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High Performance Concrete - Design & Testing of 85MPa Concrete Mix for a 60 Storied Tower Building in Toronto

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Abstract

Mix design for an 85MPa concrete was developed and tested for use in construction of a 60-storied tower building in downtown Toronto. Mix design methods considered were the ACI and Design of Normal Concrete Mixes method of the BS for which the curve between w/c ratio and compressive strength has been extended beyond 0.3. 10% of Portland cement was replaced with micro Silica as cementitious material in addition to sand and coarse aggregates. Reduced water/ binder ratio was achieved by using around 1% of superplasticizer to maintain workability. Control mix comprised of Portland cement, sand and aggregates. Testing of concrete specimen revealed improved compressive strength of up to 96MPa along with higher moduli of elasticity, lower permeability and improved durability of concrete containing 10% replacement of Portland cement with micro silica.

Keywords*:* High performance concrete, superplasticizers, supplementary cementing materials, micro silica, compressive strength

INTRODUCTION

The quality of concrete has improved tremendously over the recent years due to latest research and developments in chemicals/ supplementary cementing materials and pozzolans. High strength, high performance concretes are possible for use in tall buildings and specialized structures with efficient and economical member designs. The development of higher strength concretes has enabled skyscrapers with increased heights and sleek columns/ beams and cores along with long span structures. High performance / high strength concretes are stronger and durable. Addition of mineral admixtures like micro silica, ground granulated blast furnace slag and fly ash in concrete improves the strength and durability of concrete due to a marked improvement in the microstructure of hydrated concrete (1,2,3). Addition of microsilica reduces permeability of concrete thereby improving the chloride and frost resistance of concrete subjected to saltwater and freeze/thaw. Difference between high-strength concrete and normal-strength concrete relates to the compressive strength. ACI – American Concrete Institute defines high-strength concrete as concrete with a compressive strength greater than 6,000 psi (4,5). High-strength concrete reduces overall weight with smaller structural elements carrying loads more efficiently than normal-strength concrete and reduced overall costs. Proportioning of high-strength concrete involves making optimal quantities of the basic ingredients like Portland cement, supplementary cementing materials, suitable coarse aggregates obtained from sound rock, quality fine aggregates with optimized water and super-plasticising / water reducing admixtures. Strength, size, surface characteristics and bond with cement paste is the basic consideration for selection of coarse aggregates for high strength concrete. Pozzolan such as microsilica is most commonly used mineral admixture in high-strength/ high performance concrete (3). Pozzolans react with Portland cement hydration products to create additional C-S-H (Calcium Silicate Hydrate) gel part of the paste responsible for concrete strength. This imparts additional strength to the concrete. The super plasticizing admixtures gives the concrete adequate workability at low water-cement ratios, leading to concrete with greater strength. Use of water-reducing retarder in high strength concrete slows the hydration of the cement and allows more time to place the concrete.

ASTM C1240 is the standard specification defining micro silica for use in high strength/ high performance concretes. Micro silica for such use is an ultrafine powder collected as by-product of the silicon and ferrosilicon alloy processing. The main application of micro silica is as pozzolanic material for high strength high performance concrete. Micro silica is ultrafine material comprising spherical particles less than 1 µm in diameter which is about 100 times smaller than the average cement particle. The bulk density of micro silica depends on the degree of densification and varies from 130kg/m^3 (undensified) to 600kg/m^3 in densified form. The specific gravity of silica fume is generally in the range of 2.2 to 2.3. The specific surface area of micro silica typically ranges from 15,000 to 30,000 m^2/kg (3).

MIX DESIGN

In order to establish a procedure for mix design, a linear projection of compressive strength versus w/c ratio from Design of Normal Concrete Mixes method was considered initially beyond the limiting w/c ratio of 0.3[7]. A broad combination of ACI and BS methods was used to proportion cement/ binder, coarse aggregate, sand and superplasticizer. An initial estimate of density was made and later adjusted in the light of values actually obtained. High strength high performance concrete mix for characteristic strengths of 85MPa was designed using ordinary Portland cement (ASTM C150) with 10% micro silica conforming to ASTM C1240, crushed natural granite aggregates (maximum 10mm diameter obtained from crushing granite stone with crushing strength around 120MPa) and medium grade sand. A control mix for 85 MPa, without micro silica was also designed for comparison purposes. Table 1 gives the details of mixes. Sulfonated melamine-based superplasticizer conforming to ASTM C494 was used. Up to 9.4 l/m^3 of superplasticizer was used to maintain high workability with slumps in the range of 30-40mm for concrete containing 10% replacement of Portland cement with micro silica. A higher dosage of superplasticizer was used for the stiffer control mix to maintain workability around 25-30mm.

Table 1. Design of high strength concrete mixes.

