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INDUSTRY COUNCIL
建造業議會

BETTER UTILIZATION OF ULTIMATE STRENGTH GAIN OF CONCRETE WITH POZZOLANIC MATERIALS FOR SUSTAINABLE DEVELOPMENT OF CONSTRUCTION WORKS IN HONG KONG

RESEARCH SUMMARY

Construction Industry Council Better Utilization of Ultimate Strength Gain of Concrete with Pozzolanic Materials for Sustainable Development of Construction Works in Hong Kong Research Summary

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FOREWORD

Pulverised Fuel Ash (PFA) and Ground Blastfurnace Slag (GGBS) have been used in concrete production for years, because they can reduce use of cement, improve the workability of fresh concrete, increase strength and enhance durability of hardened concrete. While it is understood that concrete containing PFA or GGBS will increase strength after 28 days, little work has been carried out to establish the strength development of such concretes, and no consideration has been given to this strength increase after 28 days in local specifications and code of practice.

This research report presents the work carried out to study the strength development of concrete containing PFA and GGBS with commonly adopted replacement percentages. The first part of the work focused on the analysis of the plant production test data provided by local concrete batching plants and the second part on the laboratory compressive strength tests carried out on concrete cubes. On the basis of the work carried out, recommendations are made to revise the compliance criteria for the compressive strength of concrete given in the General Specification for Civil Engineering Works 2006, for concrete mixes containing at least 25% PFA or 60% GGBS.

The research work presented in this report was funded by the Construction Industry Council (CIC) Research Fund, which was set up in September 2012 to provide financial support to research institutes/construction industry organizations to undertake research projects which can benefit the Hong Kong construction industry through practical application of the research outcomes. CIC believes that research and innovation are of great importance to the sustainable development of the Hong Kong construction industry. Hence, CIC is committed to working closely with industry stakeholders to drive innovation and initiate practical research projects.

The research work described in the report was carried out by a research team led by Ir Professor Albert KH Kwan of the Hong Kong Concrete Institute. This project cannot succeed without the dedicated effort of Ir Professor Kwan and the research team, and their contributions are gratefully acknowledged.

Ir Albert CHENG
Executive Director
Construction Industry Council

PREFACE

This is a very meaningful research project conducted by volunteer researchers from the Hong Kong Concrete Institute led by the Immediate Past President, Ir Prof. Albert KH KWAN.

Supplementary cementitious materials such as PFA and GGBS have become widely used in concrete supplying to local construction industry especially for massive structural concrete elements. Allowance has actually been given in BS EN 206 for testing the compressive strength of concrete at ages later than 28 days for massive structural elements but similar allowance is not commonly accepted locally. Upon successful completion of the research project, recommendations are given to the revision of current local specification for acceptance criteria of concrete compressive strength such that the total cementitious contents and thus carbon footprints of concrete mix designs incorporating adequate amount of supplementary cementitious material can be reduced without sacrificing quality by better utilization of the foreseeable strength gain after 28 days. The Standing Committee for Concrete Technologies is encouraged to make good use of the results of this research study for their consideration of the possibility and viability of revising local concrete specifications.

This piece of research work will not be successful without the selfless dedication and devotion of the members in the Working Group and the participation of the member companies of the Ready Mixed Concrete Committee of the Hong Kong Construction Materials Association by providing their production data and involvement in the laboratory trials. As a matter of course, the support from the Construction Industry Council is undoubtedly the indispensable essence for the realization of this research. It is believed that this research study will become a showcase for research collaboration among the Construction Industry Council, learned societies and industry practitioners in future.

The Hong Kong Concrete Institute will continue to support or to actively participate in studies and researches regarding concrete and concrete related materials for the advancement of local construction industry.

