DEVELOPMENT AND APPLICATIONS OF SELF-COMPACTING CONCRETE IN NEW ZEALAND

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ABSTRACT: Self-compacting concrete has been developing in Firth Industries, New Zealand, since 1999. A broad developing program has been carried out in order to produce a marketable product, which enables to deliver consistent properties, superior quality, easiness of construction, reduction in construction (or precast production) cost and reduction in health hazards. This paper presents laboratory test results, full-scale trials and application of SCC in a number of precast products and in-situ casting structures. The results showed that SCC exhibited an excellent performance in both fresh and hardened states, and it was also acknowledged that it is possible to produce a cost effective SCC, meeting demands and conditions of the construction industry in New Zealand.
KEYWORDS: Self-compacting concrete, mix design, deformability, segregation resistance, passing ability, surface form finish quality, compressive strength, elastic modulus.

1. INTRODUCTION

Interest in Self-Compacting Concrete (SCC) arose in New Zealand when this type of concrete was realized as a milestone achievement in the concrete technology, which can bring positive benefits to the New Zealand construction industry. Firth Industries, the leader of the ready mixed industry in New Zealand, has been developing SCC since 1999 when a broad developing program was initiated. The main target of SCC development was to come up with a marketable product, which would deliver consistent properties, superior quality, increased speed of the construction process and reduction of the health hazard in comparison with compacting concrete via the vibration method. Excellent results have been obtained during laboratory tests; also full-scale and demonstration trials relating to different actual projects. Since then SCC has been used at a number of different applications primarily in the precast/prestressed industry.

This paper presents the laboratory test results on SCC containing different types of aggregates, cements and mineral and chemical admixtures. The paper also discusses some full-scale and demonstration applications in different types of commercial precast products and on-situ structural components.

2. MIX DESIGN APPROACH AND EXPERIMENTAL PROGRAM

SCC containing different types of materials was designed with the use of so-called "two-phase material" mix proportioning method. The self-compacting concrete mixes were firstly developed and tested at the laboratory and then used in full-scale trials.

2.1 Mix Design Method

All mixes were designed with the use of the two-phase material mix proportioning method, which was developed by the second author, his supervisors and co-workers **[1, 2, 3, 4]**. This mix design method considers SCC as a material consisting of two-phases, namely solid and liquid phases. The solid (aggregate) phase includes fine and coarse aggregates. The liquid (paste) phase consists of cement, mineral and chemical admixtures, water, air and superfine particles from fine aggregates. In this mix design method, criteria for the aggregate and the paste phases was defined from the point of view of high performance, economic efficiency (lowest possible paste volume and superplasticizer quantity), applicability for different materials and reduction of trial works in laboratory. **Fig. 1** illustrates the main procedure of this mix design method.

