SUPERCLASSIFIED PFA FOR SELF-COMPACTING CONCRETE

S.D. Fossey, E.A. Byars and H.Y. Zhu

Centre for Cement and Concrete, University of Sheffield, UK. E-mail: DrByars@aol.com

ABSTRACT

In recent years the demand for Self-Compacting Concrete (SCC) has grown significantly due to the tightening health and safety regulations and good concrete practice. However, the high cement contents and volumes of expensive admixtures necessary for satisfactory SCC make it largely uneconomical. This paper reports on the use of ultra fine super-classified PFA (SPFA) to achieve the required workability and cohesion for SCC with low cement contents and no need for specialist admixtures. Initial tests show self-compacting SPFA concrete displays both high workability and stability with w/c ratio as low as 0.2 and that SPFA SCC is significantly more economical than other forms of SCC.

Keywords: Self-Compacting Concrete, Super-classified PFA, Admixtures, Strength, Absorption

1. INTRODUCTION

In the 1980's a chronic skills shortage in the Japanese construction industry was partially solved by using high-workability mixes that could be consolidated without vibration [1]. This type of concrete became known as Self-Compacting Concrete (SCC). An additional advantage of SCC was found to be the ability of the concrete to flow into complex formwork, but with increasing variety and usage of SCC, some problems with excessive bleeding and segregation have emerged requiring additional expensive admixtures[2].

A major driving force encouraging the use of SCC is the impending European Health and Safety Directive covering hand-arm vibration [3]. However, SCC also has implications for traditional large concrete pours and post-tensioning placement where its uniform strength development may benefit the stressing procedure and reduce cracking. In addition, with SCC the associated reduction in labour and plant reduces cost and improves QA procedures as the sample test cubes are more representative of in-situ concrete than vibrated normal workability concrete cubes [2].

2. AIMS AND OBJECTIVES

The aims of this project were to optimise SPFA concrete mixes to maximise workability and cohesion and achieve self-compaction at low water cement ratios. Several objectives were defined as follows:

1. To assess the effects of SPFA on water demand of concrete.
2. To optimise the aggregate gradings used in combination with flowing cement paste to create cohesive flowing SPFA concrete.
3. To minimise the cement content used in very high performance self-compacting SPFA mixes.

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4. To measure the compressive and tensile strength development, absorption and UPV of the self-compacting SPFA concrete mixes.
5. To compare the economy and performance of SPFA self-compacting concrete mixes with concrete made with other materials of equal mix proportions.

3. MATERIALS

3.1 Materials properties

Selected physical and chemical properties of all cementitious materials used are given in Table 1.

Table 1. Typical physical and chemical properties of the materials used in this project

PARAMETER	OPC	PFA	GGBS	MS	SPFA
Surface Area (m^2/kg)	350	350	400	20000	13000
Specific Gravity	3.2	2.1	2.9	2.2	2.3
Particle Range (µm)	5–100	1-150	3-100	0.01–0.5	0.25–25
SiO_2 (%)	20.8	48.0	35.8	92.9	53.5
Al_2O_3 (%)	5.0	28.0	14.0	0.6	34.3
Fe_2O_3 (%)	3.2	9.0	0.5	0.9	3.6
CaO (%)	63.7	3.0	39.7	0.4	4.4
MgO (%)	2.6	2.5	8.6	1.58	1.0

3.2 Cements

Blue Circle OPC to BS12 [4] was used throughout the experimental program.

3.3 SPFA

The SPFA used throughout the research was a Class F PFA to ASTM 311[5] with a mean particle size of 6µm [6], compared to 1-200µm for Class 1 PFA[7]. The water requirement of the SPFA is shown plotted in Figure 1[6].

3.4 Pulverized-Fuel Ash (PFA)

The PFA used for this research conformed to BS3892: Part 1[8].

3.5 Ground Granulated Blast furnace Slag (GGBS)

The GGBS used complied with BS6699 [9].

3.6 Micro-Silica (MS)

The MS used was in a 50/50 ($\pm 2\%$) aqueous slurry form and complied with ASTM C 1240[10].