Characteristic Strength MPa	W/C Ratio	Cement kg	Sand kg	Water kg	Aggregate kg	Super Plasticizer
85	0.24	610	642	147	1160	9.4 l/m^3
Control	0.24	610	642	147	1160	14.1l/m^3

Note: - 10% cement replaced with micro silica for 85MPa concrete.

Control did not have any %age of micro silica.

Table 2. Sieve analysis of fine aggregate

Sieve size	Weight retained (kg)	% Weight retained	Cumulative percentage weight retained	Percentage finer
10 mm	0	0	0	100
4.75mm	0.011	1	1	99
2.36 mm	0.033	3	4	96
1.18 mm	0.267	26.7	30.7	69.3
600 μ	0.341	34.1	64.8	35.2
300 μ	0.201	20.1	84.9	15.1
150 μ	0.147	14.7	99.6	0.4
Total	1.0		285	
Fineness modulus =285/100 = 2.85				

Table 3. Sieve analysis of coarse aggregate

Sieve size	Weight retained (kg)	% Weight retained	Cumulative percentage weight retained	Percentage finer
10 mm	0	0	0	100
4.75 mm	790	39	39	61
2.36 mm	1190	58	97	3
1.18 mm	0	3	100	0
600 μ	0	0	100	0
300 μ	0	0	100	0
150 μ	0	0	100	0
Total	0	0	100	0
Fineness modulus = 636 /100 = 6.36				

DESCRIPTION OF TESTS

Following test samples were prepared for testing the 85MPa concrete and the control specimen for laboratory testing.

a. 150mm cubes & 150x300mm cylinders for compressive strength testing.

b. 150x150x750mm beams for flexural strength testing.

c. 150mm diameter, 300mm long cylinders for testing the static modulus of elasticity.

d. 150x150x750mm beams for testing dynamic modulus of elasticity.

e. 150mm cubes for testing ultrasonic pulse velocity in specimen.

f. 150mm cubes for testing initial surface absorption.

g. 150mm cubes for measuring density of concrete.

h. 150mm cubes for testing the sulphate and chloride resistance of concrete. (Samples immersed in 5% H_2SO_4 and 5% HCl solutions for 90 days and measuring weight loss).

i. All specimen were cured in water at 20^0 C for 60 days before testing.

DISCUSSION OF TEST RESULTS

Table 4. Test Results

W/C Ratio	Mix	Cube Strength 7Days N/mm^2	Cube Strength 28Days N/mm^2	Cube Strength 42Days N/mm^2	Cube Strength 60Days N/mm^2	Cylinder Strength N/mm^2	Flexural Strength N/mm^2
0.26	85MPa	72	82	85	96	76	11
0.26	Control	74	81	86	89	67	7.8

W/C Ratio	Mixes	ISAT ml/m^2/s	Elastic Modulus N/mm^2	Dynamic Modulus N/mm^2	Pulse Velocity km/s
0.26	85MPa	0.17	39362	59563	5.82
0.26	Control	0.20	37183	54123	4.27

Table 4 gives the results of testing for control as well as 85MPa concrete with 10% replacement of Portland cement with micro

Compressive strength

Compressive strength tests on 85MPa concrete specimen at 7, 28, 42 and 60 days shows that the rate of development of strength of concrete containing 10% Portland cement replaced with micro silica was similar to that for control specimen though slightly slower than the control concrete mix. The compressive strengths of 85MPa concrete with 10% Portland cement replaced with micro silica was somewhat higher than the control specimen. The compressive strength of specimen kept increasing up to 60 days when the specimen could achieve design strengths. This is typical of concretes with low w/c ratios in which hydration of cement is slow and needs water from external sources for hydration [4-6]. 85MPa concrete with micro silica developed about 74% of its design strength in 7 days while complete design strength of 85MPa developed in 42 days.

During the testing of specimen, it revealed that complete section of 85MPa concrete specimen failed suddenly on reaching failure loads while the paste and the aggregates failed simultaneously at the failure interface. This kind of failure is typical of high strength concretes [4,5]. Sudden failure of specimen can cause damage/ injury and necessary protective measures are required to be taken.

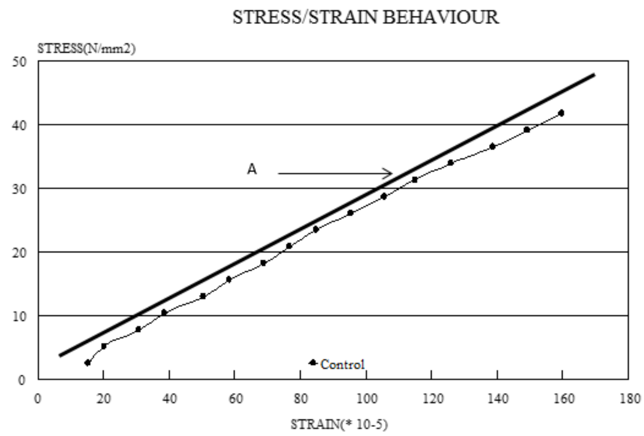
Flexural strength

The flexural strength of 85MPa concrete containing 10% replacement of micro silica have been observed to possess 3 to 4% higher flexural strength as compared to control specimen. Higher flexural strengths are certainly a consequence of higher compressive strengths and increased density of concrete containing micro silica due to which a finer microstructure results on formation of hydration products of binder in concrete.