Ir Prof. Adam SC CHOY
Vice President of the Hong Kong Concrete Institute

RESEARCH HIGHLIGHTS

Through this research study, the substantial increment in compressive strength after the age of 28 days for concrete incorporating certain percentages of Pulverized Fuel Ash (PFA) and Ground Granulated Blast Furnace slag (GGBS) have been exhibited. Notwithstanding the test age of 28 days has been proven to be reasonably fair for concrete in past decades, it may not be able to cope with the trend of introducing SCMs in concrete for purposes other than strength, such as heat reduction and durability concerns. However, due to the substantial increment in strength after 28 days for concrete incorporating SCMs up to certain percentages, the current specifications/code of practices are considered to be too conservative by ignoring the effect of prolonged strength development trend of concrete containing SCMs. Consequently, additional cementitious content, which may technically be considered as unnecessary, has to be put in concrete thus leading to higher carbon footprint just for the sake of fulfilling the 28-day requirement.

Based on the large population of plant production data collected with further verification by laboratory trials, there is substantial increment in compressive strength in the order of 10% or more after the age of 28 days up to 56 days for concrete incorporating at least 25% PFA or at least 60% GGBS in the total cementitious content.

The percentage increment in strength after 28 days is deemed not affected significantly by the grade or water binder ratio of the concrete. In this regard, a general percentage of strength increment can be estimated for a concrete with the percentages of PFA (25% or more) or GGBS (60% or more) without the need to take into account the grade or water binder ratio of the concrete.

The percentage increments in strength up to 56 days with respect to that at 28 days were studied for the recommendation of new compliance criteria for cube compressive strength for concrete incorporating SCMs (PFA or GGBS). Further increment in strength after 56 days is considered to be on the one hand largely dependent on curing conditions and on the other hand relatively small comparing to that from 28 days to 56 days. However, in the laboratory trials and collection of plant production data, 90 days cubes were also obtained for reference and the further increment up to this age can be considered as part of the safety margin.

From the data collected from plant production and laboratory trial, the percentages increment in strength for concrete incorporating 25% PFA, 35% PFA, 35% GGBS and 60% GGBS can be summarized as in the order of 11.5%, 13.2%, 6.4% and 9.6% (taken from the lower result between plant production data and laboratory trial). Except for concrete with 35% GGBS, the percentages increment in strength for concrete incorporating 25% PFA, 35% PFA and 60% GGBS are very close to each other. A general percentage increment in strength after 28 days can therefore be conservatively assumed to be 10% for concrete incorporating SCMs with these replacement percentages. The increment in strength after 28 days for concrete incorporating 35% GGBS seems not substantial enough for developing a separate compliance criterion. In this regard, recommendation for new compliance criteria for cube compressive strength of concrete will only focus on concrete incorporating PFA of at least 25% or GGBS of at least 60% for a matter of simplicity and consideration of adequate safety margin.

Three recommendations for modification of current acceptance criteria of specification/code have been made in order to take the strength increment of PFA and GGBS concrete into account so that carbon footprint of concrete can be reduced accordingly with scarifying the quality of concrete in terms of compressive strength.

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1 INTRODUCTION

1.1 Background

Since late 1980's, Supplementary Cementitious Materials (SCMs) like Pulverized Fuel Ash (PFA) and Ground Granulated Blastfurnace Slag (GGBS) have become widely used in combination with Ordinary Portland Cement (OPC) for the production of concrete in various kinds of construction works in Hong Kong, e.g. foundation works, underground structures, marine structures and massive structures.

The use of PFA or GGBS has been proven to be able to improve many performance characteristics of concrete, such as strength development at later ages, workability, permeability, durability and corrosion resistance. They also play an important role in reduction of carbon dioxide (CO_2) emission of concrete production. It was reported that CO_2 generated from the production of PFA and GGBS were about 4 kg/t and 52 kg/t respectively, which were much less than that of OPC (typically 819 kg/t) (Housing Authority, 2012). As a result, the partial replacement of OPC by either PFA or GGBS can substantially reduce the carbon footprint of concrete.

Nevertheless, the compliance criteria of local specifications (Architectural Services Department, 2012; Civil Engineering Development Department, 2014) and code of practice (Building Department, 2013) do not distinguish between OPC concrete and PFA/GGBS concrete on the design strength at 28 days. Due to the slower development in strength of PFA/GGBS concrete up to 28 days, higher cementitious contents have to be adopted in mixes containing PFA or GGBS to achieve the required design strength at the age of 28 days. The increased cementitious content results in higher carbon footprint than that is actually required if the substantial development in compressive strength after 28 days is also taken into account.

