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Overview Studies of High Strength Self-Consolidating Concrete

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Abstract**—**Self-Consolidating Concrete (SCC) is considered as a relatively new technology created as an effective solution to problems associated with low quality consolidation. A SCC mix is defined as successful if it flows freely and cohesively without the intervention of mechanical compaction. The construction industry is showing high tendency to use SCC in many contemporary projects to benefit from the various advantages offered by this technology.

At this point, a main question is raised regarding the effect of enhanced fluidity of SCC on the structural behavior of high strength self-consolidating reinforced concrete.

A three phase research program was conducted at the American University of Beirut (AUB) to address this concern. The first two phases consisted of comparative studies conducted on concrete and mortar mixes prepared with second generation Sulphonated Naphtalene-based superplasticizer (SNF) or third generation Polycarboxylate Ethers-based superplasticizer (PCE). The third phase of the research program investigates and compares the structural performance of high strength reinforced concrete beam specimens prepared with two different generations of superplasticizers that formed the unique variable between the concrete mixes. The beams were designed to test and exhibit flexure, shear, or bond splitting failure.

The outcomes of the experimental work revealed comparable resistance of beam specimens cast using self-compacting concrete and conventional vibrated concrete. The dissimilarities in the experimental values between the SCC and the control VC beams were minimal, leading to a conclusion, that the high consistency of SCC has little effect on the flexural, shear and bond strengths of concrete members.

Keywords**—**Self-consolidating concrete (SCC); high-strength concrete, concrete admixtures, mechanical properties of hardened SCC, structural behavior of reinforced concrete beams.

I. INTRODUCTION

SELF-CONSOLIDATING concrete (SCC) is a cohesive high consistency concrete mix with self-compactness properties produced to reduce the need for mechanical consolidation. Achieving self-compactness properties necessitates some alterations to the concrete mix design where high paste content and low coarse aggregate volumes are inevitable to maintain the stability and cohesiveness of the concrete mix. An effective dispersion mechanism is also another factor that controls the high consistency of concrete mixes, particularly at low water to powder ratios. Today, the expectations for concrete structures built using SCC involve enhanced longevity and improved performance during their service life. Currently, a limited number of specifications, testing techniques and standards was released presenting clear recommendations concerning the design strategies of concrete elements cast using high consistency concrete. The high audience of this technology among the construction industry has encouraged many researchers to conduct experimentations that investigate the effect of SCC on the structural performance of reinforced concrete. A common strategy was noticed to be common in the majority of the research papers published on SCC where SCC mixes were compared to regular concrete mixes. The different mix compositions and proportions engaged several variables in the comparative studies such that the bare effect of high fluidity on the structural behavior of reinforced concrete members could not be identified. The research, reported in this paper, investigates on a prime concern associated with the adverse effect that the high consistency of SCC can have on the shear and bond performance of reinforced high strength SCC members. Accordingly, a three phase research program was developed at the American University of Beirut (AUB) to address this concern. The objective of the first two phases aimed at finding the optimal mix design to be used in the placement of reinforced concrete beams; whereas the third phase consisted of testing and studying the structural behavior in flexure, shear, and bond splitting.

II. EXPERIMENTAL PROGRAM

A. Concrete Mix Constituents

1) Coarse Aggregates

The rheological properties of concrete mixes, chosen to satisfy specific application requirements, control the volume and the maximum size aggregate (MSA) to be used in the mix. A MSA ranging from 10mm to 16mm is recommended. In this research, a 10mm MSA was used to constitute a fraction of 30% of the total concrete volume as suggested in [1]-[3].

2) Fine Aggregates

To guarantee an adequate aggregate gradation and sufficient cohesiveness of the concrete mix, two types of fine aggregates were incorporated: manufactured sand (with particle sizes ranging from 0.075mm to 4mm) and natural sand (with particle sizes ranging from 0.075mm to 1.8mm).

3) Powder

The powder constituent in the concrete mix includes fine particles with sizes smaller than 0.075mm. A combination of Type I cement and limestone crushing powder was considered

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to form the powder portion of the concrete mix in this research. Maintaining the stability of the mix necessitates the use of high powder content. A constant water to powder ratio of 0.33 was considered in the production of SCC and VC mixes.