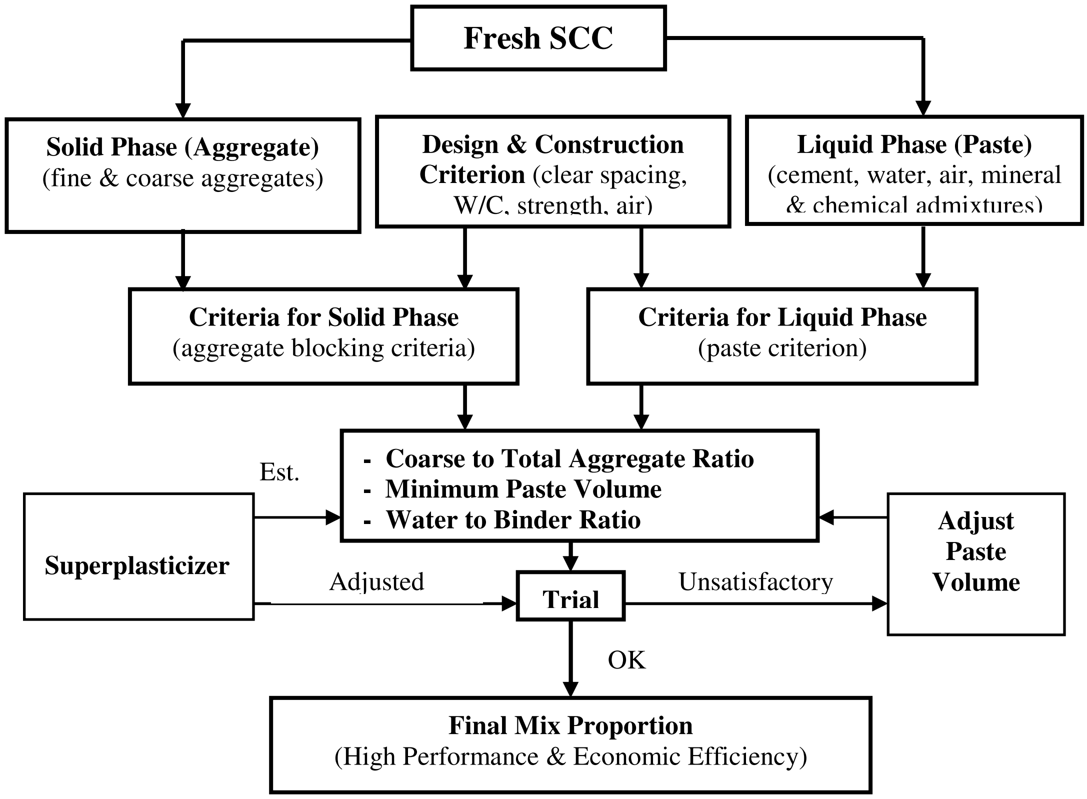

Fig. 1 Mix Design Procedure Flow Chart

As we can see from **Fig. 1**, optimum coarse to total aggregate ratio, minimum paste volume and water to binder ratio are determined from the solid and liquid phase criterion and can be selected for SCC mix design. These parameters are derived from the analysis of the material properties (particle distribution, void content and maximum size), design requirements of the structure (clear spacing between reinforcement bars, W/C, strength, etc.) and construction requirements. Typical minimum required paste volumes calculated from the aggregate blocking and paste phase criteria are shown in **Fig. 2**. The selected paste volume must meet both criteria.

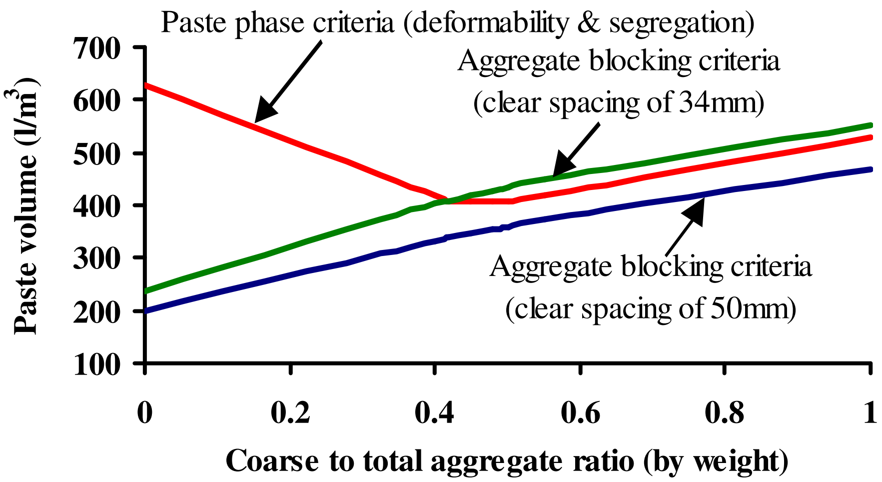

Fig. 2: Typical Minimum Required Paste Volumes Computed from Aggregate Blocking and Paste Phase Criteria.

2.2 Raw Materials Used

Binders: - General purpose Portland cement (60MPa (ISO-CEN), low alkali);
- Limestone modified cement: inter-ground GPC with 15% of limestone;
- Fly ash: class "C" (ASTM C-618);
- Milled limestone: high $CaCO_3$ content.