Stress/strain behavior

General form of the stress/strain behavior of 85MPa concrete containing micro silica is quite similar to that for control specimen. Stress strain curves for concrete containing micro silica as well as concrete control specimen remained linear up to the point of failure, typical of high strength concretes. Testing of concrete with 10% replacement of Portland cement with micro silica resulted into higher static and dynamic moduli as compared to similar concrete with Portland cement only. Idealized stress/strain relationship is shown in Figure 1.

Figure 1. Idealized Stress – Strain Curves



Control – 100% Portland cement

A – Concrete with 10% Portland cement replaced with micro silica

Figure 1. Stress Strain Relationship

Static modulus of elasticity

The average static modulus of elasticity for 85MPa concrete with 10% replacement of Portland cement with micro silica has been observed to be 6% higher than the control specimen. Static modulus of elasticity for 85MPa concrete with 10% replacement of cement with micro silica is observed to be around 39362N/mm^2 compared to 37183N/mm^2 for concrete containing Portland cement only.

Dynamic modulus of elasticity

Dynamic modulus of elasticity for 85MPa concrete with 10% replacement of Portland cement replaced with micro silica was observed to be the higher by 10% than the control specimen. Dynamic modulus of 85MPa concrete with 10% replacement of Portland cement with micro silica was found to have a dynamic modulus of 59563N/mm^2 as compared to 54123N/mm^2 for control.

Ultrasonic pulse velocity

The ultrasonic pulse velocities for 85MPa concrete with 10% replacement of Portland cement with micro silica and control specimen of concrete with Portland cement only are given in Table 4. Pulse velocity across 85MPa concrete with 10% replacement of Portland cement containing micro silica was observed to be 5.82 km/s as compared to 4.27 km/s for control specimen. Ultrasonic pulse velocity for 85MPa concrete with 10% replacement of Portland cement replaced with micro silica is around 4% higher than the control specimen.

Density of hardened concrete

The average saturated and oven-dried densities for 85MPa concrete with 10% replacement of Portland cement was observed to be 2511 and 2494kg/m^3 respectively, as compared to control mixes which were 2480 and 2456kg/m^3, respectively. The saturated and dry densities of 85MPa concrete with 10% replacement of Portland cement with micro silica are about 3% higher than the control mixes. Better hydration and packing of finer materials in 85MPa concrete with 10% replacement of Portland cement with micro silica results into lower absorption and higher density as compared to control mixes.

Initial surface absorption (ISAT)

Initial surface absorption tests for 85MPa concrete with 10% replacement of Portland cement with micro silica was observed to be 0.17 ml/m^2/s as compared to 0.2 ml/m^2/**s** for control mixes. Hence initial surface absorption of 85MPa concrete with 10% replacement of Portland cement with micro silica was observed to be 18% lower as compared to control specimen. The ISAT values are compared with the guidelines given by the Concrete Society Technical Report # 31. Results of ISAT are given in Table 4.

Shrinkage.

Shrinkage measurements of all specimen were observed to be almost similar for all specimen. No appreciable difference in shrinkage of specimen of 85MPa concrete with 10% replacement of Portland cements and control mixes were observed over a period of 90 days.

Sulphate and chloride resistance

Weight loss of specimen immersed in 5% HCL (Hydrochloric acid) solution for 90 days resulted into a weight loss of 8% for control specimen as compared to 3% for 85MPa concrete with 10% replacement of cement with micro silica. Similarly, when the specimen were immersed in 5% H_2SO_4 (Sulphuric acid) solution for 90 days, the weight loss for control specimen was 6% as compared to 1.4% for 85MPa concrete with 10% replacement of cement with micro silica. Therefore, the performance of concrete with micro silica was more than twice better in acidic environment and almost four times better in sulphate environment as compared to concrete with ordinary Portland cement control mixes. It is mainly due to the negligible amounts of $Ca(OH)_2$ present in the products of hydration along with lower permeabilities and stable compounds formed due to secondary chemical actions by the micro silica content.

CONCLUSIONS

Satisfactory 85MPa mixes with 10% replacement of Portland cement with micro silica can be designed. 85MPa concrete specimen with 10% replacement of Portland cement with micro silica developed about 8% higher compressive strengths, 4% higher flexural strength, 6% higher static moduli of elasticity, 10% higher values for dynamic moduli, about 4% higher pulse velocities, 3% higher density, low permeabilities and two to three times improved sulphate and acid resistance as compared to control specimen. 85MPa concrete with 10% replacement of Portland cement with micro silica certainly improves the strength and durability of such high-performance concrete making it a more acceptable material for major construction projects.

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