4) High Range Water Reducing Admixtures

Two types of superplasticizers were used to manipulate the consistency of high strength concrete.

The first is a second generation Sulphonated Naphtalene-based superplasticizer, an admixture commonly used in the concrete industry to create workable high strength vibrated concrete (VC) mixes. The second is a third generation Polycarboxylate Ether-based superplasticizer, an essential constituent used in the production of SCC. Its steric dispersion mechanism has proven to be highly effective in providing concrete with high consistency characteristics that are unachievable with the conventional second generation superplasticizer.

B. Steel Reinforcement

The beam specimens were similarly reinforced with two 20mm and two 12mm longitudinal reinforcing bars located respectively at the bottom and top of the beam cross section. The shear critical regions were reinforced with 8mm transverse reinforcement. The reinforcement properties are listed in Table I below.

TABLE I
REINFORCING BAR PROPERTIES

	Rebar size	f_y (MPa)	f_u (MPa)	E_s (MPa)
Bot. reinforcement	2 Φ 20	632.0	743.0	200,000.0
Top reinforcement	2 Φ 12	557.0	667.0	290,000.0
Shear reinforcement	2 Φ 8	569.0	661.0	220,000.0

C. Mix Proportioning

The first two phases of the research program revolved around finding the optimal mix design to produce a high strength SCC and a workable VC. A cylindrical compressive strength of 60 MPa was set as a target at the beginning of the program. The literature review found in [4]-[6] revealed that, until these days, numerous researches studying SCC mixes do not follow a standard procedure for mix design due to the absence of international codes detailing methods for mix proportioning. In 2009, Domone [1] published a university research paper at the University College London presenting an effective mix design method for SCC. The UCL method correlates between the behavior of SCC and that of the mortar component that occupies 70% of the total concrete volume. Domone recommends conducting extensive experimentations on mortar mixes having amix design identical to that of the intended concrete mix (excluding the coarse aggregate constituent) to provide an adequate overview on the prospective rheological properties of SCC. The small scale of mortar mixes facilitates carrying several trials until the optimal mix design is achieved prior to the production of larger scale mixes.

The UCL method was adopted in phases I and II of the experimental program. Phase I of the research had as objective to test and compare the rheological properties of identical mortar mixes having a constant w/p ratio of 0.33 and designed to suit the consistency requirements of SCC. SCC and VC mixes were made with either second or third generation superplasticizer. The outcomes of phase I narrowed the range of superplasticizer to be used in the production of the concrete mixes of Phase II. The purpose of phase II was to refine the admixture content to a common dosage that will provide SCC and VC with the adequate consistency defined by a spread flow of 700-800mm for SCC and a vertical slump greater than 200mm for VC. Table II reports the detailed mix proportions for each of the constituent materials.

TABLE II
CONCRETE MIX PROPORTIONS

Constituent materials	Mix proportioning
Powder (kg/m^3)	585
Cement (kg/m^3)	559
Natural sand 0-1.18 mm (kg/m^3)	453
Crushed sand 0-4 mm (kg/m^3)	371
Coarse aggregates 4-10 mm (kg/m^3)	807
Free Water (kg/m^3)	194

D. Specimen Design

Phase III of the research consists of studying the structural performance of beam specimens under different modes of failure. The design was carried in accordance with ACI 318-11 [7].

To meet this objective, twelve beam specimens, having 200mm width x 300mm depth x 2000mm length, were designed to exhibit flexural, shear or bond splitting failure.

Four beams, including two identical replicates for SCC and two for VC, were specified for each of the three modes of failure. Replicates were used to validate test results.

E. Testing Procedure

1) Fresh Properties

The fresh properties characterizing the fluidity of SCC can be identified by the slump flow test which was carried in compliance with ASTM C1611 [8]. For VC mixes, the vertical slump test was used to find the workability of the mix in accordance with the procedure specified in the ASTM C143 [9] standard.

2) Hardened Properties

To determine the hardened properties of concrete, standard 150mm x 300mm cylinders were extracted from the SCC and VC concrete batches used to cast the beam specimens, and were tested in accordance with ASTM C39M, ASTM C496M and ASTM C469 M standards [10]-[12] to find the concrete compressive strength f'_c, the tensile strength f_t, and the modulus of elasticity E_c.