In view of absence of consideration of the strength development after 28 days of PFA/GGBS concrete in acceptance criteria for compressive strength in local specifications (Architectural Services Department, 2012; Civil Engineering Development Department, 2014) and code of practice (Building Department, 2013), Hong Kong Concrete Institute (HKCI) conducted a research funded by Construction Industry Council (CIC) to investigate the performance, in strength development after 28 days, of PFA/GGBS concrete with various percentages of cement replacement. This proposal is also fully supported by the Standing Committee on Concrete Technology (SCCT) and the Ready Mixed Concrete Committee of the Hong Kong Construction Materials Association.

1.2 Aims and Objectives

i. To study the long term strength development of concrete containing SCMs of PFA or GGBS with commonly adopted replacement percentages.

ii. To develop for the construction industry a practically viable acceptance criterion for compressive strength of concrete containing PFA and GGBS so as to utilize the gain of strength beyond the age of 28 days.

1.3 Scope

The research covered the study of strength increment of concrete at post-28 days (42 days, 56 days and 90 days) with PFA and GGBS replacement mainly from 25% to 40% and 35% to 65%, respectively. The concrete grades involved ranged from C40 to C60 and the research period was around one year.

2 RESEARCH METHODOLOGY

In order to study the development of long-term compressive strength of concrete with locally available SCMs, i.e. PFA and GGBS, cube specimens were cast with different replacement percentages of SCMs from various local concrete batching plants of seven members (Company A to Company G) of the Ready Mixed Concrete Committee of the Hong Kong Construction Materials Association (RMCC of HKCMA). The specimens were cast, cured and tested in accordance with CS1: 2010 Section 7, 10 and 12 respectively.

With the assistance of Companies A to G of the RMCC of HKCMA, the number of production data and their reference grades and percentages of SCMs collected from the period of 2008 to 2015 were summarized in Table 1.

Table 1 Plant production data provided by Companies A to G

Companies	A	B	C	D	E	F	G
No. of sets of cube results	3500	107	524	134	795	401	231
Age tested (days)	28, 56	28, 56	28, 56	28, 56	28, 42, 56, 90	28, 56	28, 42, 56, 90
Concrete grades involved	40, 45, 50, 60	45, 60 80	40, 45, 60	40, 45, 60	20, 30, 35, 40, 45, 50, 55, 60	40, 45, 50, 60, 80	20, 30, 40, 45
Water/binder ratios involved	0.33 to 0.40	0.27 to 0.40	0.30 to 0.38	0.34 to 0.41	0.33 to 0.49	0.26 to 0.45	0.37 to 0.65
SCM used	PFA	PFA	PFA	PFA	PFA	PFA	GGBS
% of SCM used	20, 25, 30, 34, 35, 40	25, 31, 35, 40	25, 35	25, 35	21 to 40	25, 35, 40	40, 60

For the comparison with production data and to supplement the study with less popular concrete mixes in mass production, laboratory trials were carried out in accordance with the following test regime to find out the percentage of strength gain for concrete containing different percentage of SCM's after 28-days up to the age of 56 days.

Table 2 Laboratory trial for PFA concrete mix

Grade	PFA content	Slump			100mm Cubes
		100mm	150mm	200mm	
40D/20	25%	yes	yes	yes	2 nos. x 7/28/42/56/90 days
	35%	yes	yes	yes	
45D/20	25%	yes	yes	yes	
	35%	yes	yes	yes	
50D/20	25%	yes	yes	yes	
	35%	yes	yes	yes	
60D/20	25%	yes	yes	yes	
	35%	yes	yes	yes	

Table 3 Laboratory trial for GGBS concrete mix

Grade	PFA content	Slump			100mm Cubes
		100mm	150mm	200mm	
40D/20	35%	yes	yes	yes	2 nos. x 7/28/42/56/90 days
	65%	yes	yes	yes	
45D/20	35%	yes	yes	yes	
	65%	yes	yes	yes	
50D/20	35%	yes	yes	yes	
	65%	yes	yes	yes	
60D/20	35%	yes	yes	yes	
	65%	yes	yes	yes	

3 RESEARCH FINDINGS AND DISCUSSION

3.1 Compressive Strength of Concrete with PFA and GGBS as Revealed by Actual Plant Production Data

The relationship observed between the average compressive strength increment from 28 days to 56 days and water/binder ratio for concrete with PFA content of 25% to 40% are shown in Table 4 with the trend illustrated in Figure 1.

