Housing Authority Research Fund

Project Title :
Developing Application of Self-compacting Concrete to enhance Quality, Cost Effectiveness, Buildability and to reduce Noise Nuisance in Public Housing Construction
(ref: CB20030030)

Summary of Report

Research Provider :
City University of Hong Kong

Project Coordinator :
Dr. K C Lam
Department of Building and Construction
City University of Hong Kong

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1. Brief Description

A two-year research project "*Developing Application of Self-compacting Concrete to enhance Quality, Cost Effectiveness, Buildability and to reduce Noise Nuisance in Public Housing Construction*", funded by the Housing Authority Research Fund, was commenced in 2003 and completed in 2005. **Self-compacting concrete (SCC)** is a kind of high performance concrete (HPC) that does not require external vibration for placing and compacting. It is capable of flowing a certain distance by its own weight, encapsulating reinforcement of high density, and filling the formwork completely without vibration. This innovative concrete has been developed in Japan and Europe for more than 20 years aiming to resolve construction labour shortage, shorten the construction time and improve the concrete quality. Comparatively, systematic researches and applications of SCC are still very limited in Hong Kong to date. This project aims to provide preliminary evidence in application so as to allow practising engineers to implement the use of self-compacting concrete in the construction industry.

The objectives of the project consist of:

- To examine the performance of self compacting concrete by a number of experimental tests;
- To evaluate the buildability of self-compacting concrete by studying, monitoring and scrutinizing the construction process;
- To evaluate the noise levels during in-situ construction of structural components when using self compacting concrete and conventional vibrated concrete; and
- To evaluate and illustrate a detailed cost comparison between self-compacting concrete and conventional vibrated concrete both being used in local industry.

2. Final Results and Findings

SCC Fresh Properties

The investigation on the fresh properties of SCC was divided into four major groups, which are deformability (filling ability), passability, segregation resistance, and viscosity. A series of comprehensive fresh concrete tests were conducted in the following sequence: slump flow and visual assessment of segregation, J-Ring, stability test, L-box, U-box, V-funnel, and filling capacity test. Based on the fresh concrete test results, it was found that all of concrete raw materials available in Hong Kong can produce SCC mixtures. The suggested typical range of constituent in SCC is shown in following Table 1. However, other mix designs falling outside the suggested range are still possible as long as the SCC basic requirements be fulfilled as specified in the guideline.

Normally, the amounts of powder and fine aggregate consumed in SCC are relatively higher than Conventional Vibrated Concrete (CVC) in order to maintain sufficient fluidity of the mixtures to prevent segregation problems. The proportion of viscosity modifying agent (VMA) to be added in the mix was found dependent on the cementitious content. Increasing the proportion of silica fume (fume) in the mix can enhance the viscosity to the mixtures, and thus the amount of VMA is less required.

SCC Hardened Properties

SCC can be designed to fulfill the requirements of British Standard regarding hardened concrete properties such as strength development, density, final strength and durability, etc. as observed in this investigation.

Buildability of SCC

Oversea literatures about the applications of SCC were extensively reviewed. In parallel, local applications of SCC or high performance concrete (HPC) with designed slump value ≥ 200mm were revealed and 25 local practitioners having practical experience with

SCC or HPC were interviewed to examine the buildability of SCC in local context. In general SCC can achieve some outstanding finished qualities and performance during construction process over conventional vibration concrete. Nevertheless, certain constraints in using SCC in local construction environment have to be considered. Especially it demands high standard in formwork erection and quality control system during the construction process. A lack of job reference and common practice also deters the use of SCC. The opportunities and threats in implementing SCC are summarized in Table 2.