In addition, standard plain concrete beams were prepared to determine the flexural strength or the modulus of rupture f_r as per ASTM C78M Standard [13].

3) Beam Specimens

The reinforced concrete beams were tested using an MTS hydraulic machine. Spanning 1800mm between the centerlines of the supports, the beams were subject to two concentrated loads applied continuously at one third and two third of the span length (600mm). At uniform load increments of 10 kN, readings of the vertical deflection at midspan and the crack widths under the two concentrated loads and at midspan were reported. The elongations of the bottom tensile reinforcing bars inside the concrete were also monitored through strain gages connected to the computer system. A schematic view of the testing setup of beam specimen is shown in Fig. 1.

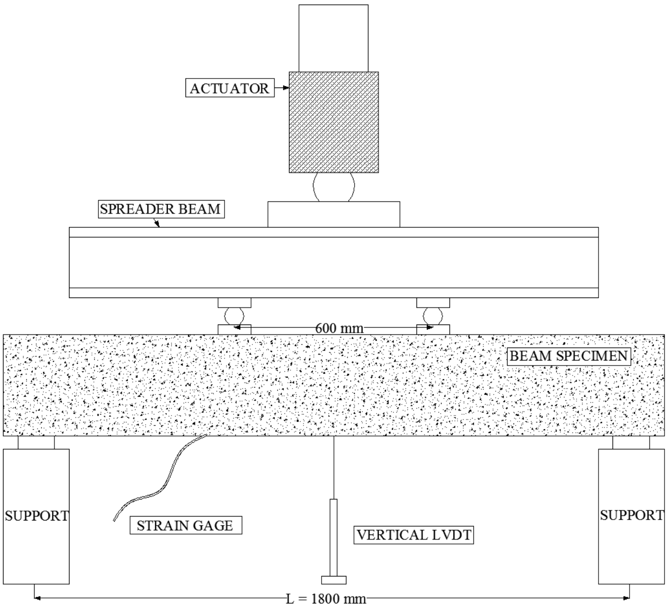

Fig. 1 Testing setup of beam specimen

III. EXPERIMENTAL RESULTS

A. Fresh Properties

1) Phase I

In Phase I, 24 small scale mortar mixes were prepared to test the effect of incremental dosages of superplasticizer on the rheological properties of mortars. All mortar mixes had identical mix proportions with exception for the bulk percentage and type of superplasticizer that was used. The outcomes of Phase I are illustrated in Fig. 2 by a chart representing the variation of the spread flow with respect to the bulk dosage of admixture. According to Domone [1], an SCC slump flow of 650 to 800mm is reachable with a mortar spread flow range of 265 to 315mm considering a coarse aggregate content of 30%. As a consequence and from the chart displayed in Fig. 2, a range of 1.20%-1.65% demonstrated to be satisfactory. The lower boundary is expected to provide high consistency for SCC and VC whereas the upper boundary forms the limit to maintain the stability of the concrete mixes.

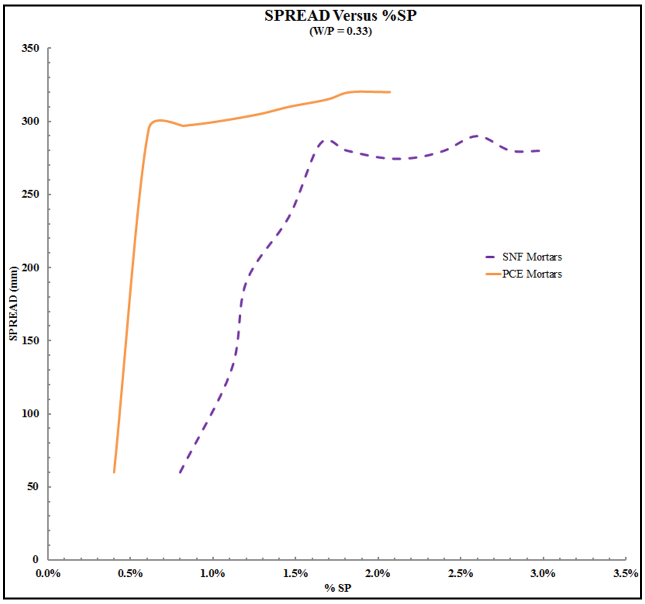

Fig. 2 Mortar spread flow to dosage of superplasticizer

2) Phase II

The experimentations of phase II lead to a common dosage of 1.6% of superplasticizer that has proven to ensure satisfactory workability properties for VC and SCC. The resulting mix design was used in the placement of reinforced concrete beam specimens. The fresh properties of the SCC and VC final mixes are shown in Table III.