3.7 Superplasticizer

A single polycarboxylate polymer water-reducing admixture to ASTM C494 [11] and BS5075[12] was used.

3.8 Aggregates

The grading of the aggregates used is described in Table 2. The coarse aggregate was a continuously-graded well-rounded aggregate with a nominal particle size of 5-10mm. The fine aggregate used was well graded concrete sand to BS812 [13].

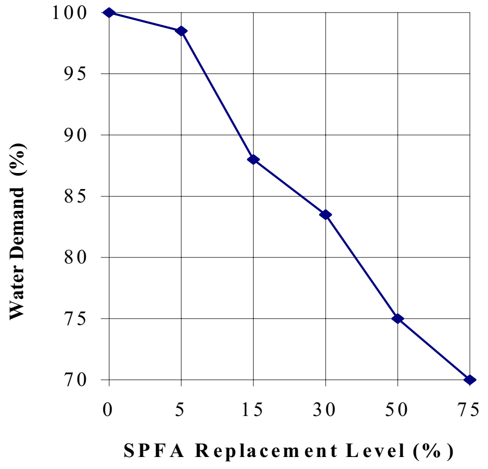

Figure 1. Water requirement of SPFA

Table 2. Aggregate Sieve Analysis

SIEVE SIZE (mm)	% PASSING BY MASS	
	10-5mm	Sand
28	100	100
20	100	100
14	100	100
10	99.4	100
6.3	42.6	100
5	15.2	98.6
2.36	6.2	85.5
1.18	-	76
0.6	-	62.1
0.3	-	17
0.15	-	3.7
0.075	-	0.1

Table 3. Final Mix Proportions

MIX CODE	FINAL MIX PROPORTIONS (kg/m^3)											
	OPC	SPFA (30%)	GGBS (45%)	MS (10%)	PFA (30%)	Water	W/B	Aggregate			SP (%Cem)	Total
								10mm	Fines	Total		
SPFA1	249	107	0.0	0.0	0.0	160	0.45	1029	842	1871	0.3	2387
GGBS	196	0.0	160	0.0	0.0	160	0.45	1036	848	1884	0.3	2400
MS	320	0.0	0.0	36	0.0	160	0.45	1069	874	1943	0.3	2399
PFA	249	0.0	0.0	0.0	107	160	0.45	1029	842	1871	0.3	2387
SPFA2	420	180	0.0	0.0	0.0	120	0.20	962	787	1749	1.0	2469

4. TEST METHODS

4.1 Rheology

Three methods were employed to test the fresh concrete rheology.

4.1.1 Slump Test

The slump test [14] was used on stiffer mixes.

4.1.2 Slump Flow Test

Where the concrete displayed a significant fluidity it was tested using the slump flow test [15]. A 600mm spread was taken to be the lower boundary for SCC. Mixes displaying excessive segregation or bleeding at this stage were rejected.

4.1.3 SSCI Test

The third test method, the 'Sheffield Self-Compactability Index (SSCI) test, Figure 2, was developed as part of the project. The top funnel section of the apparatus is filled with concrete then a gate removed, which allows the concrete to flow down a shallow slope through a throat which is heavily congested with rebar. A comparison of the results obtained using the slump flow test and the SCCI test led to the conclusion that Self-Compactability (600mm flow) corresponded to the concrete flowing to touch all four corners of the lower reservoir when the SSCI apparatus was inclined at 15º to the horizontal. However, the SSCI was found to be more sensitive to lack of cohesion in SCC mixes than slump flow. Visual observation showed aggregates "balling" in the SSCI throat in some instances, and therefore a further restriction on SCC acceptability was imposed: zero segregation in the SCCI test.