Table 1 – Suggested Mix Design of SCC

Constituent	*Normal typical range by mass (kg/m^3)*
i) Powder	500 - 600
Cement	500 – 600
PFA	0 – 250 (0 - 40% of total cementitous content, it can more than 40 % once necessary)
SF	0 – 150 (0 – 15 % of total cementitious content)
ii) Water content	170 – 210
Water/Powder ratio	0.3 - 0.4 (out of this range could also appropriate)
iii) Coarse aggregate (10 mm aggregate)	600 – 800
iv) Fine aggregate (sand)	700 – 900
Fine to total coarse aggregate ratio	Normally larger than 50 %
v) Superplasticizer dosage	0.5 – 2 % of total cementitious content/100 kg
vi) Viscosity Modifying Agent	0.2 – 0.8 % of total cementitious content/100 kg

Table 2 – Summary of Opportunities and Threats of Buildability of SCC

Opportunities	*Threats*
◆ Mechanization of the concreting process ◆ Better and assured concrete workmanship ◆ Improve structural quality ◆ Better filling ◆ Broaden placing methods ◆ Less noise emission ◆ More Design flexibility ◆ Better aesthetic appearance ◆ High strength ◆ Less rework ◆ Faster construction of large pours ◆ Offset shortage of skilled concretor ◆ Better working environment and safety	◆ Demanding formwork system ◆ Extensive mix verification ◆ Less tolerant ◆ Complicate pouring operation ◆ More resources in quality control ◆ Possibly long setting time ◆ Fast dry-out and surface crusting ◆ Possible many blowholes ◆ Difficult to form inclined surface and stepping level ◆ High temperature release ◆ Lack of references and experiences

Monetary comparison between SCC and CVC

As SCC is still new to Hong Kong, there is no established market price of its cost during the investigation. Various estimations indicated that the concrete cost of SCC would be 15%-30% higher than conventional vibrated concrete (CVC) at same grade. The higher material cost was constituted mainly by the expensive admixture cost, plus additional quality control cost in production of SCC.

The Monetary comparison considering the elementary cost factors (concrete, formwork, labour and repair costs) with different assumptions (basic, wall thickness reduction and long term maintenance effect) based on a public housing building is analyzed for a rough guidance. In general, the cost of using SCC will be higher than CVC. It is observed that the difference between the effective cost of CVC and SCC will be close if long-term maintenance cost is taken into account, on the assumption that SCC is more durable which could reduce the long-term concrete maintenance work by 50%. The summary is shown in Table 3.

Table 3 – Summary of monetary comparison between CVC and SCC for New Harmony 1 Option 1

Concrete type	*CVC*	*SCC*
Estimated concrete unit cost	100%	115% to 130%
Effective concrete unit cost accounted with all elementary cost factors	100%	106% to 121%
Effective concrete unit cost accounted with all elementary cost factors and reduction in wall thickness	100%	102% to 117%
Effective concrete unit cost accounted with all elementary cost factors and long-term maintenance cost	100%	95% to 107%

Non-monetary comparison between SCC and CVC

It was believed that SCC could offer benefits which could not be readily measured by monetary value. A multi-attribute decision analysis method, Analytic Hierarchy Process, was thus utilized to compare SCC and CVC in terms of valued-based preferences and non-monetary comparisons of benefits in the context of public housing construction. 42 respondents from local and oversea construction industry of various sectors participated in the consultation. Over 70% of them have over 10-year working experience in the field.

The result indicated that CVC and SCC scored approximate 0.4 and 0.6 respectively. It means that self-compacting concrete is valued as a preferable choice of concrete mix for public housing construction. The detailed findings are shown in Table 4.