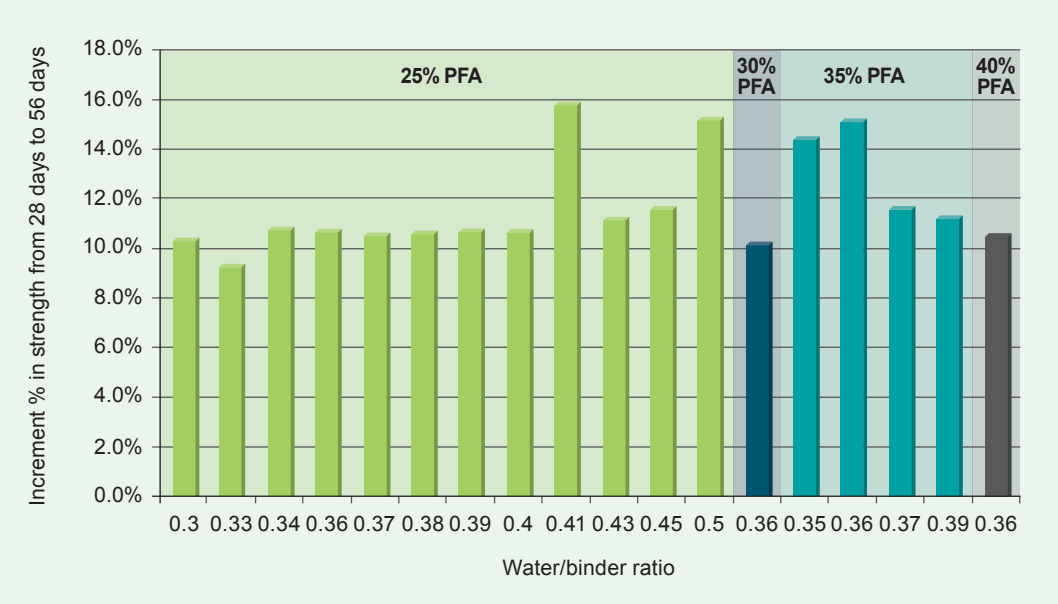

Figure 1 Increment percentage in compressive strength from 28 days to 56 days of concrete with 25% to 40% PFA replacement

Table 4 Average % increment in compressive strength for 25% to 40% PFA concrete from 28 days (28D) to 56 days (56D)

w/binder ratio	% of PFA	No. of samples	Av. % increment in compressive strength from 28D to 56D	Av. % increment in compressive strength from 28D to 56D w.r.t. % of PFA
0.30	25%	111	10.3%	11.5%
0.33		481	9.3%	
0.34		113	10.8%	
0.36		344	10.7%	
0.37		182	10.7%	
0.38		631	10.6%	
0.39		494	10.7%	
0.40		253	10.7%	
0.41		40	15.9%	
0.43		77	11.2%	
0.45		96	11.8%	
0.50		64	15.2%	
0.36	30%	131	10.3%	10.3%
0.35	35%	153	14.5%	13.2%
0.36		195	15.3%	
0.37		689	11.6%	
0.39		94	11.3%	
0.36	40%	81	10.6%	10.6%
Average % increment from 28D to 56D				11.4%

Findings from the plant production data for PFA concrete:

The plant production data were provided by six concrete producers with three locally available sources of PFA. Results obtained from the six concrete producers were found to be quite consistent. It can therefore be concluded that the increment percentage in compressive strength of PFA concrete from 28 days to 56 days is not sensitive to PFA sources included in this study.