Aggregates: - Coarse aggregates: basalt and greywacke from four different sources with maximum sizes of 19 and 13 mm;
- Coarse sand: crushed basalt and greywacke from four different sources;
- Fine sand: river and beach silica from two different sources.

Chemical admixtures: - Polycarboxylated superplasticisers from two different sources.
Steel fibres: - "Dramix RC65/35BN".

2.3 Test Parameters

Using L-box, penetration apparatus, slump cone and slump plate, the main testing parameters to assess the quality of SCC at fresh state were observed. They included slump flow diameter (F), flow time (T_{50}), penetration depth (P) and filling head drop (H). These parameters were used to assess deformability (flowability), flow velocity, segregation resistance and blocking behavior around reinforcement bars.

The main properties of hardened concrete, which were observed at the time of testing were surface form finish quality, compressive strength at different ages, elastic modulus and tensile splitting strength. The test results of a more comprehensive testing program, set out to investigate mechanical properties of hardened SCC may be reported on another occasion.

3. LABORATORY TEST RESULTS AND DISCUSSION

The main target of the testing program was to achieve good deformability, satisfactory segregation resistance, satisfactory passing ability and smooth form finish of SCC containing different materials. The next stage of the program was to assess the economics of SCC in comparison with conventional concrete. The final stage of the program was to confirm the test results obtained in the laboratory and in the full-scale trials.

3.1 Maximum Water to Binder Ratio

In order to find the highest water to binder ratio which does not cause segregation of SCC, the different water to binder ratios with different coarse to total aggregate ratios were tested.

When the maximum water to binder ratio for certain coarse to total aggregate ratio was determined, it allowed SCC to be designed with the binder content and supeplasiciser dosage being very low. Also, for certain sets of aggregates, optimum coarse to total aggregate ratio was selected to enhance SCC with low paste volume, lower superplasticiser dosage and less sensitivity to the natural variations of raw materials.

The tests on the maximum water to binder ratios and optimum coarse to total aggregate ratios indicated that SCC containing fly ash exhibited the slump flow being between 65 to 74 cm, low supeplasticiser dosage (between 1.2 and 2.3 kg/m^3) and yet stable (no segregation was observed). The typical cement contents were ranged between 250 to 410 kg/m^3 depending on design criteria and technical specifications.

3.2 Minimum Paste Volume, Segregation Resistance, Deformability and Passing Ability

Using criteria for aggregate blocking and paste phase criteria **[1, 2, 3, 4]**, the minimum paste volume for the different coarse to total aggregate ratios for certain sets of materials were computed and tested. As shown on **Fig. 3**, the minimum paste volumes for different coarse to total aggregate ratios were calculated and tested in order to achieve non-segregating SCC with slump flow being equal or exceeding 70 cm (high slump flow indicates high deformability).

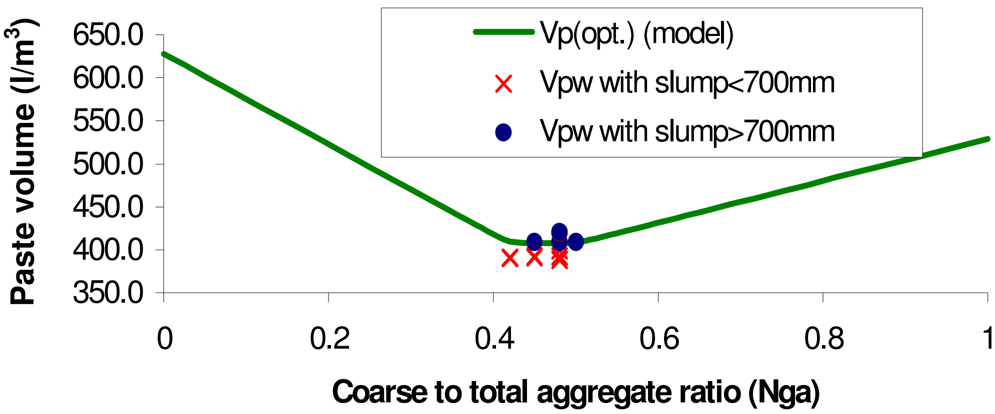

Fig. 3: Minimum Computed and Tested Paste Volumes and Different Coarse to Total Aggregate Ratios