Table 4 – Summary of Score by AHP analysis

Main Criteria	*Weighting (W1)*	*Sub-criteria*	*Weighting (W2)*	*Overall weighting (W1x W2)*	*Relative Preference (P)*		*Individual Score (S=W1xW2xP)*	
					CVC	*SCC*	***CVC***	***SCC***
(1) Functional Performance	0.311	(1.1) Design Flexibility	0.113	0.035	0.341	0.659	0.012	0.023
		(1.2) Strength Benefits	0.234	0.073	0.344	0.656	0.025	0.048
		(1.3) Durability	0.493	0.153	0.373	0.627	0.057	0.096
		(1.4) Surface Quality	0.160	0.050	0.293	0.707	0.015	0.035
					Sub-total:		0.109	0.202
(2) Construction Manageability	0.124	(2.1) Schedule Compression	0.121	0.015	0.388	0.612	0.006	0.009
		(2.2) Ease of Construction	0.177	0.022	0.351	0.649	0.008	0.014
		(2.3) Workmanship Improvement	0.402	0.050	0.208	0.792	0.010	0.039
		(2.4) Ease of Supervision	0.301	0.037	0.481	0.519	0.018	0.019
					subtotal:		0.042	0.082
(3) Environmental & Social Issue	0.093	(3.1) Reducing Nuisance to Public	0.117	0.011	0.211	0.789	0.002	0.009
		(3.2) Workers' Health	0.432	0.040	0.224	0.776	0.009	0.031
		(3.3) Wastage Reduction	0.233	0.022	0.494	0.506	0.011	0.011
		(3.4) Technology Promotion	0.218	0.020	0.170	0.830	0.003	0.017
					subtotal:		0.025	0.068
(4) Cost Implication	0.112	(4.1) Construction Cost	0.500	0.056	0.558	0.442	0.031	0.025
		(4.2) Maintenance Cost	0.500	0.056	0.385	0.615	0.021	0.034
					subtotal:		0.053	0.059
(5) Risk Consideration	0.361	(5.1) Performance Reliability	0.230	0.083	0.436	0.564	0.036	0.047
		(5.2) Application Experience	0.135	0.049	0.711	0.289	0.035	0.014
		(5.3) Site Safety	0.449	0.162	0.422	0.578	0.068	0.094
		(5.4) Cost Variation	0.186	0.067	0.505	0.495	0.034	0.033
					subtotal:		0.173	0.188
					Overall Score ($S_{overall}$)		**0.401**	**0.599**

Note:

- CVC – Conventional vibrated concrete
- SCC- Self-compacting concrete

▨ denotes higher score

Site Measurement of Noise Emission

Site measurements of actual noise emission in a construction site using highly workable concrete and conventional vibrated concrete were conducted. Table 5 summaries the increase in site measured noise level before and during the concrete pouring. Whilst the pouring method of the two kinds of concrete is different that the result obtained cannot be directly compared, it provides an insight of the actual noise generation between the SCC and CVC. The finding illustrates that the elimination of vibration in the concreting process considerably reduces the noise level in the working place. With reference to the measured result of the L_{eq}(30min), it is expected that the actual noise level of concreting could be reduced as much as 80% if using SCC instead of CVC.

Table 5 - Increase in Measured Noise Level from 'Before Concreting' to 'During Concreting'

Noise measurement type (30min)	*Increase of Measured Noise Level / dB(A)*	
	Highly Workable Concrete placed by skip	*Conventional Vibrated Concrete placed by pump*
L_{eq}	2.8	15.2
L_{10}	3.2	18.8
L_{90}	0.4	10.2
L_{max}	3.1	1.8
L_{min}	0	9.0

Predicted Noise Level (PNL) Assessment

The noise prediction based on Environmental Protection Department's practice was undertaken to assess the noise impact generated by the concreting work of a construction site of a public housing building on an adjacent domestic building (noise sensitive receiver, NSR). In general, the predicted noise levels obtained at the same location of the NSR are typically the lowest when SCC was used.

Considering the noise impact during concreting of a floor, both the maximum and minimum values of PNL at the NSR decreased by 2dB when only 1 vibratory poker was in use (SCC with limited vibration) and by 4dB when no vibratory poker was used (SCC with no vibration).

Considering the noise impact during concreting of a cap, the maximum and minimum values were found to have reduced by 2dB when the numbers of vibratory poker were reduced by 50% and by 4dB when no vibratory poker was in use. The reduction of noise level was less significant than expected since the noise from the concrete lorry mixers is still prominent even when the vibration had been removed.

The findings are summarized in Table 6 and 7.

Table 6 - Max. and min. PNL at the NSR generated by floor concreting

Predicted Noise Level at the NSR / dB(A)	***Skip Method***			***Pumping Method***		
	Conventional vibrated concrete	*SCC with limited vibration*	*SCC with no vibration*	*Conventional vibrated concrete*	*SCC with limited vibration*	*SCC with no vibration*
Maximum	88	86	84	88	86	84
Minimum	66	64	62	66	64	62

Table 7 - Max. and min. PNL at the NSR generated by cap concreting

Predicted Noise Level at the NSR / dB(A)	*Conventional vibrated concrete*	*SCC with limited vibration*	*SCC with no vibration*
Maximum	95	93	91
Minimum	69	67	65

3. Applicability and Limitations

SCC Properties and Testing Specifications

The main characteristics to distinguish SCC from other high-slump concrete can be broadly split into three categories: filling ability, passing ability, and resistance to segregation. A concrete mix can only be regarded as SCC if it can comply with all the requirements of the three characteristics.