TABLE III
FRESH CONCRETE PROPERTIES

Concrete Mix Type	Slump (mm)	Spread flow test (mm)
VC	210	-
SCC	-	790

B. Hardened Properties

Table IV presents the hardened properties of SCC and VC mixes produced to cast the beam specimens. The results compare the compressive and tensile strengths in addition to the moduli of rupture and elasticity. The experimental results were normalized to a common concrete strength of 60 MPa.

TABLE IV
AVERAGE HARDENED CONCRETE PROPERTIES

Strength (MPa)	VC	SCC
f_c'	57.9	62.4
E_c– Normalized [a]	33,698.1	34,450.8
f_t – Normalized [a]	3.9	4.2
f_r – Normalized [a]	5.2	5.9

[a] The experimental values were normalized for a common concrete strength of 60 MPa

C. Structural Performance

Summary of the test results of all twelve beams is presented in Table V. The listed data include the ultimate concrete shear load inducing the first diagonal crack and the ultimate load resisted by each beam specimen at failure. The beam designation was identified by three terms: the first term defines the concrete mix used in the placement of the specimen (SCC or VC) and constitutes one of the two variables in this phase; the second term specifies the design mode of failure and forms the second variable of phase III, whereas the third term represents the specimen number. Figs. 3–5 illustrate the stiffness characteristics of the flexural, shear and bond beams through the plotted load deflection curve corresponding to each mode of failure.

TABLE V
ULTIMATE LOADS AND MAXIMUM DEFLECTIONS AT FAILURE

Beam type	Beam notation	Concrete mix	P at first diagonal crack (kN) [a]	Pmax (kN) [a]	Δ_{max} (mm)
Flexural beams	SCC-F-B1	SCC	49	155.3	15.5
	SCC-F-B2	SCC	49	146.1	19.4
	VC-F-B1	VC	46	157.6	13.5
	VC-F-B2	VC	41	160.0	30.2
Shear beams	SCC-SH-B1	SCC	49	129.7	14.9
	SCC-SH-B2	SCC	49	105.3	8.2
	VC-SH-B1	VC	41	113.5	7.8
	VC-SH-B2	VC	46	130.2	11.2
Bond beams	SCC-B-B1	SCC	44	91.3	6.6
	SCC-B-B2	SCC	54	85.5	5.3
	VC-B-B1	VC	51	89.5	9.9
	VC-B-B2	VC	51	92.1	8.0

[a] The experimental loads were normalized at a common concrete strength of 60 MPa.