The majority of the increment percentage from 28 days to 56 days fell steadily in the range of 10% to 11% for most of the concrete mixes with 25% PFA although a few exceptions up to 15% were recorded. Both the two concrete mixes with the same PFA content of 35% and the water/binder ratios of 0.35 and 0.36 respectively have the increment percentage of around 15% in compressive strength from 28 days to 56 days. These two concrete mixes were clarified by the responsible concrete suppliers that they were used for bored pile concrete requiring prolonged workability retention and stiffening time. To cater for these properties, superplasticizers with high workability retention and retarding effect were added resulting delayed strength development effect. This explains the higher increment percentage in compressive strength after 28 days for these concrete mixes.

The increment percentages of compressive strength from 28 days to 56 days are found to be not dependent on the water/binder ratios and concrete grades of the concrete mixes. In this regard, same forecast or utilization of the increment percentage of compressive strength can be applied to all concrete grades with different water/binder ratios.

There was only one concrete producer supplying the plant production data for GGBS concrete. Due to limited sample size collected from only one concrete producer and based on the same finding as that for PFA concrete, results of the increment percentage from 28 days to 56 days for concrete mixes with different concrete grades and thus different water/binder ratios were grouped together under the same percentages of GGBS (40% and 60%). The relationship observed between the average compressive strength increment from 28 days to 56 days and 90 days for concrete with 40% and 60% GGBS content are shown in Figure 2.

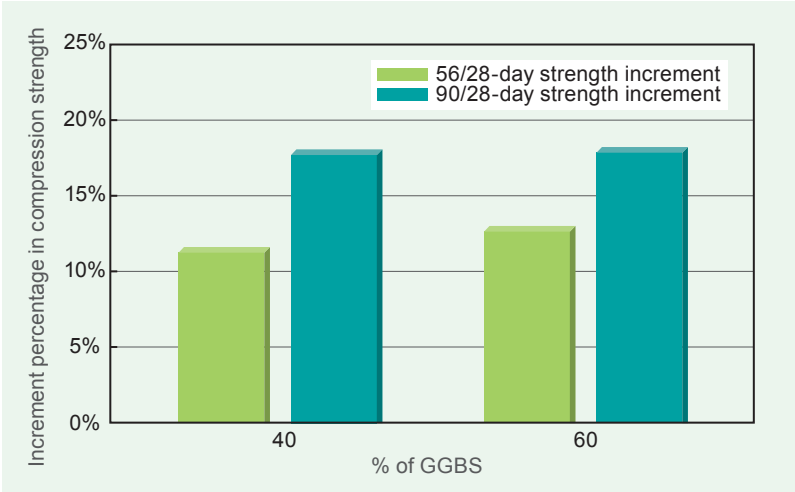

Figure 2 Increment percentage in compressive strength from 28 days to 56 days / 90 days of concrete with 40% and 60% GGBS replacement

Findings from the production plant data for GGBS concrete:

There was only one concrete producer providing the production plant data for GGBS concrete and thus only one source of GGBS was included in the study. However, based on the findings from the literature review, the increment percentage in strength was also not sensitive to the source of GGBS. Therefore, result of this study can also be applied to other sources of GGBS, which may come to the local market, providing relevant standards for the GGBS materials are complied with.

The increment percentage of compressive strength from 28 days to 56 days worked out from plant production data for 40% and 60% GGBS contents were 11% and 13% respectively, which were very similar to those of concrete with 25% to 40% of PFA contents.

The increment percentage of compressive strength from 28 days to 90 days for 40% and 60% GGBS contents were both 18%. It was therefore shown that there would be adequate safety margin if the increment percentage from 28 days to 56 days is adopted in the recommendation given for the revision of the compliance criteria for GGBS concrete at 28 days.

3.2 Laboratory Trial Mixes for Concretes Mixes with Commonly Adopted PFA and GGBS Replacement Percentage

A total of 48 concrete mixes were mixed in the laboratory trial exercise in accordance with the test regime shown in Table 2 & 3. Five concrete producers participated in the laboratory trial and shared the workload for mixing the 48 concrete mixes with the sources of raw materials currently used in their routine production.