- **Filling ability:** the ability of the SCC to flow into all spaces within the formwork under its own weight.
- **Passing ability**: the ability of the SCC to flow through tight openings such as spaces between steel reinforcing bars, under its own weight.
- **Resistance to segregation:** the ability of SCC to remain homogeneous in composition throughout the process of transport and placing.

Most of the fresh concrete tests in BS standard are not suitable for SCC as these fresh tests cannot reflect the properties of SCC, and therefore appropriate fresh concrete test method should be established to specify self-compacting concrete. The most popular fresh concrete test methods for SCC suggested are Slump flow test, L-box test, V-funnel test, U-box test, Fill-box test, Segregation test and J-ring test.

It is difficult to perform the entire fresh concrete tests especially in a congested construction site commonly in Hong Kong. Therefore, it is recommended to choose specific fresh concrete test to perform after it is verified and pass the required performance at design stage. It is believed that test method on site can be checked by slump flow test alone. L-box test or U-box test is required to evaluate once passing properties of SCC are greatly concerned. The suggested test arrangements are shown in Table 8.

Table 8 – Suggested Fresh Concrete Tests in Laboratory, Plant and Site

SCC properties	***Test Methods***		
	Laboratory/Concrete plant (Mix Design)	**Full scale test on Site**	**Site (Quality Control)**
Filling ability	◆ Diameter of Slump Flow ◆ Filling percentage of U-Box ◆ Filling percentage of Fill-vessel Box	◆ Diameter of Slump Flow ◆ Filling percentage of U-Box	◆ Diameter of Slump Flow
Passing ability	◆ Blocking ratio of L-Box ◆ Filling height of U-Box ◆ Filling percentage of Fill Box	◆ Blocking ratio of L-Box ◆ Filling height of U-Box	◆ Blocking ratio of L-Box or Filling height of U-Box (optional)
Segregation resistance	◆ Observation from Slump Flow Performance ◆ 5-mm sieve segregation ◆ T_{5min} of V-Funnel	◆ Observation from Slump Flow Performance ◆ 5-mm sieve segregation ◆ T_{5min} of V-Funnel	◆ Observation from Slump Flow Performance
Viscosity	◆ T_{50} of slump flow ◆ T_{0min} of V-Funnel	◆ T_{50} of slump flow ◆ T_{0min} of V-Funnel	◆ T_{50} of slump flow
Others		◆ Full Scale testing on structure element	

The degree of self-compactness of self-compacting concrete required in fresh state depends on the external factors including the type of application, site condition, placing method and buildability, and in particular:

- Structure design (beam, wall, slab, column or pile cap)
- Complexity of formwork design (complicated shape or aesthetic formwork design)
- Degree of congestion of steel reinforcement (cover, spacing and density of steel bar design)
- Assess or location of discharging points
- Placing method and equipment (pumping or skip)

For a particular application, the concrete producer and contractor should discuss together and select the appropriate parameters and class level with reference to the classifying system before starting the job at site. The specific self-compacting concrete characteristics should be carefully selected, controlled and justified by the experienced concrete producer and contractor or by site trials. As the acceptable limit in each case/application is different, the typical range of workability requirements for fresh SCC to be fulfilled at the concrete manufacturing plant and the time of placing will also be different. The typical ranges of acceptable value for general guidance are suggested in Table 9.