The slump flow diameters of non-segregating SCC were measured in a range between 65 and 74 cm. All tested non-segregating SCC with paste volumes similar or greater than those computed using the model based on aggregate blocking and paste phase criteria, exhibited good and excellent passing ability when they were tested in an L-box having 34-mm clear spacing between reinforcing bars. Typically, the flow time (T_{50}) to reach 50 cm of flow diameter ranged between 1 and 8 seconds.

3.3 Properties of Hardened Self-Compacting Concrete

3.3.1 Form Finishing Quality

In order to assess the quality of the concrete surface finishing, a box with the inner cross section of 100X200 mm and height of 600 mm was made. Fresh SCC was poured into the box and then de-moulded after 18 hours to 24 hours. Test results showed that, in general, non-segregating SCC with the slump flow diameter between 65 cm and 74 cm exhibited smooth surface without honeycombing (**Fig. 4**). SCC with low cement contents and containing milled limestone indicated better form finishing quality then those SCC's containing fly ash with similar cement content, similar paste volume and slump flow.

Fly Ash

Limestone

Fig. 4: Form Finish of SCC Tested in Laboratory

3.3.2 Compressive Strength

One-day compressive strength of SCC containing fly ash was varying between 3 and 22 MPa depending mainly on the fly ash content and water to cement ratio. Two and 28-day compressive strengths were typically in the range of 16 to 37 MPa and 70 to 105 MPa respectively for water to binder ratio between 0.30 and 0.35 (water to cement ratios were varying between 0.42 and 0.75) and cement contents between 250 to 410 kg. SCC containing fly ash exhibited high strength growth after two days of age, but relatively slow strength development in early age. Typical strength development of SCC containing fly ash with different cement contents can be seen in **Fig. 5**. As we can seen from **Fig. 5**, SCCs containing different quantities of fly ash have different rates of strength gain but 28-day strengths are nearly the same.

The series of SCC containing milled limestone had its water to binder ratio ranged from 0.37 to 0.45, cement contents between 250 and 325 kg/m^3 and limestone contents from 190 to 250 kg/m^3. One day compressive strength was between 6 and 11MPa, while two, seven and 28-day strengths were 12 to 19.5, 22.5 to 34 and 27 to 42MPa, respectively. The strength test results can be seen on **Fig. 6**.

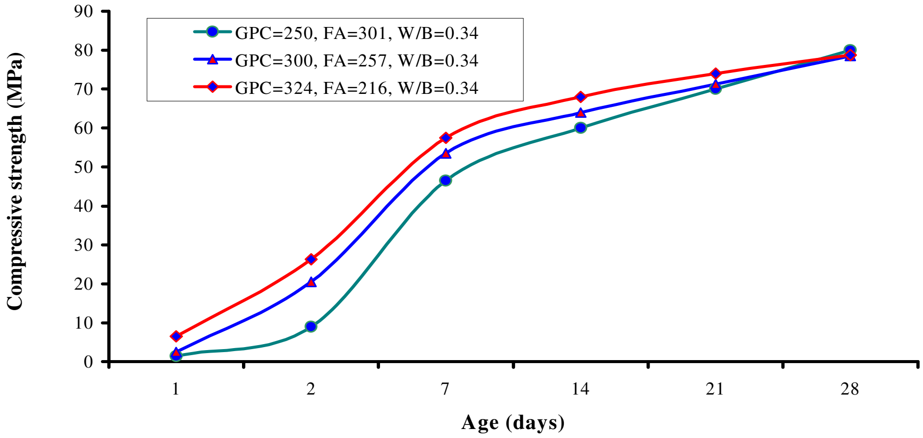

Fig. 5: Compressive Strength of SCC Containing Fly Ash and Different Cement Contents