Experimental results of laboratory trials

The results were shown in Table 5 and 6 for OPC-PFA mixes and OPC-GGBS mixes respectively.

Table 5 Laboratory results for compressive strength of OPC-PFA concrete at different ages

Grade	Designed slump (mm)	Average compressive strength (MPa)					% strength increment	
		7-day	28- day	42- day	56- day	90- day	56-day/ 28-day	90-day/ 28-day
40D/20 (25% PFA)	100	38.8	59.3	63.6	65.8	73.5	11.0%	23.9%
	150	40.2	59.2	67.3	67	69.6	13.3%	17.7%
	200	39.9	61.9	66.4	70.4	76.5	14.4%	23.7%
40D/20 (35% PFA)	100	41.7	62.7	70.8	74.8	76.5	19.3%	22.1%
	150	40.4	60.9	70.1	72.9	74.3	19.8%	22.1%
	200	41.6	64.1	68.3	74.1	81.8	15.5%	27.6%
45D/20 (25% PFA)	100	56.3	74.2	76.4	83.7	86.4	12.8%	16.5%
	150	60.9	79.3	80.9	88.8	91.5	12.0%	15.4%
	200	57.4	74.7	79.4	85.3	90.3	14.7%	21.4%
45D/20 (35% PFA)	100	51.0	71.8	75.5	81.5	83.8	13.5%	16.7%
	150	54.2	75.9	79.7	84.1	87.1	10.9%	14.8%
	200	51.6	72.1	78.4	83.7	84.1	16.1%	16.6%
50D/20 (25% PFA)	150	61.0	80.7	87.0	87.2	89.4	8.1%	10.8%
	200	59.3	77.9	84.4	87.0	91.3	11.6%	17.2%
50D/20 (35%PFA)	150	57.5	75.8	84.2	90.4	91.2	19.3%	20.4%
	200	59.9	80.3	86.6	92.5	91.8	15.2%	14.3%
60D/20 (25% PFA)	200	63.7	86.5	93.4	94.5	101.5	9.2%	17.3%
60D/20 (35% PFA)	200	54.2	80.2	84.7	89.3	95.1	11.3%	18.6%
Av. % increment in strength at 56D & 90D against 28D (25% PFA)							11.9%	18.2%
Av. % increment in strength at 56D & 90D against 28D (35% PFA)							15.7%	19.2%

Table 6 Laboratory results for compressive strength of OPC-GGBS concrete at different ages

Grade	Designed slump (mm)	Average compressive strength (MPa)					% strength increment	
		7-day	28- day	42- day	56- day	90- day	56-day/ 28-day	90-day/ 28-day
40D/20 (35% GGBS)	100	41.7	59.6	63.1	65.0	66.8	9.1%	12.2%
	150	44.2	63.7	67.1	65.5	67.4	2.9%	5.9%
	200	46.2	64.4	65.5	68.0	68.9	5.6%	7.0%
40D/20 (60% GGBS)	100	37.5	60.6	65.6	66.3	66.3	9.4%	9.4%
	150	38.0	61.4	66.7	69.0	68.0	12.3%	10.7%
	200	38.2	59.3	64.1	67.4	68.4	13.7%	15.4%
40D/20 (35% GGBS)	100	45.4	64.8	65.7	69.0	69.4	6.6%	7.2%
	150	46.4	65.3	67.9	70.2	70.2	7.5%	7.5%
	200	46.5	63.1	65.7	67.0	66.5	6.1%	5.4%
40D/20 (60% GGBS)	100	38.9	63.6	67.4	67.7	68.1	6.4%	7.1%
	150	40.2	63.6	67.6	71.3	72.8	12.1%	14.5%
	200	40.7	63.1	66.5	70.1	70.1	11.1%	11.1%
50D/20 (35% GGBS)	150	61.8	81.9	83.4	87.2	89.0	6.3%	8.7%
	200	61.9	79.4	82.1	84.8	86.5	6.8%	8.9%
50D/20 (60% GGBS)	150	54.8	83.7	87.5	84.8	88.9	1.4%	6.3%
	200	56.9	79.4	82.6	83.6	88.8	5.2%	11.8%
60D/20 (35% GGBS)	200	68.3	87.4	88.5	93.6	96.8	7.1%	10.8%
60D/20 (60% GGBS)	200	57.2	78.1	81.8	89.7	93.1	14.8%	19.2%
Av. % increment in strength at 56D & 90D against 28D (35% GGBS)							6.4%	8.2%
Av. % increment in strength at 56D & 90D against 28D (60% GGBS)							9.6%	11.7%