Table 9 - Typical ranges of acceptance value of fresh concrete tests

Test no.	***Test Method***	***Unit***	***Typical ranges of acceptance values***	
			Minimum	***Maximum***
	General test			
1	Slump Flow Diameter	mm	650	850
2	T_{50} of Slump Flow	sec	1	8
3	Percentage of U-box	%	80	100
4	Blocking ratio of L-box	%	70	100
5	V-Funnel at T_{0min}		2.5	12
6	Increase in V-Funnel at $T_{5\ min}$	sec	0	3
7 8	Percentage of Fill-vessel box Percentage of passing 5-mm sieve	% %	80 5	100 20
	Optional test			

SCC in Practice

SCC can be placed by pouring or pumping into horizontal or vertical structures. When designing the mix, one shall take into consideration the pouring/dropping height of concrete, effective distance between two discharging points, the size of the forms, the density of reinforcement and depth of the cover. The practical opportunities/benefits and risks for implementing SCC in general structural element construction are revealed in Table 10 and 11.

- *Typical Floor of Public Housing*

Unlike most private projects, the consistency of concrete grade of different structural members of a typical floor of public housing buildings eases the pouring of SCC. It is because the exhausting site control effort for distinguishing various concrete mixes and confining the unintended flow of SCC may be avoided. In addition, the large-size metal formwork and precast façade should be less susceptible to concrete leakage and grout loss than other formwork system in private projects. Due to the high repetitive nature of public housing, once a specific mix is proved successfully, it can be routinely applied in the following projects. This makes the initial resource spending on the mix design verification more cost effective in a long run.

Limitations:

- ➢ The current casting practice by a skip method divides a typical floor into several small pours of walls and slabs (typically 6 pours with size of about 80 - 200m^3), which requires a numbers of construction joints. This does not favour the use of SCC since more effort would be required to make good for the construction joints and the increase of pouring rate by SCC is less significant in a small size of concrete pour and skip method.
- ➢ To obtain a high surface quality of SCC, it is recommended to pump the SCC from the bottom of the formwork or by use of a tremie pipe of which the outlet should be kept immersed below the fresh concrete level during pouring. It is not a common practice in public housing building construction of typical floors.

- SCC tends to be high-strength in general. The current design concrete grade for typical floor of public housing is 35D mainly. The SCC may not be used in full benefit in current structural design. In addition the concrete cost difference between SCC and CVC in this range concrete grade tends to be large, compared to those in higher concrete grade (over 60D).
- The existing structural design and joint arrangements of precast façade and metal formwork shall be reviewed whether they could withstand the increased formwork pressure of SCC
- At present, there is as yet no HOKLAS accreditation for all SCC specific tests. HOLKAS accreditation is mandatory for all concrete tests in public housing construction

- *Other Structures*

For structures involving large horizontal concrete pours like pile caps and transfer plates, the enhanced pouring rate of SCC may be utilized in full strength. Moreover, those structures are usually densely reinforced that the use of SCC would facilitate the pouring and provide better finished concrete quality. When the cost of full casting of a mass structure by SCC is not justified, one may consider pouring the difficult bottom and top portions of the structure with SCC and the intermediate portion with conventional vibrated concrete to alleviate the cost.

In view of the characteristics of SCC, it is particular suitable in concreting difficult areas such as structures with poor access, limited working space and remedial work; or works required high standard of concrete workmanship such as water-retaining structures and cantilever structures.

SCC may offer high quality and innovative precast concrete products, and opportunities to regenerate the precast concrete production system. It is evidenced that SCC has been gaining an increasing market share in the precast concrete industry in Japan, Europe and USA. The main drawback of using SCC for precast concrete production in Hong Kong would be its high material cost in the current market. It is also likely to require longer setting time which may adversely affects the production cycle.

