum aggregate size of 2.36 mm at all; instead, it may be simpler to just specify a fine aggregate with a maximum aggregate size of 5.0 mm and a grading of F instead of any fine aggregate with a maximum aggregate size of 2.36 mm. Nevertheless, an old Housing Department Specification was handed to AKHK. In the old Housing Department Specification, two types of fine aggregate were specified, one with a maximum aggregate size of 5.0 mm and the other with a maximum aggregate size of 2.36 mm. So, there had been a practice of specifying fine aggregate with a maximum aggregate size of 5.0 mm and fine aggregate with a maximum aggregate size of 2.36 mm for different applications. AKHK responded by saying that he understands that the aggregate suppliers do not wish to have too many different types of fine aggregate specified because of the additional space needed for stockpiling. He then added by saying that in actual practice, the most common type could be marketed at a lower price so that most users would order the most common type and the less common types would be manufactured and supplied only on special request.

Regarding the fines content, it is also noted that in the old Housing Department Specification, the allowable fines content in the sand (fine aggregate for mortar works) was 10% by weight. Hence, fine aggregate for mortar containing 10% fines content had been in use in Hong Kong. A member of IASA expressed the concern that in large scale production, it is not easy to control the fines content in the fine aggregate for mortar and hoped that the fines content limit imposed in the Recommended Specifications would not be too stringent.

IASA also advised that most mortars are for non-structural applications. They suggested that for non-structural applications, the requirements related to alkali-silica reactivity given in Section 3.3.2 should be waived. AKHK replied that the requirements related to alkali-silica reactivity apply to both concrete and mortar, and whether these requirements could be waived is mainly a matter of whether the concrete or mortar is structural or non-structural. He followed on by saying that he would discuss this point with other stakeholders in further consultations and consider this point in finalizing the Recommended Specifications.

The revised draft Recommended Specifications was sent to IASA on March 22, 2015 to seek their advice and comments. They replied on April 17, 2015 saying that they had no further comment on the Recommended Specifications and thanking AKHK for his great effort and consideration.

2.8 Hong Kong Construction Sub-contractors Association, Plastering Sub-contractors Association, and Brick-laying & Construction Trade Workers Union

An email enclosing the preliminary draft Recommended Specifications was sent to Mr. Eric Tse, Mr. P. Wong and Mr. P.T. Yeung of HK Construction Sub-contractors Associations, Plastering Sub-contractors Association and Brick-laying & Construction Trade Workers Union on November 27, 2013 to request the arrangement of a meeting. After then, another email enclosing the preliminary draft Recommended Specifications again was sent to them on May 11, 2014. Later, the revised draft Recommended Specifications was sent to them on March 22, 2015 to seek their advice and comments.

Eventually, a meeting among AKHK, Mr. Eric Tse, Mr. P. Wong and Mr. P.T. Yeung of HK Construction Sub-contractors Associations, Plastering Sub-contractors Association and Brick-laying & Construction Trade Workers Union, and Mr. P.S. Chan of Hong Kong & Kowloon Painters General Union was held at the Hong Kong Construction Industry Employees General Union on April 15, 2015. During the meeting, AKHK explained to them what the Construction Industry Council and AKHK have been doing for the Research on River Sand Substitutes for Concrete Production and Cement Sand Mortar Production (Phase Two). AKHK also explained to them the revised draft Recommended Specifications and showed them two separate samples of manufactured sand and one sample of river sand. Furthermore, AKHK informed them that two field trials by experienced workers have been carried out and showed them the pull-out test results.

In response, they first told AKHK that the current price of river sand was not HK$150 per ton, but had recently soared to about HK$180 per ton. They were quite appreciative of what the Construction Industry Council had done for the plastering and brick-laying trades. After inspecting the manufactured sand samples, they said the more angular particle shape of the manufactured sand is not a concern because an angular particle shape can actually enhance the interlocking action between sand particles. Furthermore, after listening to the laboratory test and field trial results, they commented that the manufactured sand to be used as a river sand substitute appeared to be acceptable. They also commented that in actual practice, they usually apply splatter dash onto the concrete walls before plastering. In the field trials, no splatter dash had been applied and that was why the pull-out strength results of the plaster samples fluctuated quite substantially. If splatter dash had been applied, the pull-out strength results should be better.