3.3 Strength Development Trend of PFA Concrete in Laboratory Trials

The average percentage increment in strength at 56 days/90 days with respect to that at 28 days for 25% PFA concrete and 35% PFA concrete were found to be 11.9%/18.2% and 15.7%/19.2%, respectively. Comparing with the percentage increment in strength at 56 days with respect to those of 28 days for 25% PFA and 35% PFA collected from plant production data, which are 11.5% and 13.2%, the laboratory results and plant production results were basically in line and the slightly higher percentage increment recorded in laboratory trials for both percentages of PFA are believed to be due to better control in laboratory condition. Similar to the phenomenon observed from plant production data, the percentage increments in strength for both 25% and 35% PFA mixes seem not having direct relationship with the concrete grade or water/binder ratio.

3.4 Strength Development Trend of GGBS Concrete in Laboratory Trial

The average percentage increment in strength at 56 days/90 days with respect to that at 28 days for 35% GGBS concrete and 60% GGBS concrete are found to be 6.4%/8.2% and 9.6%/11.7% respectively. Comparing with the percentage increments in strength at 56 days with respect to that 28 days for 40% GGBS concrete and 60% GGBS collected from plant production data, which were 11.0% and 13.0%, the laboratory results and plant production results were basically in line. However, since a lower percentage (35%), as advised by the concrete producer to simulate the percentage of GGBS in façade for Housing Authority projects, was used in laboratory trial as the lower bound for GGBS concrete, the percentage increment for 35% GGBS (6.4%) is expectedly lower than that of 40% GGBS (11.0%). The laboratory results for concrete with both percentages of GGBS (35% and 60%) are deemed to have relatively large fluctuation comparing with those for PFA concrete. The average percentage increment in strength thus calculated might have been affected by some outlier results although the general trend is still in line with that of plant production results. Similar to the phenomenon observed from plant production data, the percentage increments in strength for GGBS mixes in laboratory trials seem not being affected by the concrete grade or water/binder ratio.

4 RECOMMENDATIONS

Through this research study, PFA and GGBS have demonstrated their potential abilities to have further development in concrete strength after the age of 28 days, at which compliance criteria for compressive strength are normally set. In view of this and based on the results obtained in this research study, recommendations are given to consider the strength gain of concrete incorporating substantial percentage of SCMs in the derivation of new compliance criteria for compressive strength.

Recommendation 1:

The first recommendation (Recommendation 1) is to simply extend the age, from 28 days to 56 days, for evaluation of compliance of compressive strength. Advantage of this approach is that results of the compressive strength tests at 56 days will be able to reflect the actual strength performance of the corresponding concrete incorporating SCMs for checking against the designed characteristic strength of the concrete. There is no need to change the acceptance criteria for concrete compressive strengths including those for individual results, running average and variations reflected by standard deviation or coefficient of variation, whichever is more appropriate for the concrete mix.

Based on the aforesaid Recommendation 1, with respect to the General Specification for Civil Engineering Works 2006 (Civil Engineering Development Department, 2014), only Clause 16.59 (1) is required to be changed to the following:

Clause 16.59

(1) Two test cubes shall be made from each sample of concrete taken as stated in Clause 16.58. Each pair of test cubes shall be tested to determine the compressive strength at 28 days except for designed mix concretes with at least 25% of PFA or 60% of GGBS in the total cementitious content, for which the test cubes shall be tested at 56 days.