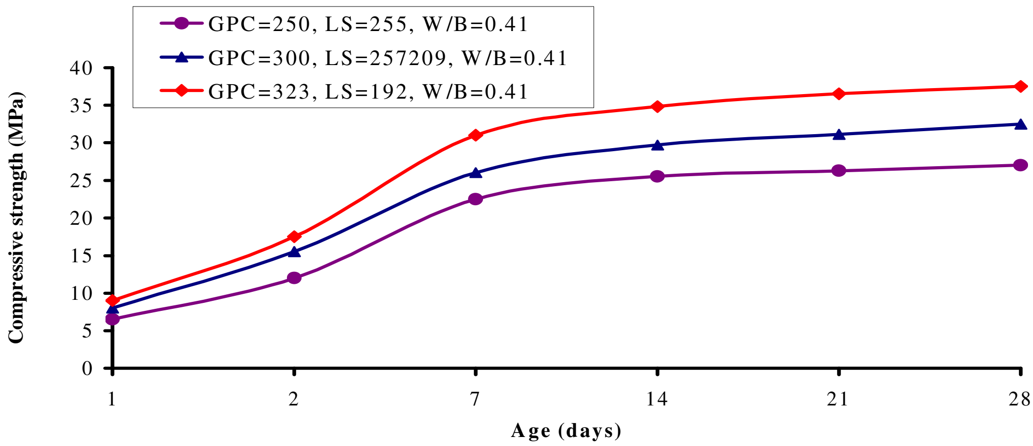

Fig. 6: Compressive Strength of SCC Containing Milled Limestone and Different Cement Contents

3.3.3 Elastic Modulus and Tensile Splitting Strength

Although elastic modulus and tensile splitting strength tests were not parts of the SCC development program's primary objectives, the desire to check if SCC could exhibit compliance with NZ codes was great. Hence, some test results were obtained. Tensile splitting strength of SCC was exceeding requirements of the NZ code of designing concrete structures by 20 to 40% and elastic modulus test results were equal or exceeding recommended values by up to 25%. A more comprehensive testing program to investigate mechanical properties of hardened SCC was carried out and results may be reported on another occasion.

4. APPLICATIONS

After laboratory testing, SCC was tested in full-scale applications to cast precast products and in-situ structures. Some applications are presented in this paper. They are as follows: septic tank units consisting of a septic tank, "wing wall" insert and roof, columns for the crane's foundation, prototype columns as a part of sheer wall, road barrier units, 'ExeLoo' unit, UV filter planks for water treatment plant upgrade.

The quality control system was predetermined for each full-scale trial and application. This included determining the moisture content of coarse and fine aggregates prior to weighing materials. The sequence of materials discharged to a mixer was as per the batching procedure adopted in Firth Industries. After the initial 2 minutes mixing, two thirds of the required dosage of superplasiciser was added and then mixed for the extra two minutes. Before casting, the spread test was carried out on site to assess flowability and segregation of SCC. Then the rest of the required quantity of superplasticiser was added to achieve required flowability and another spread test performed before the concrete had been discharged from the truck mixer.

4.1 Septic Tank

SCC was used in casting a septic tank, “wing-wall” insert unit and a roof for the tank, which is illustrated in **Fig 7**. The tank itself was cast upside down to its working position. The height of the tank was 2300 mm with a diameter of 2500 mm. The thickness of the tank’s wall was 50 mm at the bottom and 84 mm at the top. 8-mm diameter reinforcement mesh was used. The “wing-wall” unit has a very complex shape and consists of 5 50-mm thick “wing-walls”, a cylinder and a cone at the bottom of the unit.

Fig. 7: Pour of SCC; Septic Tank with the Roof and “Wing-Wall” Insert

Greywacke coarse aggregates of 13 mm maximum size and coarse sand as well as sea coastal sand were used in the SCC mix. All materials were mixed in a truck mixer.