Finally, they were happy to see that there will soon be manufactured sand complying with a certain recognized standard in the market. However, they also added that some recycled waste materials may also be used as a river sand substitute. Some companies are interested in producing manufactured sand using recycled waste materials but have not been able to do so mainly because of the difficulty in finding suitable land. One of them said that the Government should provide cheap land to support the waste recycling industry.

2.9 Hong Kong Institution of Engineers Materials Division

The preliminary draft Recommended Specifications was sent to Hong Kong Institution of Engineers (HKIE) Materials Division through an email on November 27, 2013. Subsequently, AKHK was invited to attend a committee meeting of the HKIE Materials Division on December 10, 2013. At the committee meeting, AKHK explained to HKIE Materials Division the background of the river sand shortage problem and the Construction Industry Council research project on river sand substitutes. AKHK also briefed HKIE Materials Division the contents of the draft Recommended Specifications. After some discussions, the HKIE Materials Division committee members said they need time to digest the draft Recommended Specifications and they will let AKHK know if they have any comments.

The revised draft Recommended Specifications was sent to HKIE Materials Division on March 24, 2015 to seek their advice and comments. Subsequently, AKHK was invited to attend a committee meeting of the HKIE Materials

Division on April 14, 2015. At the committee meeting, AKHK explained to HKIE Materials Division the progress made in the Research on River Sand Substitutes for Concrete Production and Cement Sand Mortar Production (Phase Two). After giving a brief account of the laboratory test and field trial results, AKHK presented the revised draft Recommended Specifications, explained the rationale behind the various requirements in the Recommended Specifications, and showed them some samples of manufactured sand and river sand. The committee members in the meeting expressed their appreciation of what the Construction Industry Council had done for the industry in helping to resolve the river sand shortage problem and establishing a local standard for aggregate for mortar. Regarding the Recommended Specifications, they have no specific comments. They said it is more important for the Construction Industry Council to keep in touch with the suppliers and users of manufactured sand, and regularly review the Recommended Specifications to keep it updated.

2.10 Hong Kong Concrete Institute

An email enclosing the preliminary draft Recommended Specifications was sent to all board members of the HK Concrete Institute (HKCI) on November 27, 2013 to request the arrangement of a meeting. So far, only one email reply suggesting some changes in the English writing of the Recommended Specifications had been received. AKHK was actually the president of HKCI at the time of consultation. He had spoken to all the board members of HKCI but most of them said that they did not really have any specific comments on the draft Recommended Specifications.

The revised draft Recommended Specifications was sent to HKCI on March 24, 2015 to seek their advice and comments. So far, there was no reply from them. AKHK was a board member of HKCI at the time of consultation. He had spoken to the other board members of HKCI but most of them said that they did not have any specific comments.

2.11 Buildings Department of HKSAR Government

The preliminary draft Recommended Specifications was sent to the Buildings Department on November 26, 2013 to seek their comments. On February 6, 2014, Mr. S.M. Leung, Assistant Director/Corporate Services of Buildings Department, replied to AKHK as follows:
Thank you for sight of the draft Specifications. As spelt out in the Foreword of the draft, the Specifications could become a good basis for the development of a formal local standard for aggregates for mortar. It is understood that the present document is a very preliminary draft subject to refinement. I would therefore be most grateful if you could keep the Buildings Department abreast of the development of the Specifications so that we can have the opportunity to share our views and comments with you. Our contact point for the issue is Mr. YL Chong (Senior Structural Engineer/Technical Services - telephone no. 31623021) whose email address is ylchong@bd.gov.hk. You may wish to contact him directly in future.

The revised draft Recommended Specifications was sent to the Buildings Department on March 24, 2015 to seek their advice and comments. They replied on April 23, 2015 giving the following comments:

I refer to your emails below to our AD/CS regarding the captioned subject and note that there are two main comments from the industry stakeholders which you had incorporated in the draft Recommended Specification for Aggregates for Mortar (draft specification): (1) waiving the durability requirements for non-structural applications; and (2) removing class F3 fine aggregate and just allowing the use of class F5 fine aggregate in plastering and screening works.