Other sub-clauses in Clause 16.59, the compliance criteria for compressive strength of designed concrete as stipulated in Clause 16.61 and Table 16.10 can be remained unchanged.

Recommendation 2:

Another recommendation (Recommendation 2) is that the general percentage increment of 10% in strength after 28 days as concluded of this study report for concrete incorporating at least 25% PFA or 60% GGBS are considered. To exert a safety factor to cater for unexpected fluctuation in the strength development trend, the increment in strength from 28 days to 56 days can be predicted to be at least 5% and the compressive strength of concrete at 56 days with at least 25% PFA or 60% GGBS is considered to be 1.05 x the compressive strength at 28 days. The strength enhancement of 5% is considered to be conservative based on the literature review and the test results obtained in this study. Instead of deferring the date of testing the compressive strength for compliance check from 28 days to 56 days, it can be considered to lower the requirements for compressive strength at 28 days by taking into account the forecast increment till 56 days with conservative estimation of 5% as mentioned above. In this recommendation, Clause 16.59 (5) (Civil Engineering Development Department, 2014) can be revised to the following:

(5) *For the purpose of assessing compliance of designed mix concrete as stated in Clauses 16.61 and 16.62, the average of the two compressive strengths of the pair of test cubes shall be calculated and referred to as the test result. For designed mix concretes with at least 25% of PFA or at least 60% of GGBS in the total cementitious content, the test result can be multiplied by the factor of 1.05.*

Advantage of this Recommendation 2 is that there is no need to change test date at 28 days and therefore no change in the completion date of works, contract requirements, payment, etc. Disadvantages of this recommendation are twofold. Firstly, the potential increment of concrete having at least 25% of PFA or 60% of GGBS after 28 days may be underestimated. Secondly, the change in the specification (Clause 16.59 (5)) may also be difficult to understand and the implementation of the revised specification for the calculation of test results has to be adapted.

Recommendation 3:

This is to simply relax the requirement for the surplus in compressive strength by deducting 3 MPa from those requirements stated in C1, C2 and C3 for the average of four test results. As a matter of safety, the minimum individual test result is not relaxed in order not to relax for the lower bound of individual test result to avoid possibility of occurrence individual doubtful test result. Based on this recommendation, Table 16.10 (Civil Engineering Development Department, 2014) can be revised as follow:

Table 7 Revised compliance criteria for compressive strength of designed mix concrete

Grade strength (MPa)	*Containing at least 25% PFA or at least 60% GGBS in total cementitious content*	*Compliance criteria*	Column A *Maximum amount by which each test result may be below the grade strength (MPa)*		Column B *Minimum amount by which the average of any four consecutive test results shall be above the grade strength (MPa)*	
			100 mm cubes	150 mm cubes	100 mm cubes	150 mm cubes
20 or greater	No	C1a	2	3	7	5
	Yes	C1b	2	3	4	2
	No	C2a	2	3	5	3
	Yes	C2b	2	3	2	0
Below 20	N/A	C3	2	2	3	2

Required changes to be made to the General Specification (Civil Engineering Development Department, 2014) based on “Recommendation 3” are probably the mildest and easiest to follow. Although this suggested approach is more conservative than the other two recommendations, it may still be a good start to utilize the strength gain of concrete incorporating SCMs after 28 days for greener concrete by reducing the total cementitious content based on the lower requirements for compliance criteria of compressive strengths at 28 days.

Potential areas for further studies

This study mainly focused on the strength development trend of designed mix concretes incorporating SCMs of up to the age of 56 days from production data and 90 days from laboratory trial data. Recommendations for the revision of compliance criteria for concrete compressive strength in the General Specification are given for concretes incorporating at least 25% PFA or at least 60% of GGBS with relatively conservative approaches. However, further development trend in longer terms, consideration of including lower percentages of SCMs, and the possibility of further relaxation for the compliance criteria for concrete incorporating SCMs at 28 days can be studied after adopting the revised specification for a certain period. The overall effect of reduction in carbon footprint in concrete with respect to the revised specification and the resulted quality performance of the concrete shall be monitored and reviewed.

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