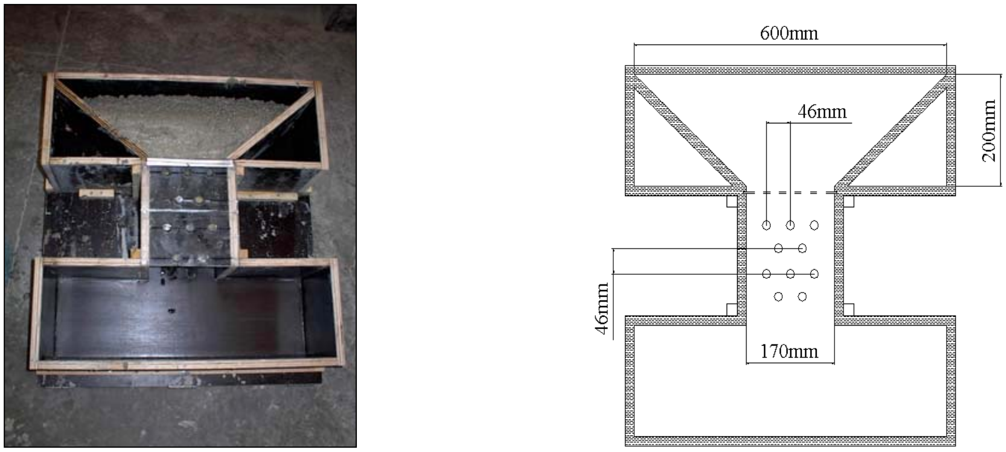

Figure 2. The SSCI test apparatus

4.2 Hardened Properties of Concrete

For each of the final mixes described in Table 3, the appropriate numbers of 100mm cube samples were made [16]. Where the concrete was self-compacting, no vibration was used. Half of the cubes were cured in water at 20ºC to BS1881 [17] and half in air at 20ºC and 65% RH. Further tests were carried out at appropriate ages as shown in Figure 3.