The tank was cast using a skip pouring SCC to the very middle of the top of the “bottom” of the tank. Excellent flow without segregation was observed.

The “wing-wall” insert and the roof required ‘Dramix’ steel fibre to be used, therefore a necessary quantity of fibres were added to the mixer and SCC was mixed for 5 minutes. A specially designed funnel was used to cast the “wing-wall” unit. The SCC with steel fibres demonstrated unique flow and passing ability flowing down, around and up through the 50-mm thickness. In order to get to the lower part of the unit (the cone), the SCC with fibres had to pass through 40X200 mm openings without blocking. Neither blockage nor segregation was observed.

The roof was cast directly from the discharge chute of the truck. Again SCC demonstrated excellent flowing properties without segregation. The form finish was very good, there was neither honeycombing nor “bug holes” on the surface of all three components of the septic tank. There was no trace of the reinforcement on the surface of the walls of the tank. Compressive strength at 2, 7 and 28 days was 14.0, 48.5 and 80.0 MPa, respectively.

4.2 Crane Foundation Columns

Four columns of the crane's foundation were cast on site. Each column was of a circular shape of ϕ750 mm. The upper part of each column was cast with SCC and had a height of 3000 mm. Reinforcement bars of ϕ28 mm were arranged in vertical direction. The clear spacing between the reinforcing bars was about 70 mm.

Graywacke coarse aggregates of 13mm maximum size and coarse sand was used in the SCC mix design; as was fine river sand. SCC was mixed in a central mixer, then discharged to the truck agitator and delivered to the site. A skip with ϕ100 mm rubber pipe at the bottom and a valve to control concrete discharge from the skip was used. The standard QC process was used. A skip with ϕ100 mm rubber pipe at the bottom with the valve to control concrete discharge from the skip was used. SCC was dropped from the 3.0m height. No segregation was observed during the cast. The SCC also exhibited satisfactory form finish surface of columns.

4.3 Prototype Column

After successful trial in crane columns, SCC was considered for the use in the sheer walls of a high rise building. The edges of sheer walls of the high-rise building were prototyped mainly to assess the filling ability of SCC. A heavily reinforced column unit 600X600X2500 in dimension was prepared (**Fig. 8**). Vertical reinforcement bars of 28mm and horizontal stirrups of 14mm in diameter were used. The minimum clear spacing was 20mm.

The same aggregates as for the crane foundation columns were used in this application. SCC was mixed in a central mixer, then discharged to the truck agitator and delivered to the site. The same skip with ϕ100 mm rubber pipe at the bottom with the valve to control concrete discharge from the skip was used. SCC was dropped from a 2.5m height. No segregation and blocking were observed.

When the column was demoulded some slices of concrete were cut from the top to assess the filling ability of SCC and reinforcing/concrete bonding. SCC exhibited excellent passing and filling properties as can be seen in **Fig. 9**. In general, form finish was very good except a small area of honeycombing at the bottom of the column where a little loss of paste might occur.

Fig. 8: Reinforcement Cage of Column

Fig. 9: Cut Slice from Top of the Column

4.4 UV Filter Plank

The plank was 1018 mm height, 1995 mm length and 105 mm width. There were 128 plastic ϕ40 ducts densely distributed in the whole structure (see **Fig 10**). Also 'D12' reinforcement was used. The clear spacing between the obstructions was approximately 36 mm. The most critical parameters of this structure were surface quality of at least one face of the plank and the thickness of it. Using conventional vibrated concrete, the plank needed to be cast lying horizontally. In this case, the accuracy of the thickness would not be guaranteed. Hence SCC was offered to overcome this problem. In the case of using SCC, the plank was cast standing vertically.

Greywacke coarse sand and coarse aggregates of 13 mm maximum size and coastal fine sand were used. The SCC was mixed in a truck mixer. Standard batching and QC procedure were used. SCC was poured into the mould directly from the truck's discharging chute and placement was completed within a few minutes. Excellent passing ability and yet no signs of segregation were observed. The form finishing quality was "spotless", neither honeycombing nor small "bug holes" were visually observed (see **Fig. 10**).