2. Please note that we have no comment on item (2) above. As regards item (1), our comments below are relevant.

3. Section 3.3 of the draft specification on durability stipulates that the durability requirements for the aggregates only apply to structural applications, i.e. applications in which the mortar would become part of the concrete structure to carry loading. This statement is very vague and need to be specific as regards the definition of 'structural applications'. Moreover, you may have to clarify the rationale behind why durability requirements are needed to be complied with for structural applications of the proposed aggregates, but not for non-structural applications. Durability should always be an important factor to decide whether any kind of material is suitable or not to be used in construction works, no matter it is to be used structurally or non-structurally. Waiving the durability requirements would mean that the aggregates do not have to comply with the requirements on drying shrinkage and alkali-silica reactivity. Alkali-silica reaction (ASR) produces a gel that can absorb water and expand to cause cracking and disruption of the concrete. The consequence of ASR in concrete could be devastating. Hence, PNAP APP-74 limits the reactive alkali of concrete expressed as the equivalent sodium oxide per cubic metre of concrete should not exceed 3.0 kg.

In response to the above comments by the Buildings Department, the revised draft Recommended Specifications has been further revised to have the durability requirements imposed as follows:

For any mortar, whose failure would endanger the safety of the building (e.g. the mortar is part of the structure) or the safety of the general public (e.g. failure of the mortar could lead to falling off of rendering or tiles), the aggregate to be used shall comply with the durability requirements ...

2.12 Contractor's Authorized Signatory Association

An email enclosing the preliminary draft Recommended Specifications was sent to Mr. K.Y. Lee of Contractor's Authorized Signatory Association on May 11, 2014 to request the arrangement of a meeting. So far, there was no response.

The revised draft Recommended Specifications was sent to them on March 24, 2015 to seek their advice and comments. So far, there was no reply from them. Presumably, they have no specific comments and no request for making any changes to the revised draft Recommended Specifications.

3. Summary of Comments Received

Generally, the stakeholders consulted have no strong objection to the draft Recommended Specifications. In fact, they appreciated the effort of the Construction Industry Council in helping to resolve the river sand shortage problem by looking for suitable river sand substitutes.

A summary of the comments received is presented in the following:

(1) The Recommended Specifications should be practicable and not too complicated (comment by HKCA).

(2) For non-structural applications, the durability requirements in Section 3.3 of the Recommended Specifications may not be suitable (comment by HKCA).

(3) Cost implication of using manufactured sand instead of river sand: would the cost of manufactured sand be higher than that of river sand? (comment by HKCA).

(4) Adaptability of workers to the use of manufactured sand: training of workers will need to be provided (comment by HKCA).

(5) The fines content in 0/2.36 mm fine aggregate tends to be higher than that in 0/5.0 mm fine aggregate and is generally more difficult to control (comment by IOQ-HK).

(6) The difference between class F3 fine aggregate (fines content $\leq$ 3%) and class F5 fine aggregate (fines content $\leq$ 5%) is not significant and it may be simpler to remove the class F3 fine aggregate and just allow the use of class F5 fine aggregate in plastering and screeding works (comment by IOQ-HK).

(7) It may be simpler to just specify a fine aggregate with a maximum aggregate size of 5.0 mm and a grading of F (at least 80% passing the 2.36 mm sieve) instead of any fine aggregate with a maximum aggregate size of 2.36 mm (comment by IASA).

(8) In an old Housing Department Specification, the allowable fines content in the sand (fine aggregate for mortar works) was 10% by weight; hence fine aggregate for mortar containing 10% fines content had been in use in Hong Kong (comment by IASA).

(9) In large scale production, it is not easy to control the fines content in the fine aggregate for mortar; it is hoped that the fines content limit imposed in the Recommended Specifications would not be too stringent (comment by IASA).

(10) For non-structural applications, the requirements related to alkali-silica reactivity given in Section 3.3.2 of the Recommended Specifications should be waived (comment by IASA).

(11) The durability requirements should be imposed not only on mortar for structural applications, but on all mortar, whose failure would lead to safety concerns (comment by Buildings Department).

The above comments have been considered when preparing the revised draft of the Recommended Specifications.

- End of Appendix E -