Table 10 – Applicability to General Structural Elements

Vertical Structural Element – (e.g. wall or column)	
Opportunities / Benefits	▪ Flexible and innovative placing methods - pouring from the top or pumping from bottom of formwork ▪ Quality concrete casting is possible at no headroom, e.g. intermediate walls or columns ▪ Reduce defects and honeycombs around the openings and box-outs ▪ Reduce honeycombs at the bottom portions of tall walls and columns ▪ Less dislocation of vertical bars, cover spacers, switch boxes, box-outs, etc ▪ Facilitate dense reinforcement or composite structural design ▪ Thinning concrete sections ▪ Structural benefit of high strength ▪ Enable cast-in-situ delicate detailing on the exterior walls ▪ Improve surface quality provided with appropriate placing method ▪ Fast placing due to time gain of no vibration and less movement of pouring equipment ▪ Reduce danger of placing of external walls ▪ Less noisy
Risks	▪ Full hydrostatic formwork pressure should be assumed ▪ Grout loss at toe of formwork ▪ Higher uplift force on formwork or buoyant units ▪ Catastrophic concrete leakage if formwork bursts ▪ Leakage through vertical construction joints ▪ Overflow of concrete at the openings ▪ Possibly visible line markings between discontinuous concrete lifts ▪ Possibly many blowholes ▪ Time gain due to no vibration is diminished if pouring by skips ▪ Draining of concrete to the adjoining slabs ▪ Greater variation of concrete properties due to rainwater ▪ Possible prolonged setting time affects formwork striking

Table 11 – Applicability to General Structural Elements

Horizontal Structural Element – (e.g. floor, slab or beam)	
Opportunities / Benefits	▪ Fast placing due to less movement of pouring equipment ▪ Reduce honeycombs at the junctions and supports of beams ▪ Save manpower for vibration of large pours ▪ Self-leveling flat surface reducing tamping work ▪ Reduce wastage of over-ordered concrete due to easy checking of poured concrete level ▪ Less dislocation and depression of horizontal bars ▪ Less defects around box-outs and BS junction boxes ▪ Reduce danger of placing of cantilever slabs or beams ▪ Facilitate dense reinforcement or composite structural design ▪ Thinning beam concrete sections ▪ Structural benefit of high strength ▪ Less noisy
Risks	▪ Uneasy to make inclined or stepping unformed surfaces ▪ Uneasy to form monolithic kickers for vertical elements ▪ Fast drying-out of surface incurs shrinkage crack ▪ Less finishability due to fast crusting of top surface ▪ Concrete leakage through vertical construction joints ▪ Catastrophic concrete leakage if formwork bursts ▪ Widespread concrete flow that uneasy to allow temporary break of a pour ▪ Variation of concrete properties due to rainwater ▪ Possible prolonged setting time affects work of following trades

4. Resource Implications

With consulting the local concrete suppliers, the constituent materials for SCC are readily available in the market and the existing ready-mixed concrete plant in Hong Kong is generally capable to produce SCC without additional setup. The major problem is a lack of an agreed SCC standard.

As evaluated in the previous section, the cost of implementing SCC casting in public housing is generally higher than current concrete option. The major cost factor is the concrete cost of SCC which is estimated 15-30% higher than the conventional vibrated concrete in the current market. The formwork cost is also expected to be increased to cater for the high formwork pressure and prevention of grout loss of SCC. On the other hand, SCC may lead to cost saving in concreting labour and repair work.

To assess the fresh properties of SCC in design and construction stages, it requires specific testing equipment which differs from the current testing equipment and procedures in use for conventional vibrated concrete. It is observed that these equipment and testing persons with relevant experience are not readily available in the field.

For construction, additional resources and manpower will be required to verify the concrete designs and quality delivered on site, at least, in the initial stage. Workload of site supervision on compacting work of in-situ concrete could be released, but the supervision on the fresh concrete quality before pouring as well as the workmanship of formwork erection should be strengthened.

5. Further Investigations

SCC is new to both research and application fields of building industry in Hong Kong. The relevant local data, experiences and documents are still very limited to date. This research project is therefore exploratory in nature.

With the limitations of time and resources, the designated mixes in this report to examine the SCC properties only concentrate on water to cementitious content ratio at 0.3, 0.35 and 0.4 and the cement content kept at constant in the same w/c series. Investigations on other designated mixes out of the above range may be required in further stage. In long term, researches on the SCC mix constituents and design leading to lowering material cost should be initiated.

For public housing construction, the full benefit of SCC in practical construction should be explored in terms of comprehensive review of building designs to adopt the characteristics of SCC as well as development of innovative concreting methods to suit local tight construction process and maintaining the quality of SCC. Such investigations should be substantiated by practical trial runs on site.

Hong Kong Housing Authority

香港城市大學
City University of Hong Kong
Department of Building and Construction

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