Fig. 10: Arrangement of Plastic Ducts and Form Finish of UW Filters Plank

4.5 Road Barrier Unit

In order to demonstrate flowing ability of SCC, a road barrier unit was selected for such test. The unit was 6 m long and had a "Y" shape in cross-section with 500 mm thickness at the top, 200 mm at the bottom and was 1000 mm height. This unit was cast in conjunction with concreting the UV filter plank (see above) using the same batch of concrete. The discharging chute of the truck was positioned in the middle of the unit and SCC was poured into the unit at full discharging speed. SCC flowed very rapidly from the middle to both sides of the unit exhibiting excellent flowability and no segregation (**Fig. 11**).

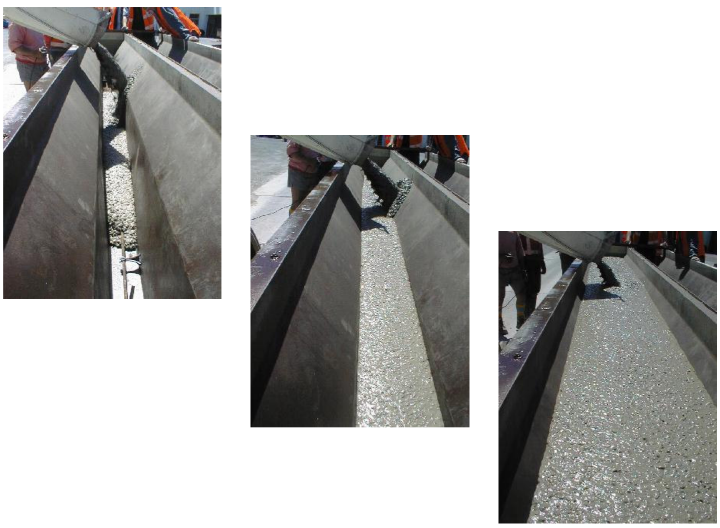

Fig. 11: Casting SCC in Road Barrier Unit

Fig. 12: Form Finish of Road Barrier Unit

The quality of form finishing surface was superior (**Fig. 12**).

4.6 'ExeLoo' Unit

This structure is part of a complete set of a stand-alone toilet unit found in public places like parks, beaches, etc. The structure consists of three vertical walls 80 mm thick and a floor of 120 mm thickness. The height of the structure was about 2200 mm. Coarse sand, coarse aggregates of 13 mm maximum size (both basalt) and coastal fine sand was used. 35-mm long 'Dramix' steel fibres were used to replace some of the reinforcement. SCC was mixed in the central mixer and then discharged to a truck agitator. A specially made funnel was installed on the top of one of the vertical walls to assist with the pouring of SCC through an 80 mm opening. An ordinary skip was used to transport and pour the SCC.

SCC demonstrated excellent flowability: flowing underneath, around and rising inside the opposite wall. Again no segregation was observed. The form finishing quality was of good quality except the area inside the unit at the bottom where loss of paste through the mould joints was noticed while pouring SCC.

5. CONCLUSION

A broad development program on self-compacting concrete containing different materials from different sources was carried out in the laboratory and in the fields. The results have shown that the two phase material mixture proportioning method can be successfully used in designing SCC with the aspect of high performance, economic efficiency, reduction of trial works at the laboratory and adjusting mix proportions of SCC with different materials for different applications. Moreover, the laboratory and full-scale trial test results indicated that it is possible to produce a marketable high performance self-compacting concrete which can meet the requirements of the construction industry in New Zealand. This leads to the fact that SCC has been considered in the industry as a product, which will be able to improve the quality and durability of structures, potentially reduce the cost of construction and create much healthier working environment in construction and production sites. Indeed, SCC is the milestone achievement in New Zealand's concrete technology.

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