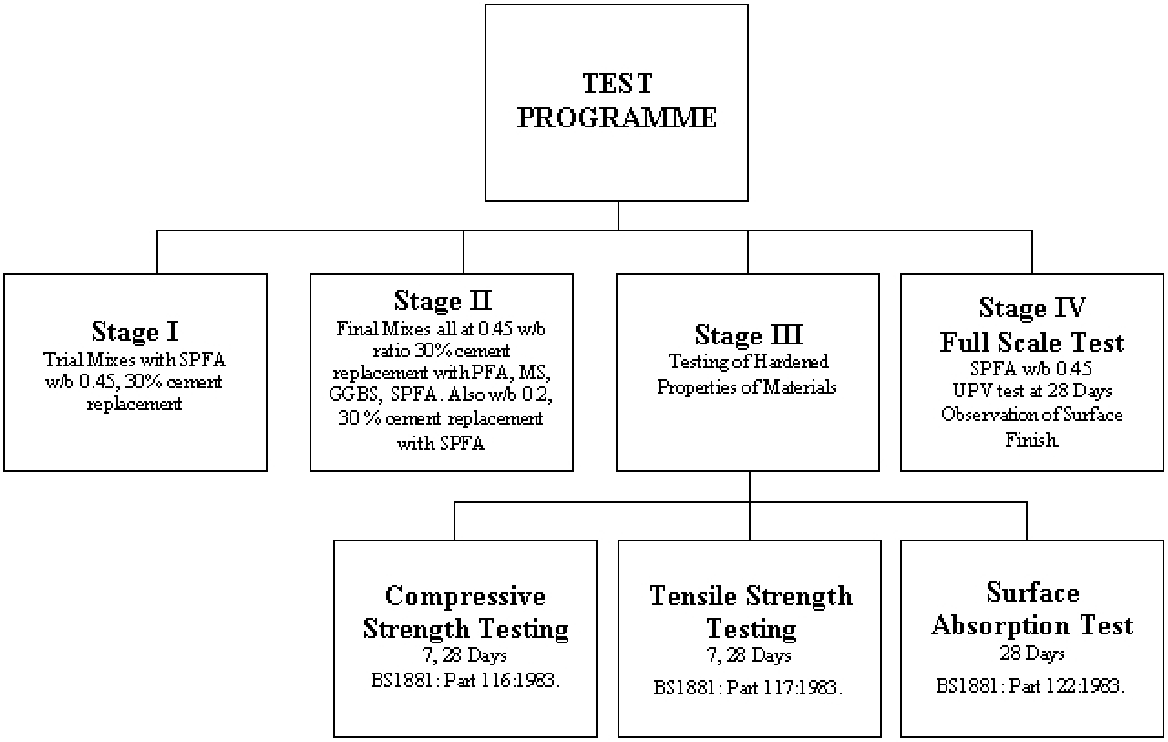

Figure 3. Testing Flow Chart

4.2.1 Compressive Strength

Cubes were tested for compressive strength at 7 and 28 days to BS1881 [18]. The air-cured cubes were saturated prior to test by immersion in a water tank for 24 hours (7 day test) or 48 hours (28 day test).

4.2.2 Tensile Strength

The indirect tensile strength of the cylinders was tested [19] at 7 and 28 days, with the air-cured cylinders being saturated as per the compression test samples.

4.2.3 Surface Absorption

Absorption tests were carried out on both the water and air cured samples after 28 days [20]. Cubes were preconditioned by oven drying for 72 hours, or until the % mass change in 24 hours was ≥0.2%.

4.2.4 Ultrasonic Pulse Velocity (UPV)

The UPV test was carried out on a full size element (a column measuring *1.5x0.2x0.2m* cast from SCC1) and tested to BS1881: Part 203 [21].

4.3 Mix Development

From previous studies carried out at the CCC [6], it was decided to use SPFA at a 30% replacement for cement and a w/b ratio of 0.45 for the initial trials. The influence of fine aggregate content on the concrete stability and the ratio of coarse to fine aggregate was carefully monitored duringa series of trials and particular attention was given to cementitious material and superplasticizer minimisation, as shown in Table 4. Mixes were proportioned on a trial and error basis to assess the influence of changes and the rheology assessed using the slump flow test, Table 4. If the flow equalled or exceeded 600mm, the mixes were also tested using the SSCI test to assess cohesiveness.

Table 4. Summary of the Mix Proportions used during the development of SCC with SPFA

MIX CODE	MIX PROPORTIONS (Kg/m^3)									Flow (mm)	SSCI TEST
	OPC	SPFA	WATER	W/B	AGGREGATE			SP (%Cem)	TOTAL		
					10mm	Fines	Total				
TRIAL 1	218	93	140	0.45	1179	786	1965	1	2416	510	×
TRIAL 2	218	93	140	0.45	1179	786	1965	0.5	2416	600	×
TRIAL 3	218	93	140	0.45	1179	786	1965	0.25	2416	350	×
TRIAL 4	218	93	140	0.45	1297	668	1965	0.5	2416	-	×
TRIAL 5	218	93	140	0.45	1139	825	1964	0.6	2415	520	×
TRIAL 6	218	93	140	0.45	1139	825	1964	0.65	2415	540	×
TRIAL 7	218	93	140	0.45	1120	845	1965	0.65	2416	540	×
TRIAL 8	218	93	140	0.45	1100	864	1964	0.6	2415	520	×
TRIAL 9	218	93	140	0.45	1100	864	1964	0.5	2415	560	×
TRIAL 10	187	80	120	0.45	1173	885	2058	0.6	2445	400	×
TRIAL 11	187	80	120	0.45	1173	885	2058	1	2445	450	×
TRIAL 12	187	80	120	0.45	1173	885	2058	2	2445	450	×
TRIAL 13	233	100	150	0.45	1055	863	1918	0.25	2401	580	×
TRIAL 14	249	107	160	0.45	1029	842	1871	0.3	2387	640	✓
SPFA1	249	107	160	0.45	1029	842	1871	0.3	2387	650	✓

Instability and segregation were found to be the greatest hurdles during trial mixing and required significant manipulation of the fines content of the concrete mixes.

The SPFA concrete mix that was adopted as self-compacting had a Coarse: Fines (C: F) ratio of 55:45, Table 4. Trial 13 was almost self-compacting (580mm slump flow) and had an excellent aggregate distribution with no sign of segregation, Figure 4, suggesting that the mix had excellent cohesivity.