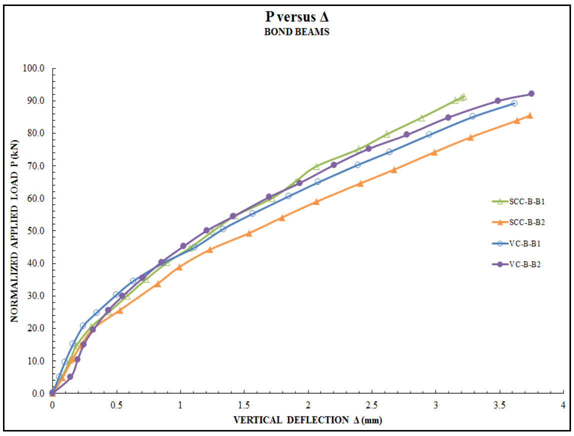

Fig. 3 Load-deflection curves of the bond beams

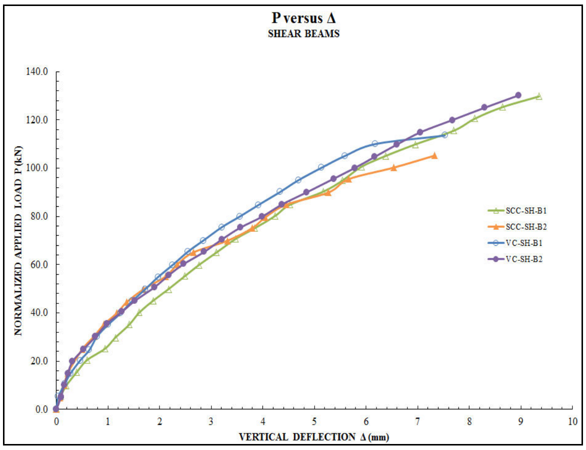

Fig. 4 Load-deflection curves of the shear beams

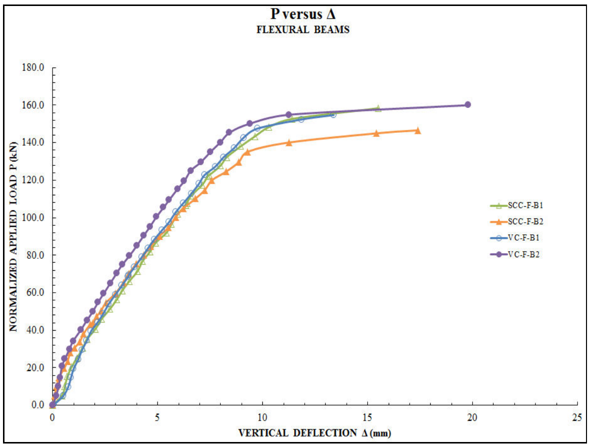

Fig. 5 Load-deflection curves of the flexural beams

IV. ANALYSIS OF TEST RESULTS

A. Fresh Properties

The laboratory tests of the first phase of the research conducted on identical small scale mortar mixes revealed that the dispersion mechanism created by third generation PCE-based superplasticizers is more efficient than the second generation superplasticizers dispersion and produce self-compactibility properties at a significantly lower dosage of admixture. In addition, the high consistency procured by PCE superplasticizers is hardly achievable with SNF-based superplasticizers. Referring to the observations reported during the experimental phase, the distinctive viscous nature of third generation superplasticizers appeared to provide mortars with high stability and segregation resistance differently from the case of second generation superplasticizers.

B. Hardened Properties

The tests on hardened concrete cylinders and plain concrete beams disclosed some of the effects of SCC rheological properties on the mechanical strength of concrete. It was noticed that the higher consistency of SCC was accompanied with a higher compressive strength and a slightly greater splitting strength and modulus of rupture. The analysis of the experimental results led to the assumption that the more effective hydration, triggered by the more efficient dispersion of Polycarboxylate Ether-based superplasticizer, constitutes a possible cause for the differences in the strength of hardened concrete mixes.

C. Beam Specimens

The dissimilarities in the experimental values between the SCC and the control VC beams were not major. The analysis of the results revealed the following facts concerning the behavior of reinforced concrete beams cast using high consistency and vibrated concrete mixes having identical mix designs:

The cracking patterns of SCC and VC indicate that the high consistency of concrete has little effect on the crack width, height and density.

The SCC and VC flexure beams exhibited similar behavior under identical loading conditions, leading to the conclusion that the high fluidity of concrete has little impact on the flexural strength of reinforced concrete.

The results of the shear beam specimen tests contradicted the findings of Boel et al. [14] where tests on SCC beams revealed lower shear capacities than VC beams. The difference in the experimental methodology demonstrates this discrepancy in the outcomes.

The bond beams indicate that the bond between steel and concrete was not affected by the high flowability of fresh SCC mixes. The majority of the researches found in the literature review [15]-[18] agreed with this statement since equal bond strengths were found for normal concrete and SCC.

The distinctive experimental program has separated the effect of high consistency from the impact that mix proportioning variables can have on the structural performance of SCC. In conclusion, this research proves that the high fluidity of SCC is not the factor that is affecting the structural behavior of SCC.

Recommendations for future researches consist of increasing the volume and the maximum size of coarse aggregates in the concrete mixes while keeping the self compactibility characteristics intact.

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