4.4 Full Scale Trial

A full-scale sample column was cast in the lab to study self-compactability at full scale. The element, measuring 1.5m x 0.2m x 0.2m, was cast in one pour using mix SPFA1, then cured overnight in a humid environment in accordance with BS1881 [17]. At 28 days the sample was tested with UPV [21] to establish any variation of density with depth.

Extending from the data of the 0.45w/b trials, a 0.2w/b ratio mix (SPFA2) was developed as shown in Table 5.

Table 5. Summary of the mix proportions used to develop mix SPFA2

MIX CODE	**MIX PROPORTIONS (kg/m3)**									**FLOW (mm)**	**SSCI TEST**
	OPC	**SPFA**	**WATER**	**W/B**	**Aggregate**			**SP (%Cem)**	**Total**		
					10mm	**Fines**	**Total**				
TRIAL 15	420	180	120	0.2	962	787	1749	2.00	2481	720	×
TRIAL 16	420	180	120	0.2	962	787	1749	1.50	2478	710	×
SPFA2	420	180	120	0.2	962	787	1749	1.00	2475	710	✓

Figure 4. Section through a cylinder of Trial 13

5. RESULTS

5.1 Rheology

Table 6 summarises the rheology test results measured on the five final mixes. It can be seen that the workability of the two mixes containing SPFA is far superior to the other mixes despite the mix proportions being identical.

Table 6. Rheology results

TEST	**SPFA1**	**GGBS**	**MS**	**PFA**	**SPFA2**
SSCI	PASS	FAIL	FAIL	FAIL	PASS
Slump Flow (mm)	650	-	-	-	710
Slump (mm)	-	220	50	210	-

Observations were made with reference to the stability of the mix throughout the testing procedure and it was noted during rheology testing that SPFA displayed an excellent degree of cohesion as shown in Figure 5. Cutting through a cylinder of SPFA1 confirmed the cohesivity of the mix, which showed excellent aggregate distribution throughout the sample and no bleeding or laitance.

Figure 5. Mix SPFA1 following a slump flow test and the aggregate distribution in a hardened sample

5.2 Effect of alternative replacement materials

It was found that only SPFA produced fluid, cohesive, self-compacting concrete mixes using the minimum cementitious materials and low water content of SPFA1. To produce a high fluidity concrete using other cement replacement materials requires greater volumes of water, cementitious materials and admixtures. The implications on cost mean that whilst generally the use of SCC can be expensive, the inclusion of SPFA can reduce costs to a competitive level, (see Figure 7).

5.3 Hardened Properties

5.3.1 Compressive Strength

The compressive strength results of the water and air cured samples are shown plotted in ure 6. It is clear from these that the SPFA1 concrete, whilst in this set of tests having slightly lower compressive strength than other comparable mixes, develops greater strength with time in both water and air-curing environments.

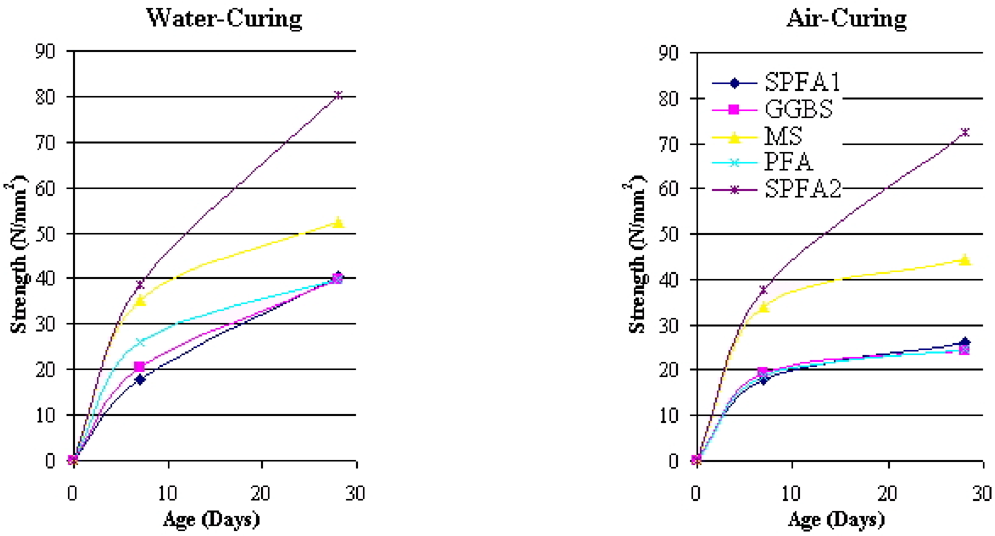

Figure 6. Compressive strength development for air and water cured samples

5.3.2 Tensile Strength

The tensile strength trends, Table 7, are similar to those observed for compressive strength development. The SPFA1 mix initially has a slightly lower tensile strength than other mixes, but this increases relatively with time.

Table 7. Tensile strength results

MIX CODE	Water Cured (N/mm^2) Age (Days) 7	Water Cured (N/mm^2) Age (Days) 28	Air Cured (N/mm^2) Age (Days) 7	Air Cured (N/mm^2) Age (Days) 28
SPFA1	3.7	5.6	2.5	4.6
GGBS	4.2	5.7	3.1	4.3
MS	4.9	6.4	4.0	5.1
PFA	3.9	5.4	2.9	4.4
SPFA2	4.9	7.1	4.2	6.4

5.3.3 Water Absorption

The results from the water absorption test, Table 8, show that the SPFA mixes have significantly lower absorption than other mixes. All air-cured samples showed greater absorption than water-cured ones, yet it is clear from these results that the SPFA mixes are significantly less affected by air curing than similar mixes made at the same w/b ratio with other materials. This is of particular note when one compares the strength results of the SPFA1 and MS concrete mixes, the latter developing considerably higher strength at the age of 28 days, when the absorption tests were conducted. The differences between the SPFA and the PFA concrete absorption is also very well defined with air-curing, which suggests an unexpectedly high level of pore refinement with SPFA.

Table 8. Water Absorption Results

MIX CODE	PRECONDITIONING MASS (kg) Age (hours) 0	PRECONDITIONING MASS (kg) Age (hours) 24	PRECONDITIONING MASS (kg) Age (hours) 48	PRECONDITIONING MASS (kg) Age (hours) 72	SATURATED MASS (kg)	WATER ABSORPTION (%)
Water Curing						
SPFA1	2.356	2.341	2.326	2.322	2.341	0.80
GGBS	2.275	2.261	2.252	2.249	2.277	1.27
MS	2.359	2.350	2.346	2.343	2.362	0.83
PFA	2.392	2.381	2.373	2.370	2.392	0.93
SPFA2	2.386	2.385	2.383	2.382	2.397	0.63
Air Curing						
SPFA1	2.286	2.284	2.282	2.282	2.324	1.84
GGBS	2.194	2.194	2.192	2.191	2.294	4.70
MS	2.247	2.245	2.244	2.242	2.310	3.01
PFA	2.306	2.305	2.304	2.302	2.405	4.45
SPFA2	2.365	2.365	2.364	2.364	2.407	1.40

5.3.4 Full Scale Trial

A 1.5×0.3×0.3m column of SPFA1 concrete was cast and tested using UPV at 28 days to establish if there was any variation in density with depth, which could identify segregation. Readings were taken over the full height of the column and are shown in Table 9.

Table 9. UPV Test Results

Height Above Ground (m)	Time Reading (µs)
1.5	46.0
1.2	45.3
0.9	45.0
0.6	45.3
0.3	44.3
0.0	45.4

The minimal difference in the readings suggests that the concrete is of constant density and that no significant degree of segregation has taken place, which implies that the SPFA1 concrete mix developed in this study has the potential to be used for full-scale works.

6. DISCUSSION

The SPFA used in this study has proved to be extremely effective for making self-compacting concrete. Indeed, when the total binder contents used in this study to make 0.45 w/b ratio SCC are compared with those from other studies, it can be seen that the use of SPFA results in SCC with a binder content of 105-270 kg/m^3 lower than used in comparable studies around the world [22], Figure 7.

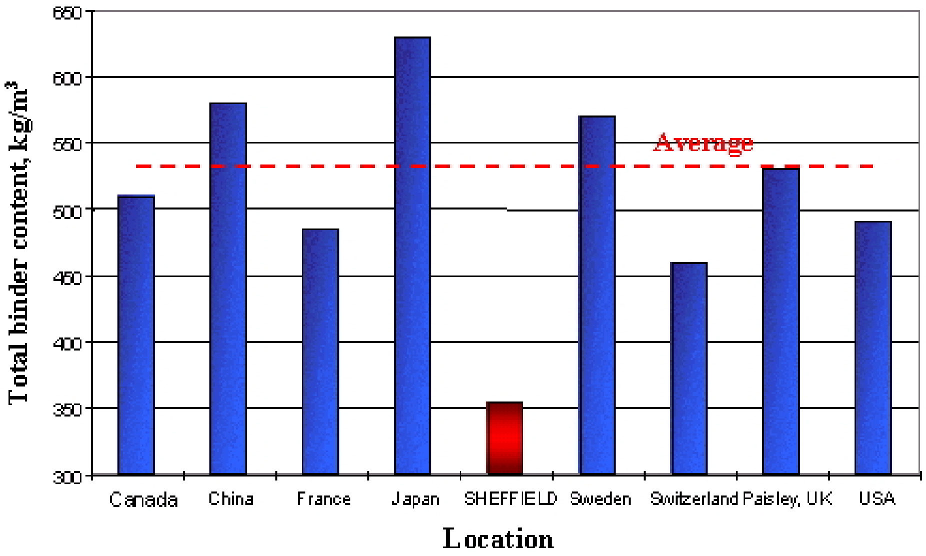

Figure 7. Comparison between total binder contents used in this research and leading projects worldwide.

The explanation for this lies with the nature and properties of the SPFA particles. As a Bingham fluid, in order to maximise the ability of concrete to deform under its own self-weight, the internal yield stress must be minimised. This can be achieved by preventing the formation of Van der Waals bonds between adjacent cement particles as they flocculate in the cement paste. Generally, this is achieved via the addition of expensive admixtures, which adhere to the cement particles and impart a charge, causing repulsion. This deflocculation improves the dispersion of free water throughout the mix thereby increasing the workability of the concrete. PFA can work in the same way, coating the surface of the cement particles and giving them a charge[23]. SPFA will similarly adsorb to the surface of cement particles however due to the smaller particle size, SPFA does this more effectively. Further, in common with PFA, SPFA is hydrophilic in nature and introduces additional water entrainment into the mix thereby giving more consistent dispersion of free water and in turn reducing the tendency for bleeding and segregation and increasing cohesion due to the higher number of interparticular contact points associated with the smaller SPFA particles.

The research on this new area of concrete and ash technology is continuing at the CCC to develop a complete range of SCC mixes using SPFA at various levels and at staged water-binder ratios, in addition to ultra-high strength, compactable concrete for flexible architectural solutions.

7. CONCLUSIONS

1. Superclassified PFA (SPFA) has been shown to suitable for making low cementitious content, extremely cohesive, self-compacting concrete at water-binder ratios between 0.2 and 0.45.
2. A 30% replacement of SPFA for cement has been found to be the optimum replacement level.
3. When SPFA is used to make SCC, the cementitious content is markedly lower (up to 280kg/m^3) than other SCC concretes made with conventional materials.
4. Virtually zero segregation or bleeding and extremely high cohesiveness and flow characteristics are observed in SCC made with SPFA.
5. The SSCI test has been shown to be more sensitive to the tendency for SCC mixes to segregate than the slump-flow test and has been adopted as a second check on SCC developed at Sheffield University.
6. Self-compacting SPFA concrete mixes may be considerably more durable than similarly-proportioned concrete mixes made with other alternative cement replacement materials, as shown by their significantly lower absorption, which indicates a better resistance to physical penetration of aggressive ionic species.
7. In a large-scale trial, the SPFA SCC cast as a column exhibited no signs that segregation of any description had taken place over it's height.

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